Faculty of Engineering

The University of Nottingham

UNITED KINGDOM · CHINA · MALAYSIA

An Investigation into the Overheating Risk in Low-Energy New-Built Homes

Vasileios Sougkakis

Bsc, Msc

Thesis submitted to the University of Nottingham

for the Degree of Doctor of Philosophy

September 2016

To my father

ABSTRACT

Recently, overheating in British housing has received increased attention due to climate change and consequent impact on the thermal comfort and the health of building occupants. The risk of overheating becomes even larger considering the requirements for higher insulation and airtightness levels set by building regulations. Passive design strategies, such as the use of thermal mass and ventilation, for regulating indoor temperatures may improve the thermal comfort of occupants without the use of energy intensive equipment.

Modern Methods of Construction (MMC) are expected to play a significant role in the future outputs of the housing construction sector. However, MMC, which generally present low levels of thermal mass, are treated with scepticism by designers since they are considered to be more prone to overheating compared to masonry constructions. Due to the lack of extensive research data on the thermal performance of these systems, however, it can be inferred that concerns may be based on the perception of the industry rather than actual data. Therefore, the work presented in this thesis investigated the risk of overheating in dwellings built with MMC.

The analysis considered the performance of the constructions from various perspectives following a route from the general investigation to the more specific characteristics of the building elements. First, an investigation of the zone temperatures obtained through monitoring and through whole building dynamic simulations was performed, in an attempt to evaluate the relative performance of different construction types and building elements. Next, the interaction of the various building elements with their surrounding space was assessed through monitoring the heat flows and the temperatures on the surface of these elements in situ. Finally, a more detailed investigation of the dynamic characteristics of these elements under fixed conditions was conducted through laboratory testing and Finite Element Analysis (FEA).

A parametric simulation study of ambient temperatures in a timber frame building considered the potential to use non-traditional materials for regulating internal temperatures. Results showed that overheating was an issue in most of the zones examined for the conventional timber frame construction. The use of additional materials resulted in reduced overheating levels of up to 85% in some cases; this evidence may be used to inform designers when considering measures to reduce the overheating risk of MMC. In another study of two houses built with different construction methods, it was found that the timber frame and modern masonry walls had very similar performance, with the latter presenting slightly reduced levels of overheating in some cases (up to 12% lower compared to timber frame).

Monitoring the heat flows at the surface of the building elements in situ as well as through laboratory testing and FEA showed that difference in performance between masonry constructions and MMC was not always as clear as expected from the construction characteristics of the elements. It was clear that conventional masonry constructions do not benefit fully from the increased mass and had comparable performance with some MMC. Phase Change Materials (PCM) were also found more responsive than conventional plasterboard in situ, although some discrepancy compared to the theoretical performance was identified. The findings of this study may be useful for designers so that optimum use of the benefits of thermal mass is made.

PUBLICATIONS

Published

Refereed scientific journal publications

RODRIGUES, L., SOUGKAKIS, V. & GILLOTT, M. 2015. Investigating the potential of adding thermal mass to mitigate overheating in a super-insulated low-energy timber house. *International Journal of Low-Carbon Technologies*.0, 1-12

Refereed Scientific Conferences Papers

SOUGKAKIS, V., RODRIGUES L., GILLOTT. M. & TUBELO, R. 2015. As-Built Performance Evaluation of a Prefabricated Low-Energy Timber Dwelling: The Nottingham H.O.U.S.E. In *PLEA 2015 – 31st International PLEA Conference.* Bologna, Italy

SOUGKAKIS, V., RODRIGUES, L., NAZER, H. & GILLOTT, M. 2014. Comparing the thermal performance of timber frame vs masonry low-energy dwellings in the UK today and in the future. *SET 2014 - 13th International Conference on Sustainable Energy Technologies.* Geneva, Switzerland

RODRIGUES, L., GILLOTT, M. & SOUGKAKIS, V. 2013. The Use of Thermal Mass to Mitigate Overheating in an Affordable Low-Energy Pre-fabricated Timber House. *SET 2013 - 12th International Conference on Sustainable Energy Technologies,* Hong Kong

Book Chapters

RODRIGUES, L., TETLOW, D., GILLOTT, M. & SOUGKAKIS, V. 2014. Chapter 10: The Application of Phase Change Materials to Improve the Climate Resilience of a Low-Energy Prototype House. *In:* DINCER, I., MIDILLI, A. & KUCUK, H. (eds.) *Progress in Sustainable Energy Technologies Vol II: Creating Sustainable Development.* Switzerland: Springer International Publishing.

ACKNOWLEDGEMENTS

Carrying out this research project has been a challenging an adventurous journey with many great but also many intense moments. A lot of hard work was required but it would not be enough if I did not have the support of many people. I would like to thank the following:

My supervisors Dr Lucelia Rodrigues and Professor Mark Gillott for giving me this great opportunity as well as for their guidance and support throughout the course of this project. This project would not be possible without your help.

Dr Chris Wood for his guidance and help in the experimental setup and for all the fruitful discussions on the data analysis.

Professor John Chilton for his valuable feedback and informative comments during project reviews.

Technicians David Oliver and John Moss for offering the resources required and more importantly their vast engineering skills.

The occupants and staff of the houses and offices monitored for welcoming me and tolerating with the equipment that invaded their lives

To all my friends and colleagues that were there for me and made these years of my life one of the most memorable experiences

My brother, Petros, and my mother, Athanasia, for their constant moral support they provided throughout the difficult times.

My wife, Effie, for the love and encouragement throughout these years and for patiently tolerating with my unpredictable schedule. And of course my wonderful daughter, Dimitra, who brightens our lives.

Finally, this work is dedicated to the person that inspired me the most, my father Dimitris. He always believed in me and encouraged me to follow my aspirations. Despite the fact that he is not with us anymore he will always be the person to look up to. This work would have never happened if it wasn't for him.

TABLE OF CONTENTS

LIST OF EQUATIONS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ARCC CN: Adaptation and Resilience to a Changing Climate Coordination Network

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

ATTMA: Air Tightness Testing and Measurement Association

BIM: Building Information Modelling

BRE: Building Research Establishment

BUPAS: Buildoffsite Property Assurance Scheme

CDF: Cumulative Distribution Function

CEH: Creative Energy Homes

CfSH: Code For Sustainable Homes

CIBSE: Chartered Institution of Building Services Engineers

COPSE: Coincident Probabilistic climate change weather data for a Sustainable built Environment

CTF: Conduction Transfer Method

CVRMSE: Cumulative Variation of Root Mean Squared Error

DECC: Department of Energy and Climate Change

DEFRA: Department for Environment, Food and Rural Affairs

DER: Dwelling Emission Rate

DFEE: Dwelling Fabric Energy Efficiency

DSY: Design Summer Hear

EAHE: Earth-Air Heat Exchanger

EDSL: Environmental Design Solutions Limited

EFUS: Energy Follow-Up Survey

EPBD: Energy Performance of Buildings Directive

EPC: Energy Performance Certificate

EPS: Expanded Polystyrene

EPSRC: Engineering and Physical Sciences Research Coucil

ERP: Enterprise Resource Planning

FEA: Finite Element Analysis

FEES: Fabric Energy Efficiency Standard

FSC: Forest Stewardship Council

HFP: Heat Flux Plate

HLC: Heat Loss Coefficient

ICF: Insulated Concrete Formwork

LCF: Low Carbon Futures

LCIP: Local Climate Impacts Profile

MMC: Modern Methods of Construction

MVHR: Mechanical Ventilation Heat Recovery

NHBC: National House Building Council

NMBE: Normalised Mean Bias Error

PCM: Phase Change Material

PCP: Precast Concrete Panel

PDEC: Passive Downdraught Evaporative Cooling

PHPP: Passivhaus Planning Package

PMV: Predicted Mean Vote

PPD: Percentage of People Dissatisfied

PRF: Periodic response Factor

PV: Photovoltaic

RF: Response Factor

SAP: Standard Assessment Procedure

SCCIP: Scottish Climate Change Impacts Partnership

SIP: Structural Insulated Panels

TAS: Thermal Analysis Software

TER: Target Emission Rate

TFA: Treated Floor Area

TFEE: Target Fabric Energy Efficiency

TMP: Thermal Mass Parameter

TRY: Test Reference Year

UKCES: UK Commission for Employment and Skills

UKCIP02: UK Climate Impacts Programme

UKCP09: UK Climate Projections

UoN: University of Nottingham

URF: Unit response Function

WG: Weather Generator

ZCH: Zero Carbon Hub

NOMENCLATURE

A: Area (m^2)

ACH: Air Change per Hour (1/h)

A_j: Inside CTF coefficient, j = 0,1,2,…,m

B_j: Cross CTF coefficient, j = 0,1,2,…,m

c: Effective thermal capacity (Wh/m^2K)

C_{clo}: Convective heat loss from clothed surface (W)

C_j: Flux CTF coefficient, j = 0,1,2,…,p

c_j: Specific heat capacity of layer j (kJ/kg·K)

C_m: Heat capacity of a building element adjacent to zone m (J/K)

C_p: Specific heat capacity (kJ/kg·K)

C_{res}: Convective heat loss from respiration (W)

D_j: Outside CTF coefficient, j = 0,1,2,…m

d_j: Thickness of layer j (m)

D_T: Duration of test to determine the in-situ thermal resistance of building elements (days)

E_{is}: Heat losses by water vapour diffusion from skin (W)

E_{res}: Heat losses from respiration (W)

E_{SW}: Evaporative heat losses by sweat from skin (W)

f: Decrement factor

H: Net metabolic heat production (W)

h_{ey} = Number of hours of exceedance of temperature

K: Conductive heat transfer from skin to the outer surface of clothing (W)

k: Conductivity (W/m·K)

L_{mn}: Periodic thermal conductance (W/K)

L_p: Period of fundamental harmonic (s) n: Current time step

n_{heavy}: Number of massive surfaces of a typical room

p: Number of variables

Q: Power input, W

q: Heat flux (W/m^2)

$q_{i,\,n}$: Heat flux at the inside surface of a bulding element at time n (W/m^2)

$q_{o,\,n}$: Heat flux at the outside surface of a bulding element at time n (W/m^2)

$\hat{q}_{m,n}$: Complex amplitude of heat flux at the surfaces of an element adjacent to zones m and n respectively (W/m^2)

Q_n = Hourly heat gain in the surface under consideration (W)

R: Solar aperture (m^2)

R_{clo}: Radiative heat loss from clothed surface (W)

$r_{i\text{-}i}$: Response of the inside surface due to an excitation on the same surface (W/m^{2}K)

$r_{i\text{-}o}$: Response of the internal surface due to an excitation on the outside surface (W/m^{2}K)

r_j = Response factor at time j (W/m^{2}K)

$r_{o\text{-}o}$: Response of the outside surface due to an excitation on the same surface (W/m^{2}K)

$r_{o\text{-}i}$: Response of the external surface due to an excitation on the internal surface (W/m^{2}K)

$r_{Pearson}$: Pearson product moment coefficient

R_s: Thermal resistance of the boundary layer (m^{2}K/W)

R-value: Thermal resistance (m^{2}K/W)

S: Solar irradiance, W/m^2

T: Temperature (K)

t: Time (s)

T_{accept}: Acceptable temperature limits (^{o}C)

T_{comf}: Optimal comfort temperature (^{o}C)

T_i: Temperature on the inside surface of a building element (K)

T_{lim}: Range of acceptable temperatures (^oC)

T_{max}: Maximum acceptable temperature (^oC)

$T_{m,o}$: Mean outdoor temperature (^oC)

T_o: Temperature on the outside surface of a building element (K)

T_{od-n}: Daily mean temperature for the n-th day prior to the current day (^oC)

T_{op}: Operative temperature (^oC)

T_{rc}: Constant zone temperature (K)

T_{rm}: Exponentially running mean of the daily mean outdoor temperature (^oC)

T_{sa}: Sol-air temperature (K)

u_0 = Steady state component of time series (^oC)

u_m = Amplitude of m-th sine wave of a harmonic (^oC)

U-value: Thermal transmittance (W/m^2K)

v_m = Amplitude of the m-th cosine wave of a harmonic (^oC)

W_e: Weighted exceedance

WF: Weighting factor

x: Distance in the x-direction (m)

x_i: Independent variable

$\overline{x}$: Average value of independent variables

Y_{mm}: Thermal admittance of the surface of a building element adjacent to zone m (W/m^2K)

Y_{mn}: Periodic thermal conductance of a building element adjacent to zones m and n (W/m^2K)

y: Distance in the y-direction (m)

y_i: Dependent variable

$\overline{y}$: Average value of independent variables

y_i^{meas}: Value of measured variable

$\overline{y}^{meas}$: Average value of measured variables

y_i^{sim}: Value of simulated variable z: Distance in the z-direction (m)

Z: Heat transfer matrix

Z_{mn}: Element of heat transfer matrix

Greek letters

α: Thermal diffusivity (m^2/s)

β = Constant (<1) in the calculation of the running mean temperature

δ: Time step duration (hours)

ΔT: Temperature difference, (K)

$\bar{\theta}n$: Average values of temperature at zone n (^oC)

$|\hat{\theta}n|$: Amplitude of temperature sine wave variation at surface adjacent to zone n (^oC)

κ: Areal heat capacity (kJ/m^2K)

ρ: Density of the material (kg/m^3)

ρ_j: Density of layer j (kg/m^3)

φ: Phase difference of the heat flow (rad)

$\bar{\Phi}n$: Average value and heat flow (W)

$|\hat{\Phi}n|$: Amplitude of heat flow sine wave variation (W)

ω: Angular frequency (rad/s)

ψ: Phase difference of the temperature (rad)

CHAPTER 1. INTRODUCTION

1.1 General Background

The UK construction industry is facing two major challenges. In order for a projected housing shortage to be avoided, it is required to deliver significantly more houses per year than it historically did. Following a declining trajectory from the 1970s onwards, annual housing completions amount to approximately 170,000 – 180,000 units on average. However, due to a projected increase on the number of households as a result of population increase and reduction of the household size, significantly more dwellings will be required per annum. It is expected that the number of UK households will exceed 27.5 million by 2033 (Department for Communities and Local Government, 2010b). Several studies have estimated that a figure between 230,000 to 330,000 dwellings will be required to tackle the projected housing shortage (Banham et al., 2012, Holmans, 2013, Miles and Whitehouse, 2013).

The second challenge that the industry faces is that the new houses are required to be constructed to very high levels of energy efficiency standards. Under the Kyoto Protocol Agreement, the UK undertook the commitment to reduce its greenhouse gas emissions in 2012 by 12.5% compared to the 1990 levels. In addition, the UK has set the legally binding target to reduce its CO_2 emissions by 34% by 2020 and by 80% by 2050 compared to the 1990 levels (Climate Change Act 2008, The Climate Change Act 2008 (2020 Target, Credit Limit and Definitions) Order 2009). Achieving these targets requires decarbonising all sectors of the economy: industry, power and heat production, buildings, transport and agriculture, land use, forestry and waste. With regards to the residential sector, building regulations setting requirements for increased levels of insulation and air tightness were put in effect. In addition, policies and schemes that aimed at delivering highly energy efficient houses were set. Despite the fact that these policies have now been withdrawn (Zero Carbon Homes, Code for Sustainable Homes) it is expected that they will be replaced by similar strategies. Furthermore, voluntary low-carbon standards for buildings posing even stricter requirements for energy efficiency, such as the Passivhaus Standard, are becoming increasingly popular.

These high levels of insulation and air-tightness aimed at reducing the heating load of buildings but may lead to a controversial effect. It is widely considered that such measures may lead to buildings with increased risk of overheating since their ability to reject and dissipate unwanted heat will be limited. Overheating was not considered historically to be an issue of great importance in the UK. Over the past decades however, the risk of dwellings suffering from elevated temperatures has gained significant attention. This was mainly due to the occurrence of recent heatwaves in the UK and Western Europe with severe consequences for the most vulnerable sections of the population. It was reported that the 1995 heatwave resulted in 619 excess deaths in England and Wales while the 2003 heatwave resulted to an estimated 30,000 – 35,000 deaths across Europe (ZCH, 2012); in the UK this figure reached approximately 2,000 additional deaths (Richards Partington Architects, 2012). Currently 20% of the UK building stock is considered to be subject to overheating (Zero Carbon Hub, 2016). This figure is likely to increase when considering the effects of climate change. Climate projections suggest that in the future hotter and drier summers will be experienced in the UK and that extreme weather events (such as the heatwave in 2003) will occur more often (Gething, 2010, Gething and Puckett, 2013). The cooling demand of buildings is therefore expected to increase while the heating demand is expected to decrease in the future.

One of the main strategies to reduce the occurrence of elevated temperatures in dwellings is the use of thermal mass. Building elements with high levels of thermal mass have the ability to absorb excess heat from a zone and readmit it back to space at a later stage when the indoor temperatures have decreased. Peak indoor temperatures and the cooling load of buildings may be reduced in this manner. The use of this strategy is wide in countries with hot climate and large diurnal temperature variation and significant research has been conducted to investigate the overheating occurrence of dwellings built with different levels of thermal mass in the UK climate (Orme and Palmer, 2003, Orme et al., 2003, Hacker et al., 2005a, Arup Research and Development and Bill Dunster Architects, 2005, Hacker et al., 2008, Rodrigues, 2009, Peacock et al., 2010, Kendrick et al., 2012, Gupta and Gregg, 2012, Rodrigues et al., 2013a, Rodrigues et al., 2014, Sougkakis et al., 2014, Rodrigues et al., 2015).

It is considered that the industry will struggle to deliver the high rates of housing deliveries at such high levels of quality and energy efficiency. Miles and Whitehouse (2013) argued that the industry capacity using conventional construction methods is between 130,000 and 150,000 units. Modern Methods of Construction offer the potential for achieving the additional house building rates required at a consistent level of energy performance and their use is expected to rise significantly over the following years.

However, most MMC methods have low levels of thermal mass and as a consequence they are considered to have increased risk for overheating compared to traditional masonry construction methods. To date there has been very little research on the actual thermal performance of MMC methods and it is considered unfair to dismiss the benefits that they may offer in the building sector based on assumptions on their performance (Rodrigues, 2009). In addition, Kendrick et al. (2012)

argued that conventional masonry construction methods do not benefit fully from the merits of thermal mass, as the masonry materials are either decoupled from the space or are not truly heavyweight. For these reasons, the work presented in this thesis focuses on the overheating risk of MMC constructions and compares that to conventional construction methods used in house building.

1.2 Research aims and objectives

The aim of this work is to address the following research questions

a) whether dwellings built with Modern Methods of Construction are likely to overheat in the current and future climate, and
b) if so, is this risk of overheating higher for dwellings built with MMC compared to those built with traditional construction methods

The main objectives of the work are:

- To determine the likelihood of overheating of MMC dwellings in the current and future climate
- To compare the overheating risk of MMC dwellings against that of dwellings built with conventional construction methods
- To investigate the thermal performance of non-conventional lightweight materials and identify their ability to provide additional levels of thermal mass in buildings without adding much weight to the structure
- To provide data on the in-situ thermal performance of building elements constructed with MMC and modern masonry methods
- To provide evidence on the in situ performance of PCM boards and compare against their theoretical lab-based performance
- To determine the thermal response of building elements constructed with MMC and modern masonry construction methods under specific temperature excitations set by methods commonly used to assess the transient response of walls

1.3 Timeliness and Significance

As MMC methods are on the verge of becoming widespread amongst developers, this work is considered timely and relevant. It aims at providing evidence on the actual thermal performance of these methods so that designers are able to make informed decisions when considering the energy performance of potential solutions.

To date there has been no similar study examining the thermal performance of MMC constructions with such scrutiny and holistic manner. The novelty of the work also lies on the fact that it is the first study to report on the in-situ performance of MMC building elements and PCM boards for such long-term monitoring period. Furthermore, it provides a methodology to evaluate the transient thermal response of these elements and to assess the ability of the most common methods used to characterise the dynamic response of constructions in estimating their performance under actual operating conditions. Finally, the studies conducted at the course of this project address the need for additional monitoring studies on overheating and the performance gap and are a significant contribution to this growing body of knowledge.

1.4 General Methodology

The research approach followed a route from the general to the more specific applications. The thermal performance of constructions was first evaluated at a whole house and zone level by assessing indoor air temperatures. Next, the temperatures and heat flows occurring at the surface of building elements in situ under normal operating conditions were examined in order to investigate the effect of the construction methods on the resulting indoor conditions. Finally, to isolate all other parameters affecting the response of the different construction elements, these were examined under controlled conditions. The general methodology for each step of the analysis is presented below.

Whole Building level

The risk of overheating and the effect of the construction type on the resulting temperatures was first investigated though the analysis of zone and average whole house temperatures through monitoring and dynamic simulations. Two case studies were examined at this stage: The Nottingham H.O.U.S.E., a timber frame modular building located at the Department of Architecture and Built Environment, University of Nottingham (Chapter 4) and the Green Street case study (Chapter 5) where the performance of two dwellings, one of timber frame and one of masonry construction were assessed.

The monitoring study was conducted with the use of Tinytag TGU 4500 and TGU 4017 sensors for recording internal zone and external temperatures. The relative performance of the constructions was assessed through investigating the frequency of temperatures exceeding specific thresholds established by CIBSE. Peak zone temperatures and daily temperature fluctuation were also considered in the analysis. Similarly, the zone temperatures from the dynamic simulations were also assessed with the same criteria.

Performance of building components in situ

In order to determine the effect of the constructions on the resulting indoor temperatures, the next step of the analysis involved monitoring the performance of building elements in situ. Heat flows occurring at the surface of various building elements of different construction methods were recorded for a minimum period of 12 months. These building elements were found in zones of the Creative Energy Homes project.

Heat flows were recorded with the use of a HUKSEFLUX HFP01 heat flux sensor that was installed at the surface of the external wall, the internal wall and the ceiling (internal or external depending on the zone) of the selected zones. T-type thermocouples were also installed in the vicinity of each heat flux sensor to monitor the surface temperature of the element as well as the air temperature in each zone. The analysis considered the evaluation of the zone temperature, the net daily average amount of heat occurring at the surface of the elements as well as the daily average amount of energy absorbed and released by the elements.

Response of building components under controlled conditions

The thermal response of specific building components was investigated under controlled conditions at third stage of the analysis in order to assess their performance in isolation to other design parameters that are met in situ. This was performed through experimental investigation in laboratory conditions and through the use of appropriate Finite Element Analysis software (FEA). A model of each construction element was created in commercial software ANSYS Workbench 16.1 using the Transient Thermal Analysis component. Validation of the software was first conducted by comparing simulation results to the ones obtained by physical testing of a brick wall in a climate chamber. The response of the walls under the following set conditions commonly used to determine the dynamic characteristics of building elements was then investigated:

- Unit sinusoidal temperature excitation
- Unit pulse temperature excitation
- Actual temperature conditions

1.5 Thesis outline

In the first chapters the relevant background information is provided to the reader. Information on the nature of Modern Methods of Construction and the context at which these are used (housing market, building regulations and low carbon standards) are presented in Chapter 2. In Chapter 3, concepts central to the rest of the study are presented. The reader is introduced to the issues of overheating, climate change projections and thermal mass as strategy to regulate internal temperatures.

In Chapter 4, the investigation of the thermal performance of the Nottingham H.O.U.S.E. is presented. The building served as a case study to assess the ability of timber frame construction, and consequently most MMC methods, to deliver houses with high level of energy performance and examine the overheating potential of timber frame constructions through the analysis of zone air temperatures. In addition, the potential of non-traditional materials that are lightweight and readily available to be incorporated in existing MMC constructions, to provide additional levels of thermal mass was considered in a parametric analysis.

In Chapter 5 the relative performance of MMC dwellings compared to those built with modern masonry methods is presented through a case study; the Green Street development. The study reports on the findings a three year monitoring period of the zone temperatures in two dwellings, one of timber frame and the other of masonry cavity construction, with similar design features. Furthermore, a parametric simulation analysis is conducted to isolate other design factors that are affecting the resulting internal conditions and assess the current and future risk of overheating of these constructions.

Following the analysis of air temperatures, the next step of the study is to evaluate the heat flows occurring on the surface of MMC building elements under normal operating conditions. Building elements of different constructions found at the Creative Energy Homes (CEH) Project, were monitored for a minimum of twelve months. The description of the houses and the constructions investigated are presented in Chapter 6 and the results of the study are presented in Chapter 7.

The transient response of the external wall constructions found in the CEH project is further evaluated through an integrated methodology involving physical testing in a climate chamber and Finite Element Analysis (FEA) simulations. The methodology and the results are presented in Chapter 8. Finally, the conclusions of the work and suggestions for advancing research in the performance of MMC are presented in Chapter 9.

CHAPTER 2. HOUSING AND MODERN METHODS OF CONSTRUCTION

Housebuilding industry in the United Kingdom is facing some major challenges. In order to tackle a predicted housing shortage the annual deliveries will be required to increase, exceeding considerably the annual historic output. Due to the increasingly stricter requirements set by Building Regulations on energy efficiency, new dwellings will also have to be built to higher levels of insulation and airtightness.

In order to meet this two-fold challenge the industry will need to change the way it operates, through modernizing and rationalizing its processes and methods. Traditional practices that are predominantly used for the construction of dwellings have resulted in the sector being characterised as ineffective. Modern Methods of Construction (MMC), which are not used extensively at present, have several advantages to offer compared to traditional construction methods and the potential to improve the efficiency of the construction sector. Evidence suggests that MMC are expected to represent a significant proportion of the housing output in the future. However, there are still concerns on the performance of these systems among the industry stakeholders.

The performance of these systems is central to this work and therefore the relevant background information on MMC is given in this chapter. First, the context at which the house construction industry operates is presented. The conditions of the housing market and the building regulations that are setting the requirements on energy efficiency, along with other popular voluntary low carbon standards, are discussed in detail. Next, information on the nature of MMC systems is provided. The drivers that suggest that these methods will become widespread in the future and the barriers that are currently limiting their use are discussed. Examples of successful use of these methods are also provided to highlight the ability of these methods to be utilised both at large scales as well as high levels of performance. Finally, the concerns regarding the thermal performance of dwellings built with MMC, which is the focus of this work, are discussed.

2.1 Housing Market

The UK construction industry is one of the main sectors of the UK economy with an output of approximately £103 billion in 2014 representing approximately 6.5% of the total output of the UK economy, and employing 2.1 million people (Infrastructure and Projects Authority, 2016). The industry was particularly affected by the recession.

The economy in total after an initial decrease in output in 2008, stabilised in 2009 and then followed a steadily increasing route since. This was not the case with the construction industry that experienced several drops and surges. The sector experienced a major decline in output until 2009, when it briefly stabilised and managed to increase in 2010 and maintained those output levels until 2012. In 2012 -2013 the industry experienced another major decline. As of 2013, steady increase in output has been experienced reaching levels similar to the 2008 figure for the first time in seven years (Figure 2-1).

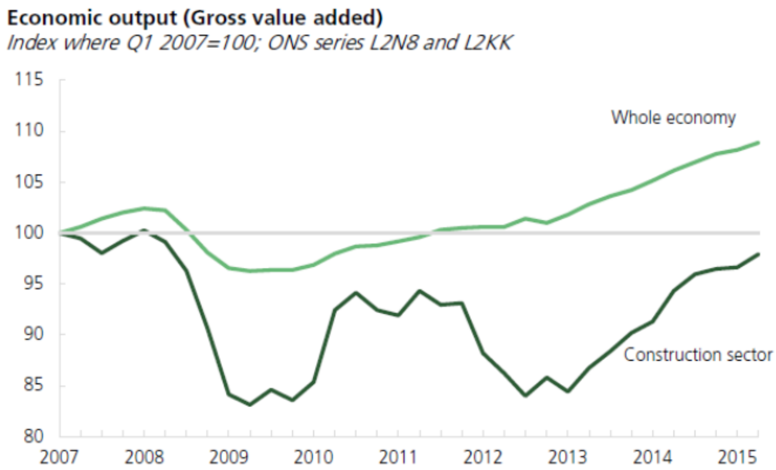


Figure 2-1: Trajectory of the economic output in terms of Gross Value Added of the construction industry and the whole economy (Rhodes, 2015)

The housing sector has also been hit hard by the economic downturn, with housebuilding activity experiencing severe decline since 2008 with periods of minor recovery. New housing completions in the United Kingdom fell rapidly from 2008 until 2011 when they recovered briefly during the period 2011 – 2012 and then fell back in the following year. As of 2012 housing completions followed an increasing trajectory remaining however significantly lower than the 2007-8 peak; approximately 152,380 dwellings were completed in the UK in 2014-2015 compared to approximately 218,500 in 2007-2008 (DCLG, 2015).

However, despite the evident effect of the economic downturn to the short and medium term output of the housing sector, this only seems to be part of a more general trend towards a long-term decline in annual deliveries as seen in Figure 2-2 (DCLG, 2015). It is apparent that the housing deliveries have dropped significantly since the 1970s and, since the 1980s, had somewhat stabilised to an average of 170,000 – 180,000 units per year.

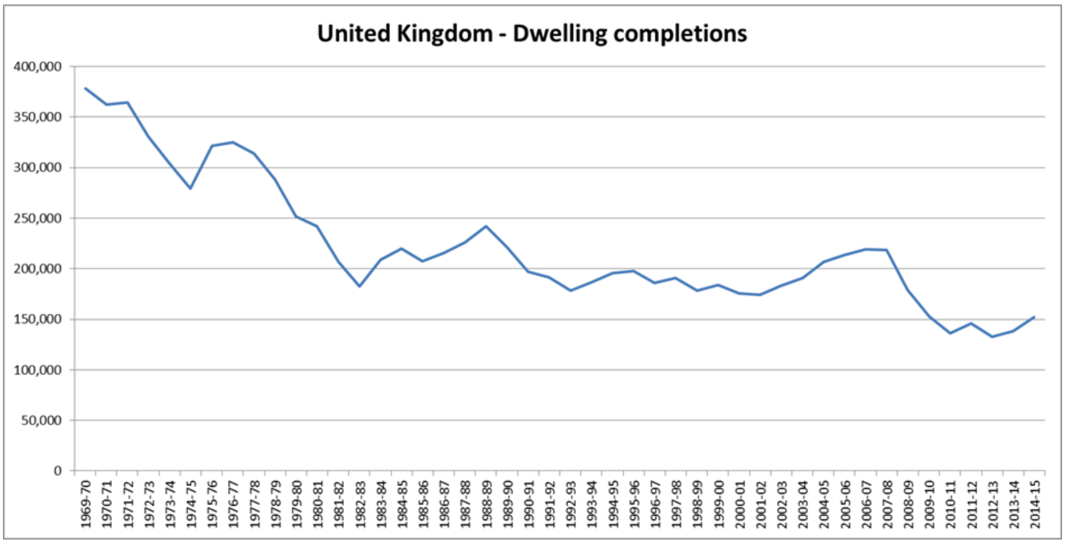


Figure 2-2: Annual building completions in the UK

The reduced levels of housing deliveries combined with increased demand in new housing are considered the main factors which have contributed to a shortage in the housing market. The UK government decided in 2007 to set ambitious targets for delivering two million homes by 2016 and three million by 2020. An annual delivery rate of 240,000 new dwellings was set for achieving this target (The Secretary of State for Communities and Local Government, 2007). However, this target was never met. During the following years of recession the housing construction industry experienced significant reductions in output and these building rates were far from being achieved with housing shortage being exacerbated.

The latest household projections suggest that by 2037 the number of households in England will increase by 5.2 million (27.5million in 2037 compared to 22.3million in 2012). The expected average annual increase of households is 210,000 households per annum (220,000 by 2022) (Department for Communities and Local Government, 2015). Several reports have been published estimating the required annual housing delivery demand in England to tackle the predicted housing shortage: Holmans (2013) argued that 240,000 – 245,000 new dwellings will be required annually until 2031. Miles and Whitehouse (2013) suggested that between 230,000 and 330,000 additional dwellings will be required each year while a report by the Future Homes Commission estimated the required rate of annual housing deliveries to 300,000 (Banham et al., 2012).

In any case, it appears that the housing industry will be required to provide significantly higher volumes of housing deliveries than what is currently providing. However, this is not the only challenge. New houses are not only required in large volumes, they also need to meet the very strict requirements on energy efficiency that have been set by building regulations as a result of the climate change policy in the UK. The environmental targets for the UK and the resulting regulatory context for the built environment are presented in the following sections.

2.2 Building Regulations and UK carbon targets

The UK policy on climate change derives from the country's targets on reducing greenhouse gas emissions. Under the Kyoto Protocol Agreement, European Union member states agreed to reduce their greenhouse gas emissions by a specific percentage, individual to each country, compared to emissions levels of the 1990 baseline year[1], so that an EU average of 8% reduction would be achieved for the period 2008-2012. The individual target for the UK had been set in the EU Decision 2002/358/EC to 12.5 percent emissions reduction (Council of the European Union, 2002). The baseline year emissions for the UK have been calculated to 779.9 $MtCO_2e$ (Webb et al., 2014). A Statistical release published by the Department of Energy and Climate Change (DECC) in February 2015 reported that UK has achieved an average of 607.9$MtCO_2e$ for the period 2008-2012 corresponding to 22%emissions reductions from the 1990 levels (Bates, 2015).

In addition, the UK government was one of the first to set the legally binding commitment to reduce greenhouse gas emissions by 34% for the year 2020 and by 80 per cent for the year 2050 compared to the 1990 emission levels Under the Climate Change Act 2008 (Climate Change Act 2008, The Climate Change Act 2008 (2020 Target, Credit Limit and Definitions) Order 2009). Towards achieving that goal, four carbon budgets for the periods 2008-2012, 2013-2017, 2018-2022 and 2023-2027 have been set. Each carbon budget sets the maximum allowable amount (cap) of greenhouse gas emissions over the respective period in the UK (Table 2-1).

Table 2-1: The four carbon budgets for the period 2008 – 2027 (DECC, 2011)

	First Carbon Budget (2008-2012)	**Second Carbon Budget (2013 – 2017)**	**Third Carbon Budget (2018 – 2022)**	**Fourth Carbon Budget (2023 – 2027)**
Carbon Budget level ($MtCO_2e$)	3,108	2,782	2,544	1,950
Percentage reduction from 1990 levels	23%	29%	35%	50%

[1] 1990 was the baseline year set for the emissions of carbon dioxide, methane and nitrous dioxide. The baseline year for fluorinated compounds was 1995

In July 2009 the Department of Energy and Climate Change set the strategy for the transition to a low-carbon economy with a view to meet the requirements of the first three carbon budgets in "The UK Low Carbon Transition Plan: National strategy for climate and energy" (Department of Energy and Climate Change, 2009). In December 2011 the policy document "The Carbon Plan: Delivering our low carbon future" superseded and updated the UK Low Carbon Transition Plan, setting out the proposals and policies to meet all four carbon budgets, dealing primarily with the fourth carbon budget (DECC, 2011).

The Carbon Plan sets specific strategies on decarbonising the economy for the different sectors: industry, power production, buildings, transport and agriculture, land use, forestry and waste. For the period up to 2020, the actions proposed aim at applying the most cost effective and proven technologies as well as promoting the use of the most promising technologies in each sector. This will result in achieving emissions reductions through already mature technologies applied in areas where they are most cost effective and also laying the foundations for new technologies which are not yet widespread to reach maturity, and economies of scale to be created. The strategy from 2020 onwards considers wider use of these new technologies, which will by then become more established and will allow for significant emissions reductions, as well as exploring areas where further emissions reductions, albeit from less cost effective applications, can be achieved.

2.2.1 Building Regulations

The current legislation that most buildings in England and Wales have to comply with, are "The Building Regulations 2010" and "The Building (Approved inspectors etc.) Regulations 2010" which came into force in the 1st of October 2010 and are set under the power of the Building Act 2004 (Planning Portal, 2015). Requirements on energy efficiency in buildings in England are set by Regulations 23, 25A, 25B, 26, 26A, 26B (in Wales only), 28, 29 and 40 and Part L of Schedule 1. Guidance on compliance to the energy efficiency requirements for new dwellings in England is given by the 2013 edition of the 'Approved Document L1A – Conservation of fuel and power in new dwellings' (incorporating the 2016 amendments). Compliance to building regulations is demonstrated when the following criteria are met (HM Government, 2013a):

1. The Dwelling Emission Rate (DER) and the Dwelling Fabric Energy Efficiency (DFEE) rate are not higher than the Target Emission Rate (TER) and the Target Fabric Energy Efficiency (TFEE) rate respectively.

2. Minimum requirements on the performance of the fabric elements and fixed services are met. Minimum levels of performance for the fabric of dwellings are presented in Table 2-2 below.
3. Provisions have been taken on the use of passive measures to control heat gains in the summer period, regardless of whether consideration on the use of mechanical cooling has been taken or not.
4. The as-built performance of the dwelling should be consistent with the DER and DFEE rate. Post-construction calculation of the DER and the DFEE considering the actual construction of the building should demonstrate that the TER and TFEE are not exceeded.
5. Necessary provisions have been considered, so that the operation and maintenance of the dwelling is performed in a manner to satisfy the energy-efficient use of the dwelling.

Table 2-2: Limiting fabric parameters (HM Government, 2013a)

Parameter	Maximum permissible value
Roof	0.20 W/(m^{2}K)
Wall	0.30 W/(m^{2}K)
Floor	0.25 W/(m^{2}K)
Party wall	0.20 W/(m^{2}K)
Swimming pool basin	0.25 W/(m^{2}K)
Windows, roof windows, glazed roof-lights, curtain walling and pedestrian doors	2.00 W/(m^{2}K)
Air permeability	10.0 m^3/(hm^2) at 50 Pa

The definitions of the Dwelling and Target Emission Rate and the Dwelling and Target Fabric Energy Efficiency rates are given in the Government's Standard Assessment Procedure (SAP). SAP is the Government's methodology to calculate the energy performance of residential building, compliant to the requirements of the Energy Performance of Buildings Directive (DECC, 2014). At the time of this work, the SAP 2012 was in effect. DER represents the annual CO_2 emissions of a dwelling expressed in kg/(m^{2}year) for space and water heating, ventilation and lighting less the emissions saved by energy generation technologies; TER is defined as the CO_2 emission rate of the notional building, a building of the same geometry as the actual dwelling using certain reference values (specified in the Appendix R of the SAP). The Dwelling Fabric Energy Efficiency (DFEE) rate is the annual energy requirement for space heating and cooling per square meter of floor area. Target Fabric Energy Efficiency rate (TFEE) is the fabric energy efficiency calculated for the notional dwelling multiplied by a factor of 1.15 (DECC, 2014).

SAP takes into account factors such as materials and insulation used, air leakage of dwelling, characteristics of ventilation and heating systems, solar gains, space cooling requirements, fuel type for space heating, cooling, ventilation and domestic hot water equipment and the use of renewable energy technologies in calculating the energy performance of dwellings. Apart from the Fabric Energy Efficiency (DFEE and TFEE) and the Dwelling CO_2 Emission Rating (DER and TER), other indicators for evaluating the energy performance of buildings also calculated using SAP include the energy consumption per unit floor area, the energy cost rating (SAP rating) and the Environmental Impact rating (EI rating).

<u>Zero Carbon Homes and tightening of Building Regulations</u>

In 2006, the UK Government published the consultation document "Building a Greener Future: Towards Zero Carbon Development" and announced the plan for delivering Zero Carbon Homes (Department for Communities and Local Government, 2006). The UK zero carbon target was in compliance to the EU Directive 2010/31/EU on the energy performance of buildings (recast) which sets the requirement that all new buildings occupied and owned by public authorities are nearly zero-energy buildings by the 31^{st} of December 2018, while this will apply to the rest of the new buildings by the 31^{st} of December 2020 (Zero Carbon Hub, 2014b).

The route towards achieving Zero Carbon Homes was through a progressive tightening of the energy efficiency requirements set by building regulations. The specifications set in the 2013 edition of the Approved Document L1A aimed at delivering 6% reduced carbon emissions across all new housing building mix compared to the previous 2010 edition which, in turn, resulted in 25% reduced carbon emissions compared to the 2006 Approved Document L1A (HM Government, 2010, HM Government, 2013a).

The approach adopted towards achieving the zero carbon homes standard was based on three steps following the hierarchical order (Zero Carbon Hub, 2010):

1. Minimum standards on fabric performance. These are set by the Fabric Energy Performance Standard (FEES), expressed in kWh/m^2/year and ensure high levels of fabric performance as a minimum.
2. Further emissions reduction through the incorporation of low and zero emissions technologies on-site and directly connected heat networks
3. Use of a range of allowable solutions for addressing the remaining emissions

The first two steps together account for the on-site emissions reductions and were regarded as 'Carbon Compliance', while the allowable solutions aimed at offsetting the residual emissions away from site. The schematic representation of the three step approach is presented in Figure 2-3.

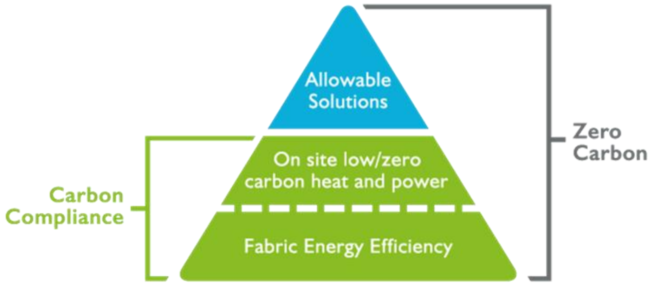


Figure 2-3: Schematic of the Zero Carbon Policy approach (Zero Carbon Hub, 2015b)

Table 2-3 below presents the proposed levels of FEES and Carbon Compliance for the different building types (Zero Carbon Hub and NHBC Foundation, 2013):

Table 2-3: FEES and Carbon Compliance for different building types

Building Type	Fabric Energy Efficiency Standard (FEES)	Carbon Compliance
Detached houses	46 kWh/m^2/year	10 kgCO_2/m^2/year
Semi-detached houses	46 kWh/m^2/year	11 kgCO_2/m^2/year
End-terrace houses	46 kWh/m^2/year	11 kgCO_2/m^2/year
Mid-terrace houses	39 kWh/m^2/year	11 kgCO_2/m^2/year
Apartments	39 kWh/m^2/year	14 kgCO_2/m^2/year (up to 4 storeys)

In 2015, the Government announced that it would not proceed with the implementation of the allowable solutions and the additional tightening of building regulations in 2016, effectively withdrawing the zero carbon policy. Instead, it committed to review the energy efficiency requirements through the Building Regulations (Ares, 2016).

2.2.2 Other standards

Apart from the building regulations, other voluntary building standards have also been setting very high requirements on the energy efficiency of the building fabric and the carbon emissions of new dwellings. The most popular standards in the UK that have influenced the industry considerably over the past years are the Passivhaus Standard and the Code for Sustainable Homes. Despite the fact that the latter has now been withdrawn in an attempt by the Government to consolidate and simplify Building Regulations, the Code contributed significantly towards a low-carbon sustainable housing industry and influenced greatly the construction of dwellings. For this reason, the main features of both the Passivhaus Standard and the Code for Sustainable Homes are presented below.

Passivhaus Standard

The Passivhaus Standard is one of the most popular low energy building standards and it sets even more stringent requirements than current building regulations and the proposed Fabric Energy Efficiency Standard. It is considered a useful tool for delivering low-energy building envelopes, through a fabric first approach. A Passive House is defined as "a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air" (Passipedia, 2012). In order for a building to receive Passivhaus certification, certain conditions regarding its performance need to be met. These are presented in Table 2-4 below.

Table 2-4: Requirements to be met for a dwelling to be certified as Passivhaus (Passivhaus Trust, 2015)

Parameter	Requirement
Specific heating demand, or alternatively	≤ 15 kWh/m^{2}year
Specific heating load	≤ 10 W/m^2
Specific cooling demand, or alternatively	≤ 15 kWh/m^{2}year
Specific cooling load	≤ 10 W/m^2
Specific primary energy demand	≤ 120 kWh/m^2 year
Air tightness	≤ 0.6 ACH @50Pascals

The requirements on the specific heating and cooling demand (and load) as well primary energy demand are calculated by the Passivhaus Planning Package (PHPP), a spreadsheet based model developed by the Passivhaus Institut (PHI), which is exclusively used for the certification purposes. Primary energy demand includes energy requirements for space heating and cooling, domestic hot water, appliances, lighting and fans/pumps. Achieving these performance targets requires a balance between the use of very high insulation levels for opaque and transparent elements, high levels of airtightness, and the elimination of thermal bridges. The following values are recommended, although not obligatory (Mead and Brylewski, 2010)

- Opaque fabric U-value ≤ 0.15 W/m^2;
- Windows and doors U-value ≤ 0.80 W/m^2;
- Thermal bridging Y-value ≤ 0.01 W/m^2K; and
- Whole house MVHR system with 75% efficiency;

Code for Sustainable Homes

The Code for Sustainable Homes (CfSH) was the national assessment method for evaluating the energy efficiency and sustainability performance of dwellings in England, where it replaced the EcoHomes standard, Wales and Northern Ireland. The performance of a dwelling was measured against nine main categories of environmental impact, which in turn included a number of environmental issues. A scoring system had been set with specific number of credits for each issue and category. Based on the overall score obtained, a dwelling achieved a rating between one and six indicated by the respective amount of stars (Department for Communities and Local Government, 2008a). The categories, the number of credits and the weighting factor for each category are presented in Table 2-5 below.

The first category, Energy and carbon dioxide emissions, is relevant to this work and mainly the issues Dwelling Emissions Rate (Ene 1) and Fabric Energy Efficiency (Ene 2). The issues included in this category and the respective number of credits for each issue, are presented in Table 2-6.

Issue Ene 1 aimed at limiting the CO2 emissions from the operation of houses. Credits were awarded for levels of improvement of the Dwelling Emission Rate (DER) above the Target Emission Rate (TER) set by the building regulations as specified in Table 2-7 (as calculated by SAP 2012).

Table 2-5: Categories, credits and weighting factors of the Code for Sustainable Homes rating scheme (Department for Communities and Local Government, 2010a))

Category	Number of Credits	Category Weighting Factor
Energy and CO_2 emissions	31	36.4
Water	6	9.0
Materials	24	7.2
Surface Water Run-off	4	2.2
Waste	8	6.4
Pollution	4	2.8
Health and Well-being	12	14.0
Management	9	10.0
Ecology	9	12.0
Total	107	100.0

Table 2-6: Summary of issues and credits for the category Energy and CO_2 emissions (Department for Communities and Local Government, 2010a)

Issue	Issue ID	Available credits
Dwelling emission rate	Ene 1	10
Fabric energy efficiency	Ene 2	9
Energy display devices	Ene 3	2
Drying space	Ene 4	1
Energy labelled white goods	Ene 5	2
External lighting	Ene 6	2
Low and zero carbon technologies	Ene 7	2
Cycle Storage	Ene 8	2
Home Office	Ene 9	1
Total		31

Table 2-7: Issue Ene 1 assessment criteria, credits awarded and requirements for achieving specific levels of the Code (Department for Communities and Local Government, 2014b)

% Improvement of DER over TER	Credits	Mandatory requirement
≥ 6%	1	
≥ 12%	2	
≥ 19%	3	Level 4
≥ 32%	4	
≥ 44%	5	
≥ 56%	6	
≥ 70%	7	
≥ 84%	8	
≥ 100%	9	Level 5
Zero net carbon dioxide emissions	10	Level 6

Table 2-8: Fabric Energy Efficiency levels and associated credits (Department for Communities and Local Government, 2014b))

Fabric Energy Efficiency (kWh/m^2/year) according to building type

Apartments, mid-terrace houses	End-terrace, semi-detached and detached houses	Credits awarded	Mandatory requirement
≤ 48	**≤ 60**	3	
≤ 45	**≤ 55**	4	
≤ 43	**≤ 52**	5	
≤ 41	**≤ 49**	6	
≤ 39	**≤ 46**	7	Levels 5 and 6
≤ 35	**≤ 42**	8	
≤ 32	**≤ 38**	9	

Issue Ene 2 aimed at establishing minimum levels and improving the fabric energy efficiency of dwellings in order to minimize their current and also future carbon dioxide emissions. Credits were awarded when specific performance levels had been met. These levels according to building type are presented in Table 2-8. The proposed Fabric Energy Efficiency Standard targets should be met in order to achieve levels 5 and 6 of the Code.

The market conditions and the building regulations that were presented in the previous paragraphs are the great challenges that the housing industry faces. Meeting these challenges with traditional construction methods will be very difficult and it is the author's belief that Modern Methods of Construction (MMC) have a significant role to play. These methods, their characteristics and the issues regarding their use are presented in the following sections.

2.3 Modern Methods of Construction

In the UK, and mainly in England which is the dominant market and accounts for the largest share of housing stock, 'traditional construction' is considered masonry construction which involved the use of locally found materials such as stone and clay. The main types of masonry construction found today are solid walls, which consist of a single loadbearing layer usually from brickwork and adequate thickness to provide weatherproofing, and cavity walls which consist of two separate wall leaves separated by a cavity to provide additional protection from rain. The inner leaf, commonly blockwork, provides structural stability while the cavity and the outer leave which is usually brickwork serve as protection from rain and moisture. The two leaves are tied together by steel ties. Initially, there was no insulation but as a result of the progressive tightening of building regulations the cavities of these walls gradually received partial or full insulation (Emmitt and Gorse, 2014). Masonry construction is the dominant construction method, with solid walls accounting for 26% and cavity walls 66% of the building stock in the United Kingdom (Piddington et al., 2013).

2.3.1 Types of Modern Methods of Construction

Modern Methods of Construction (MMC) is a term used to describe a number of construction methods which are substantially different than the 'traditional' brick and block construction (Energy Saving Trust, 2005a, Gaze et al., 2007a). MMC differ from traditional methods either in the construction processes adopted or the materials used. The potential of MMC to facilitate in delivering increased housing numbers was acknowledged by Kate Barker in her "Review on Housing Supply". Recommendation 33 of the Barker Review stated that "the House Builders Federation, in conjunction with NHBC, Construction Skills and other interested parties, should develop a strategy to address barriers to modern methods of construction" (Barker, 2004). As a response, the Barker 33 Cross-Industry Group was formed comprising stakeholders from over 50 organizations and gave the following definition of MMC (Barker 33 Cross-Industry Group, 2006): "Modern Methods of Construction are about better products and processes. They aim to improve business efficiency, quality, customer satisfaction, environmental performance, sustainability and the predictability of delivery timescales. Modern Methods of Construction are, therefore, more broadly based than a particular focus on product. They engage people to seek improvement, through better processes in the delivery and performance of construction".

The term MMC includes a very wide selection of constructions ranging from complete housing systems to building components or assemblies and there is still an on-going discussion about what exactly can be considered MMC. A widely accepted classification system adopted by most of the stakeholders was developed by the Housing Corporation in 2003, according to which MMC fall into one of the following categories (Energy Saving Trust, 2005a, Ross, 2005, Ross et al., 2006)

1. Volumetric (also referred to as modular construction). Three dimensional modules manufactured in a factory and transported on site for assembly. Usually these units have already the services installed and most of the finishing works performed at the factory with onsite works including mostly jointing of the units and only final stages of the external cladding; although external cladding may also be applied onsite to a large extent (Mapston and Westbrook, 2010). Volumetric units can be produced from most materials (steel, timber, concrete or composites). Mapston and Westbrook (2010) classified volumetric buildings in three main types: temporary buildings which can be disassembled and reinstalled in another location, permanent buildings with a lifespan comparable to that of traditional buildings and comprise of one or more units and park homes or caravans which are similar to bungalows which are of standard design, constructed in factory with services and finishes applied offsite.
2. Panellised systems are flat panel elements manufactured in factory facilities and transported on site for assembly to construct the superstructure of the building or to fit within an existing structure. Panel systems include walls, roofs and floors (with the latter two usually being referred to as 'cassettes') and can be constructed from most materials; usually they are timber-frame, steel-frame, precast concrete panels (PCP) and structural insulated panels (SIP). Panellised systems may be subdivided into closed and open panels based on the degree of factory installations. Closed systems are panels with insulation and

most of the services, finishes etc. fitted prior to transportation to the site, whereas open systems have the insulation, services, components and finishes installed on site.

3. Hybrid construction is a combination of volumetric construction and panellised systems. It involves the use of 'pods' which are readily finished volumetric units for highly serviced areas such as kitchens or toilets or larger room units which can be fitted in an existing structure. Pods and room units can be constructed from steel, timber, concrete or fiberglass and depending on the application may comprise structural or non-structural elements of a building (Mapston and Westbrook, 2010).
4. Sub-assemblies and Components. This category includes factory made components, usually prefabricated foundations, roof and floor cassettes, roof structures as well modern joists, I-beams etc.
5. Non-offsite manufactured modern methods of construction. This category includes innovative on-site construction methods and the use of traditional materials and components in an innovative manner. Typical methods of this category are tunnelform construction, aircrete products and insulating concrete formwork (ICF). Timber frame of steel frame panel systems may also be constructed on site.

Modern Methods of Construction offer a number of advantages to the building process and the potential to improve the efficiency of the housing industry. However, care needs to be taken in order to utilize their potential and detailed planning that takes into account the particular features of these methods is required for their successful implementation (Gaze et al., 2007b). When these conditions are met, projects built with MMC may benefit from the following:

1. Shorter construction time. MMC have the ability to reduce significantly the time required on-site for achieving weather-tight conditions and for the completion of a construction. The time savings vary according to the construction type used, with volumetric construction achieving the highest performance, and may be up to 50% compared to traditional construction methods (Parliamentary Office of Science and Technology, 2003).
2. Reduction on the demand for skilled labour onsite. A typical characteristic of most MMC is that they involve a degree of work carried at factory conditions away from the erection site, reducing the demand for onsite workforce. Also, the manufacturing processes taking place at the factory results in requiring less specialized in construction labour. Consequently, MMC have the ability to deliver higher output levels using the same workforce as traditional construction methods; it has been reported that up to four times higher building deliveries can be achieved (Fawcett et al., 2005).

3. Higher levels of construction quality. Traditional construction has often been characterised of poor construction quality. Offsite construction offers the advantage of manufacturing taking place in controlled factory conditions where quality control can be well monitored which results in achieving higher precision in the component production and consistency in the final product specifications.
4. Higher levels of energy efficiency. Most MMC lend themselves to incorporating high levels of insulation and achieving high levels of airtightness. In addition, high construction quality in the manufacturing process of these methods also allows for meeting those energy efficiency standards consistently. This is not the case for traditional construction where site conditions and weather may affect the quality of the construction and vary from one project to another.
5. Waste reduction. The use of MMC in house building can reduce the amount of construction waste produced due to more precise manufacturing procedures and the use of standardised material and component specifications. Furthermore, in offsite construction it is for the interest of the manufacturer to use less material for the final product while factory conditions allow for recycling of raw material.
6. Increased levels of health and safety compared to traditional construction. Completing a part of the construction in a controlled environment where increased safety measures can be taken and reducing the time spent to the construction site where unpredictable conditions take place decreases the number of accidents.
7. Increased predictability of project cost and time, as a result of detailed planning at early stages, the manufacturing taking place in a controlled environment where the process can be planned and monitored.
8. Reduced disturbance onsite. Moving the manufacturing process away from the building site results in transporting complete or semi-complete building elements, instead of different materials from different suppliers, results in reduced lorry deliveries. In addition, reduced demand for onsite workforce results in fewer cars in the construction area. Reduced transportation requirements and shorter onsite built times result in reduced levels of disturbance in the area where the construction takes place. This is proven to be particularly beneficial for projects in dense areas of cities
9. Improved productivity through completing part of the work in controlled factory setting.

Significant scope exists therefore for the wider use of MMC which have the potential to improve greatly the performance of the construction industry. However, their use is currently limited and disproportionate to their potential benefits. The drivers and barriers to their wider application are discussed in the following section.

2.3.2 Drivers

The housing shortage mentioned above is considered the strongest driver for driving growth in both the construction industry and the offsite construction sector. In order to tackle the projected shortage it is expected that the industry would be required to produce much higher rate of annual housing deliveries than it traditionally has. In addition, Miles and Whitehouse (2013) suggested that the current capacity of the industry with traditional construction methods accounts for approximately 130,000 – 150,000 units per annum, a figure that is half or less than the projected housing requirements presented in Section 2.1. They also identified that the private rented sector, social housing and self-build sector are the market segments with the highest potential for growth. Furthermore, these sectors can benefit greatly from the greater speed of construction and the higher quality offered by MMC, which may lead to further use of these methods in building construction. Speculative house builders do not appear to have much interest for increasing their annual output or the use of MMC.

Another market related factor which act as a driver for the use of MMC is the government's long-term intention for rationalizing and improving the construction industry performance. This intention has been well documented in two of the most influential reports, 'Constructing the Team' published in 1994 by Sir Michael Latham (Latham, 1994), and 'Rethinking Construction' published in 1998 by Sir John Egan (Egan, 1998), as well as a series of other government and industry report published since. These are presented in Table 2-9. These reports underpinned the fact that the industry is inefficient and under-achieving and proposed changes in the processes, supply chain and procurement methods and relationships between stakeholders.

The Latham and Egan reports also called for change and for exemplar demonstration projects. However, progress has been limited since; Wolstenholme (2009) reported that almost ten years after the Egan report, the industry showed little progress due to limited commitment of the stakeholders to the recommendations made. The Government Construction Strategy published two years later also noted the under-performance of the industry and called for changes in the procurement practices and supply chain relationships and encouraged the use of offsite components, systems or even buildings (Cabinet Office, 2011). It is obvious that the industry can benefit greatly from the merits of offsite construction and it is believed that, if progress is to be made, then MMC is expected to play a vital role.

Table 2-9: List of the main reports dealing with issues regarding the construction industry performance

Year	Report	Description of main industry issues dealt in each report and proposals made
1994	Constructing the Team (Latham Report)	Commissioned by the UK government the report dealt with identified problems in the construction industry. Use of standardised contracts, partnering between supplier and client and establishing long-term relationships between the construction companies were recommended among other actions.
1998	Rethinking Construction (Egan Report)	Conducted by a Task Force appointed by the Deputy Prime Minister. Five key drivers of change were identified: committed leadership, focus on the customer, integrated processes and teams, quality driven agenda and commitment to people. The report set targets of 10% annual reductions in construction time and cost and 20% reduction in defects.
2001	Modernising Construction	Report conducted by the national Audit Office. It highlighted the importance of modernising the procurement and delivery mechanisms of construction projects to tackle inefficiencies. Recommendations were made for better integration of the design, planning and construction stages, long term relationships and partnering between clients and contractors and for the industry to make greater use of innovation
2002	Accelerating Change	Published by the Strategic Forum for construction called for 20% of projects by value to be completed by integrated teams and supply chains by 2004, which would be increased to 50% by 2007.
2004	Review of Housing Supply	Commissioned by the Chancellor and Deputy Prime Minister, Kate Barker reviewed the problems of the house building industry and its inability to meet the increasing demand. A series of recommendations for improving the industry's performance and providing a more stable housing market were proposed
2007	Callcutt Review of Housebuilding Delivery	Report commissioned by the UK Govenrment. The report examined how the nature of the house building industry affects the supply of new homes and proposed recommendations on achieving the required output.
2009	Never Waste A Good Crisis	Published by Constructing excellence the report assessed the degree of implementation of the recommendations made by the Sir John Egan ten years after 'Rethinking Construction' was published. The report concluded that most recommendations were only partially adopted with limited benefits for industry. A number of blockers which restrain progress were identified and a set of suggestions for improving performance were made
2011	Government Construction Strategy	The Government Construction Strategy argued that public sector construction does not benefit from best value and that it has not achieved the potential for growth though public procurement projects and infrastructure developments. It called for transformation on the business relations between public sector and construction industry and set the target for 20% reduction in the project costs. Also called for the construction industry to increase collaboration in place of adversarial relations and adopt innovation
2013	Construction 2025 Industrial Strategy: government and industry in partnership	Report published jointly by Government and industry. Identified the potential of the construction industry for excellence and growth and set ambitious targets of performance for 2025 to reduce costs by 33%, construction time by 50%, reduce its emissions by 50% and reduce the gap between imports and exports by 50%.

The use of Modern Methods of Construction is also being encouraged by various programmes of the UK government aimed at increasing housing output. The Housing Zones programme which was published in August 2014 aims at developing thirty Housing Zones on brownfield sites encourages the use of 'offsite and innovative approaches to delivery'. This is done by including them explicitly to the prioritization criteria of the expressions of interest for designation of the Housing Zones (Department for Communities and Local Government, 2014c). In addition, the Affordable Housing Programme which aims at delivering 165,000 new affordable houses for the period 2015-2018 also welcomes the use of offsite construction technologies (Homes and Communities Agency, 2014). It was announced that one fifth of the houses to be built during the first stage of the program will be constructed with 'advanced housing manufacture' which involve offsite manufacture of components (Department for Communities and Local Government, 2014a).

The stricter requirements on energy efficiency set by building regulations and the popular low carbon building standards, discussed earlier in sections 2.2.1 and 2.2.2, are also considered a major driver for the wider use of MMC. Modern construction methods are able to achieve consistently high insulation and airtightness levels and, as most of these systems consist predominantly of insulation they can achieve the U-values required for each building element with minimum thickness, lower than would be achieved through traditional construction. The ease at which MMC can meet building regulations requirements and the fact that they can do so without compromising much of the usable building space will be expected to shift the trend towards these methods.

Apart from the above market drivers, other trends have also been identified which are expected to boost the use of MMC and offsite systems. Bernstein et al., (2011) identified the increased interest in lean construction techniques and Building Information Modelling (BIM) use and the turn towards green building as the industry trends that have great potential to increase the use of MMC in the USA. Furthermore, they underpinned the role of architects, engineers and general and specialty contractors towards increasing the use of prefabrication in construction. The UK construction industry and government is also aiming at wider use of BIM and digital technologies in construction project development, and this is expected to contribute towards a wider use of offsite solutions (HM Government, 2013b).

Lu and Bausman (2009) suggest that an increase in research & development investment, training of manufacturers, designers and contractors, and collaboration of the key project players at an early planning stage, are actions that could increase the contribution of offsite construction methods and techniques. In the report “Technology and Skills for the Construction Industry – Evidence Report 74” published by the UK Commission for Employment and Skills (UKCES), Vokes et al., (2013) argued that the strong links of the offsite construction with the growing manufacturing sector will be a further driver for the growth of the offsite sector.

2.3.3 Barriers

So far, offsite construction and MMC in general have not received wide acceptance by industry and the general public and still account for only a small proportion of housing deliveries due to a number of inhibiting factors. In a survey amongst the top 100 UK house builders it was found that they were highly concerned with the following issues regarding the use of offsite MMC (Pan et al., 2005, Pan et al., 2008):

- High capital costs. It is believed that the use of MMC would result in increased capital cost compared to conventional construction. The survey also identified a perceived difficulty on achieving economy of scale as a barrier on the wider use of innovative construction techniques. A report conducted by the National Audit Office concluded that the cost of panellised systems is comparable to that of traditional construction, while it can be more expensive for other types of MMC (Fawcett et al., 2005).
- Systems interface complexity. There is a great concern on the house builders that MMC components would require complex interfaces to connect to traditionally built structures or between MMC components themselves, even though there is no evidence suggesting such an issue.
- Early freeze design. Successful development of MMC projects requires an early freeze design the degree of which depends on the manufacturer’s lead-in times and the manufacturing capacity. The nature of the UK planning system however does not favour this attribute and may cause significant delays in the manufacturing process.

Other factors limiting the benefits of MMC systems were also identified by this study, although considered less significant, were: limited manufacturing capacity, lack of onsite skills which will still be required and the significance of the role of land on the house building development process and reluctance of the house building industry to innovate (Gaze et al., 2007a).

Another study by Nadim and Goulding (2010) reported similar findings. The study was conducted among 47 large construction organisations covering a wide range of the construction industry and 36 valid responses were analysed. It was found that the participants considered high initial cost, inflexible design and the public’s resistance to change as the main inhibitors for the take-off of the offsite industry. In addition, the lack of an overall strategy and ineffective coordination among the project participants were also identified as factors that contribute to failure of offsite practice.

Both these studies highlighted the importance of high initial costs of MMC to housebuilders. However, Miles and Whitehouse (2013) argued that the construction cost accounts for only 25% of the total development cost and therefore the influence of MMC may not be as significant. In contrast, insufficient land supply for housing development and the fact that acquiring the required planning consents is very time consuming, often taking years, established the land as the predominant factor in the housebuilding industry.

The use of new construction methods is often seen with reluctance by contractors which are inexperienced with these methods and prefer to work with traditional methods that they are familiar with. The UK Commission for Employment and Skills survey reported in 2013 that many SME sub-contractors that use traditional construction methods are reluctant to use or even feel threatened by MMC (Vokes et al., 2013). On the other hand, from the consumer perspective, MMC houses are often seen with scepticism mainly due to previous bad experience of prefabricated houses which had unconventional design and in some cases performed poorly (Ross, 2002). These are further discussed in the following section. However, this is not considered the decisive factor for consumers, since other factors such as price, the building quality and location appear to be considered more important when choosing a house.

The provision of mortgage and insurance is also a factor of particular interest to the purchaser and is considered a potential barrier for the take-off of MMC. Mortgage lenders and insurance providers based on experience of post war non-traditional buildings are often sceptical on the use of new and innovative construction methods and products. From 2003 the BRE has been suggesting that since the post-war period MMC has acquired negative connotations but "with developments in lightweight, high strength materials and modern production techniques, prefabrication has much to offer today's construction industry" (Stirling, 2003, Waghorn et al., 2015). The main concerns for mortgage lenders are with regard to the durability of the innovative systems, the whole life costs, reparability, life span, adaptability, insurance availability and maintenance of demand, while insurance lenders are concerned about the absence of a risk profile for MMC and issues regarding the resilience and reparability of buildings constructed with MMC (Department for Communities and Local Government, 2008b). In an attempt to overcome these concerns, the Buildoffsite, along with the Royal Institute of Chartered Surveyors, Lloyd Register, Building LifePlans Limited and the lenders, have established the Buildoffsite Property Assurance Scheme (BUPAS). This scheme is an assurance process which involves assurance of no structural costs for a period of 60 years, latent defect insurance for a period of 10 to 12 years, accreditation of manufacturers and constructors and the creation of a database of structural components for each property (Buildoffsite, 2012)

Skills shortage is also considered a potential limiting factor for MMC. Whilst the use of MMC may reduce the need for on-site skills, it will require for a more qualified working force at the manufacturing plants (Gaze et al., 2007a). Miles and Whitehouse (2013) identified the following required skills for offsite construction: specialised design for offsite applications, production engineering, procurement and handling of materials and multi-skills in project assembly. They argued that there is no evidence to support that the lack of skills has limited the expansion of the sector, however if there was a significant increase in demand, then the lack of skills would likely be a restrictive factor.

Similarly, Vokes et al., (2013) identified the following core skills, knowledge and behaviours required for offsite construction: knowledge and understanding of the individual requirements and characteristics of the different trades and collaboration, marketing of the benefits of offsite to the investors and the clients, effective project management, skills in information and digital technology, integrated planning and design, and adoption of whole-life approach to the design. An extended use of MMC will lead to the development of new job roles and to the evolution of existing jobs in order to incorporate a range of the aforementioned skills. Unless adequate training is provided to address these issues, the growth of offsite methods is likely to be inhibited without realising its full potential.

2.3.4 MMC in the UK and globally

United Kingdom

Methods of construction other than the traditional ones are not new in the UK. After the First World War, the UK was facing significant housing shortage due to a deficit in housing that existed prior to the war and was exacerbated by the absence of any new construction or maintenance activity during the war as well as the need to provide homes to the returning soldiers after the war. The industry challenges at the time were shortages in material (brick and timber) and skills (Marshall et al., 2014). Several construction methods were developed using mainly concrete, steel and timber. However, they were not widely used; it has been estimated that system-built houses, as they are commonly referred to, accounted for approximately 250,000 out of the 4.5 million dwellings constructed in Great Britain in the period 1919 - 1939 (Ross, 2002).

Similar conditions after the Second World War led to the further use and development of non-traditional building systems which, to a great extent, were used for social housing. The need to replace the damaged and destroyed building stock and provide housing to the war veterans, along with the excessive steel and concrete war industry which had been inactive after the war led to the development of new and evolution of existing building systems (Nicol et al., 2014). Two types of system-built houses were constructed to tackle the acute housing shortage: temporary 'pre-fabs' with a short lifespan (that most of them exceeded although very few still exist today) and permanent houses several thousands of which still exist today; it has been estimated that 500,000 such houses were constructed (Marshall et al., 2014). During this period, many systems of precast and in-situ concrete and timber and steel frame were developed (Ross, 2002).

In the following decades, namely 1950 – 1970, the building industry focused in the development of building systems with a high degree of prefabrication, often called ‘industrialised building’. Medium and high-rise buildings made of precast concrete panels were very popular from the mid-50s while in the 60s and 70s systems of volumetric construction usually from lightweight steel or timber were developed. In the late 70s and early 1980s timber frame panellised systems were the most commonly used accounting for approximately 30% of the housing deliveries (Ross, 2002).

Problems encountered with concrete medium and high-rise buildings caused negative public attitude towards industrialized buildings. Marshall et al. (2014) suggested that the performance issues of these buildings were due to poor design, inadequate control of processes and poor construction as unskilled workforce was carrying out the building process. The most famous case of concrete high-rise system-built failure was the collapse of the Ronan Point from a gas explosion. The collapse took place due to insufficient restraint ties between the walls and the floors and caused negative reaction from the public (Ross, 2002). Furthermore, several concrete systems were found to have structural problems where the reinforcement had been corroded and the concrete had been deteriorating. A number of these buildings were found to be defective under the Housing defects Act 1984 and they were either demolished or repaired to a great extent (Ross, 2002, Marshall et al., 2014).

In addition, parts of frame of several steel frame houses in certain areas of the UK were found to have been corroded requiring even replacement in some cases. Other problems with system-built housing identified, include cladding deterioration (often requiring replacement of the cladding as these systems were not being produced anymore) and condensation problems occurring in steel frame houses (Ross, 2002). However, BRE after undertaking a series of assessments suggested that the majority of steel frame and steel clad houses had similar levels of performance to many houses built with traditional construction methods.

Timber frame houses were also found to be performing similar to houses built with traditional methods. However, the popularity of these houses, which accounted for almost a third of all new dwellings in that time, was severely damaged after an episode of the ‘World in Action’ programme reported on decay problems in a limited number of timber dwellings and implied that this could be the case for most such dwellings.

All the aforementioned issues caused reluctance of the public towards the non-traditional construction methods. This however seems unfair, since in general these have been found to perform similar to traditional construction methods. Ross (2002) reported also on a number of problems identified with masonry construction and argued that performance problems are seen with more tolerance in traditional construction, while when such issues occur in non-traditional building systems they are considered as problems inherent to the construction methods.

Contrary to the rest of the UK however, timber frame construction in Scotland is very popular amongst house builders and is considered the main construction method as it accounts for approximately 75% of all new built houses (Palmer, 2000, Davies, 2009). Smith et al. (2013) conducted a study on the offsite sector based on the responses of 17 companies operating in different areas of the sector (designing, manufacturing and supplying products). Based on the data of these companies, it was found that the value of the offsite manufacturing sector, considering sales in the UK market, was £125 million at the time of the study while the estimated value for the following five years without considering the construction of new manufacturing facilities was £230 million. The annual output of the interviewed companies dropped from 8,800 houses/apartments (mid 2008) to 6,000 in 2011/2012 while the manufacturing capacity of these companies was 16,500 units. However, the Scottish government has been engaged to support MMC through the Greener Homes Innovation Scheme, a Fund set for delivering low-carbon houses built with offsite construction methods, and through supporting skills development schemes as was announced in the Scotland's Sustainable Housing Strategy (Scottish Government, 2012, Natural Scotland, 2013).

Whilst MMC may still not have the desired impact in the UK construction sector (apart from the exception of Scotland), they have caused a significant impact in other countries. Most typical markets where MMC and mainly prefabrication methods have been used extensively in house building include those of Japan, Sweden, Germany and the USA. The following section presents an overview of the MMC industry in these countries.

Japan

The prefabrication housing industry in Japan is very successful with high output levels, high degree of automation and highly customized end-product (Linner and Bock, 2012). The Japanese construction sector is considered to be very vibrant with high output levels. The housing construction industry reached a peak in 1996 with more than 1.6 million dwelling starts and has followed a declining trajectory since. In 2012 the dwelling starts reached almost 900,000 units. The share of prefabricated houses to the total dwelling starts over the period 1992 – 2012 varied from approximately 12.5% to 18% with a mean value of roughly 15% (Ministry of Land Infrastructure Transport and Tourism, 2014).

The main factors which contributed to the growth of the prefabrication industry in Japan are the non-speculative nature of the greatest share of the house-building industry, the historical connections of traditional architecture to standardized construction and the cultural connection of the people to the land and not the buildings (Barlow and Ozaki, 2005, Linner and Bock, 2012). The consistently high demand for prefabricated housing has allowed industry companies to invest in equipment, services and systems in order to provide high-quality and innovative end-product; prefabricated houses in Japan are considered to be of superior quality, well-designed and equipped with cutting edge technology features (Linner and Bock, 2012). The high degree of customization was achieved through great investment in customer relations and innovation in the production system by moving from "economies of scale in production towards economies of scope" (Barlow and Ozaki, 2005).

The highly efficient manufacture process of Sekisui Heim and the Toyota Homes, two of the largest prefabricated house providers, is described by Linner and Bock (2012)). The steel frame volumetric construction process of these companies achieves prefabrication levels of 80% and 85% respectively. At the first stage of this process the steel frame modules are fabricated and the modules then run through the production line where further fittings are installed. At the final stages furniture and services are also fitted. The process is supported by highly advanced Enterprise Resource Planning (ERP) management and Building Information Modelling (BIM) systems which allow the on-time provision of the components in the production line and the successful completion of the highly customized houses. Extensive quality controls are undertaken in order to deal with potential errors on time and ensure the reliability of the systems. The manufacturing process produces minimum waste, through eliminating cut-off and management of the resulting waste through reuse and recycling. The modular units when completed are transported to the site just on time and are rapidly assembled. The works for the on-site house completion last less than a month.

Sweden

The Swedish construction presented a lot of similarities to the UK one. Historically, Swedish construction industry had been characterized low levels of efficiency and competitiveness, and increased costs. Traditional construction was run by temporary project specific organizations with the completion of a project involving a series of fragmented processes; furthermore the industry was dealing with housing and skills shortages (Engström et al., 2009a, Engström et al., 2009b).

As in the UK, government support along with shortages in housing deliveries and skills were the main drivers for the uptake of the offsite construction industry (Engström et al., 2009b). The prefabrication industry in Sweden emerged as a response to a great demand for apartments in the 1940s and 1950s. Government schemes such as the Million Program (construction of one million apartments in a period of 10 years) announced in 1964 boosted the development of a mass production industry. An increased demand for single family houses also allowed for smaller companies to develop. The development of the MMC industry in Sweden was therefore a consequent of government support, high demand, repetition and economies of scale (Lessing, 2006)

In mid 1970s with the end of the Million Program the demand for new flats dropped, which led to the mass producing industry not being able to operate efficiently. In contrast, the single-family housing market did not present such a rapid drop in demand and therefore the companies operating in this sector maintained similar working methods and routines (Lessing, 2006). The single-family house sector was run mainly by a large number of small companies and was characterized by a high degree of prefabrication (Lessing, 2006). The dominating material for housing construction in Sweden, as well as the rest of the Nordic countries is timber, mostly used for single-family houses; Timber accounts for 90% of construction in single-family houses and approximately only 7% in multi-storey buildings (Thelandersson et al., 2004, Mahapatra et al., 2012).

United States of America (USA)

The evolution of MMC and offsite construction methods in the U.S.A. presents some similarities to other countries. Offsite application for housing construction emerged after World War II as a result of a great demand in housing (Lu, 2007). Offsite techniques appear to have significant degree of penetration in the U.S. construction industry. A study conducted by Lu and Bausman (2009) through the use of questionnaires valued the degree of use of offsite techniques to 23% in 2006. In another study among the construction industry stakeholders published in 2011, 85% of the respondents were found to be using offsite practices to some degree, out of which 37% to a high degree (Bernstein et al., 2011).

The construction industry in the U.S.A. is highly fragmented comprising mainly by small companies with about 80% of the 710,000 businesses operating in 2002 having less than 10 employees and 98% fewer than 100 employees (National Research Council of the National Academies, 2009). A study conducted by the National Research Council addressing the issue of increasing the efficiency and productivity of the construction sector, identified among other interrelated processes, the use of prefabrication and offsite processes and techniques as a means for radical improvement of the industry (National Research Council of the National Academies, 2009, Bernstein et al., 2011). Extended use of BIM was also identified as an effective measure to improve productivity, which has been also recognized as a major potential driver of the prefabrication industry (Bernstein et al., 2011, Buildoffsite, 2012).

Germany

Prefabrication industry in Germany emerged around the 1920s but the greatest boost in production occurred in the decades that followed World War II up to the 1960s as a response to the great housing demand (Fertighauswelt, 2014). Although these houses were considered to be of low quality and contributed to a poor reputation for prefabrication construction, the industry was able to shift the negative public perception by increasing standardization, developing certification schemes and by informing the public on the benefits of offsite construction, resulting in the wide acceptance and increased use of these methods (Lu, 2007).

The main construction techniques involve timber-frame and structural insulated panels as well as concrete and masonry systems for wall and roof panels (Venables et al., 2004, Lu, 2007). It is estimated that the share of the prefabricated houses accounts for the 15% annual output of the housing sector which is translated into approximately 20,000 houses (Linner and Bock, 2012). The predominant techniques for prefabricated houses are timber based; however, suppliers of masonry and concrete products developed innovative offsite solutions and methods in order to reduce construction times and compete with the timber prefabrication industry (Venables et al., 2004).

2.3.5 Demonstration Projects

There are numerous case studies of projects demonstrating the merits of MMC. A particularly interesting example of offsite construction presented in the Buildoffsite Review 2012 is the construction of eight accommodation blocks in three different sites by the company Caledonian Modular for the Royal School of Military Engineering (Buildoffsite, 2012). 73% of this project was built on the company's manufacturing plant and achieved high levels of performance in terms of waste minimization, on-site construction time reduction and cost certainty. These benefits were attributed to the use of efficient methods for minimizing waste and the establishment of strong relationships with the suppliers in order to minimize lead times and ensure that the products match the design specification. The latter also results in minimizing cut-off waste.

As timber-frame construction is not very common for multi-storey residential buildings the two cases studies presented by (Mahapatra et al., 2012) are considered particularly interesting: a seven-storey building and a complex of three five-storey residential buildings both located in Berlin. Both of these cases incorporate efficient heating systems and have achieved very high energy performance standards (the latter being certified Passivhaus) and reported very low heating costs; care was needed, however, in one case in order to satisfy the authorities requirements on fire safety (Svirskaitė, 2011). Mahapatra et al. (2012) reported that the cost of the group of the five storey buildings was estimated to be 10% lower than if it were to be constructed by traditional methods.

Another successful example of multi-storey timber building is the Stadthaus in London. The Stadthaus is constructed from cross laminated timber panels and according to the architects it is considered to be the "tallest modern timber residential building in the world" (Fortmeyer, 2011, Waugh Thistleton Architects, 2014). It is considered to have set a precedent for timber buildings of such height in Europe with the innovative construction method being included in the UK Building Regulations as an Appendix (Lowenstein, 2008, Detail Green, 2009). The project benefited from cost and time savings as well as significant carbon emissions savings even considering the transportation of the panels from Austria, where they were manufactured, to the UK while the carbon emissions reductions by the timber construction were accounted for by the local planning authorities thereby not requiring the 10% carbon reduction of the London Plan (Lowenstein, 2008, Detail Green, 2009, Fortmeyer, 2011).

With regard to achieving high performance standards, there are numerous examples of single family houses designed and built to very high specifications. The Creative Energy Homes (CEH) project is an example of this as it encompasses seven houses built to various degrees of energy efficiency. The seven dwellings were built with different types of MMC to meet high performance standards. These dwellings are being monitored in order "to stimulate sustainable design ideas and promote new ways of providing affordable, environmentally sustainable housing that are innovative in their design" (Gillott et al., 2010b). The project contains some of the first low-energy and zero-carbon houses in the UK, mostly built using MMC.

2.3.6 Concerns on the use of MMC

Even though the MMC dwellings have demonstrated the ability to achieve very high efficiency standards, there are concerns on the overheating potential of these buildings. These concerns might be justifiable, although not enough case studies are yet available to fully quantify this issue. The changes in UK building regulations that have resulted in an increase in insulation levels may also result in buildings that are much more sensitive to any alteration in energy inputs, especially if they are built using certain common MMC configurations with low levels of thermal mass.

Several monitoring studies have identified the overheating potential of existing dwellings built to high efficiency standards (Richards Partington Architects, 2012, Department for Communities and Local Government, 2012, NHBC Foundation, 2012) while various researchers have speculated that, in future climate scenarios, well insulated houses with low levels of thermal mass could result in substantially higher and uncomfortable room temperatures (Athienitis and Santamouris, 2002, Orme et al., 2003, Arup Research and Development and Bill Dunster Architects, 2005, Hacker et al., 2008, Rodrigues, 2009, Zero Carbon Hub, 2010). Some studies also suggest that overheating occurs in MMC houses through case studies (Rodrigues, 2009, Rodrigues and Gillott, 2011, Rodrigues et al., 2013c) but these studies are not yet widespread enough for a definitive conclusion.

2.4 Conclusions

Modern Methods of Construction are not currently used widely in the UK; however, the work presented in this chapter shows that their use is expected to expand significantly in the future. Historic and recent building activity indicates that traditional construction methods alone will not be sufficient to produce the increased number of housing deliveries at the high levels of construction quality required.

The characteristics of MMC present a unique potential for these methods to facilitate the housing industry in increasing the housebuilding output and coping with the major industry challenges. The main drivers expected to drive the growth of these methods were presented in this section as well as the factors which are currently inhibiting their wider use. Examples of markets where MMC are used more extensively were presented as well as successful cases of buildings which benefited fully from the merits of MMC. These examples highlight the ability of these methods to perform well when used in mass production and for achieving high levels performance.

As the use of offsite methods and MMC is expected to increase, so do concerns on their performance. One of the major concerns is the risk of overheating in MMC dwellings due to lack of available thermal mass associated with most of these methods. Increased levels of insulation and airtightness required by building regulations may also exacerbate this risk, especially in future warming climate conditions. This may lead to dwellings that will suffer from uncomfortably high temperatures and consequently may lead to increased use of air-conditioning systems. Therefore, conducting this research project is considered timely and fully justified as it is dealing with an issue of significant importance for the housing industry, the building occupants and the government policy on climate change.

In order to evaluate therefore the risk of overheating of these methods in the current and future climate, the next chapter provides the background for the analysis presented in the following chapters. The definitions and the main methods and tools used by industry practitioners and researchers to assess overheating and thermal comfort and the effect of thermal mass on internal conditions are provided. Research on the occurrence of overheating in UK dwellings is also presented and the climate change projections which are used to assess the future performance of dwellings are discussed.

CHAPTER 3. ASSESSING OVERHEATING IN UK HOUSING IN CURRENT AND FUTURE CLIMATE

The concern about the overheating risk of dwellings, especially those built with MMC, discussed in Chapter 2, is an issue which has been raised recently in the UK. Historically, buildings were designed to provide comfort during the heating season. Increased summer temperatures, however, occurring during the last decades and projections of a future warming climate have established mitigation of overheating high in the agenda of building thermal performance (Hacker et al., 2005b).

Warming climate is not the only cause of resulting high indoor in buildings. A number of other factors have been identified: design issues such as orientation, inability to provide adequate ventilation (due to pollution, noise, security issues, privacy), lack of shading, site context and associated heat island effect and internal heat sources such as occupant activities, electrical appliances, hot water services and communal heating systems may lead to excessive internal temperatures (Richards Partington Architects, 2012). The most common strategies for reducing overheating have been identified to be: reducing internal gains, shading, ventilation and the use of thermal mass coupled with night-time ventilation (Orme et al., 2003, Energy Saving Trust, 2005b).

This chapter provides the background information required for the analysis performed in the following chapters. At first, the concepts of thermal comfort and overheating are introduced to the reader. Next, the main compliance and design tools to assess overheating are presented followed by evidence from research studies on the extent of overheating in UK housing.

With thermal mass been identified as one of the passive main strategies to regulate internal elevated temperatures, the main simplified methods for the preliminary assessment of thermal mass on indoor temperatures are also presented. Finally, as the risk of elevated temperatures in UK dwellings will increase in the future, the latest climate change projections are also discussed in the following paragraphs.

3.1 Aim and Objectives

The work presented in this chapter aims at providing the relevant background information required for the analysis presented in the following chapters. The main objectives of this work are:

- To introduce the concepts of thermal comfort and overheating in residential buildings;

- To discuss the main methodologies used by design and compliance tools to assess the risk of overheating in dwellings;
- To present the evidence of overheating that arises from the review of monitoring and simulation studies and justifies the need for this research project; and
- To discuss the increased risk of elevated temperatures occurring in UK dwellings in the future based on the latest climate change projections.

3.2 Overheating and thermal comfort

Overheating is an issue of increasing significance to the design of buildings, however there is no precise definition of it (Nicol and Spires, 2013). It is usually assessed with respect to potential effects on health, thermal comfort or productivity of users; in building design it is mainly assessed with respect to thermal comfort (Mylona et al., 2015). Therefore, in order to evaluate overheating it is useful to examine first the different approaches to define and evaluate thermal comfort, which is commonly defined as 'that condition of mind which expresses satisfaction with the thermal environment' (BSI, 2005).

The importance of thermal comfort in the design of buildings lies on the fact that it is a reflection of the users' satisfaction. In addition, the preferred temperature determines to a great extent the resulting energy consumption for that building; failure to provide comfortable conditions in low-energy buildings may lead occupants to the use of energy intensive solutions to achieve desirable internal conditions (Roaf et al., 2009).

The main environmental and personal factors which affect a person's thermal perception of its surroundings are (Parsons, 2010):

- Air temperature
- Radiant temperature
- Humidity
- Air velocity
- Insulation from clothing
- Activity rate

The mechanisms of heat exchange between a person and the surrounding environment (heat generated by metabolism which is lost though respiration and through the skin) are described by the Heat Balance Equation (Nicol and Spires, 2013):

$$H - E_{is} - E_{SW} - E_{res} - C_{res} = K = R_{clo} + C_{clo} \quad \text{Equation 3-1}$$

Where,

H = the net metabolic heat production

E_{is} = heat losses by water vapour diffusion from skin

E_{SW} = evaporative heat losses by sweat from skin

E_{res} = heat losses from respiration

C_{res} = convective heat loss from respiration

K = conductive heat transfer from skin to the outer surface of clothing

R_{clo} = radiative heat loss from clothed surface

C_{clo} = convective heat loss from clothed surface

Fanger suggested that thermal comfort conditions are met when the heat balance is achieved within narrow limits of sweat rate and mean skin temperature; this requirement was set because it was argued that heat balance could be achieved even in the absence of comfortable conditions through the human physiological processes (shivering, sweating etc.) (Parsons, 2010, Nicol and Spires, 2013).

A series of tests were performed in thermal chamber where approximately 1300 participants exposed to different environments were wearing standardised clothing and completed specific tasks. Participants were asked either to rate the thermal sensation in a scale between -3 and +3 (-3 being cold, 0 neutral and +3 hot) or to adjust the temperature until they considered the resulting conditions thermally neutral (Djongyang et al., 2010). Based on the heat balance equation, these tests led to the development of the Predicted Mean Vote (PMV) index, an index of the mean comfort vote from a number of people for a given level of clothing and activity to rate the environment they are experiencing. Another index in relation to the PMV was developed predicting the percentage of people that would experience discomfort in a certain environment was developed, the Percentage of Peopled Dissatisfied (PPD).

The PMV and PPD index are the most widespread methods of the so-called ‘rational’ or ‘heat-balance’ approach to define thermal comfort (Djongyang et al., 2010). Thermal comfort assessments based on the PMV and PPD indexes require estimations on humidity levels and air movement as well as assumptions on specific clothing and activity rates. Therefore, they are considered suitable for evaluating conditions in mechanically conditioned buildings where temperatures are closely controlled. Their use on free-running dwellings where temperatures vary significantly over time presents limited applicability (Nicol and Spires, 2013). Instead the use of methods based on the adaptive approach is considered more suitable for these cases.

In contrast to the heat balance approach that involved tests performed in climatic chambers under steady state conditions, adaptive models were developed based on field studies and assumed that people make adjustments and modify the environment in order to alter the environmental conditions and reduce discomfort. They also relate the external temperatures with maximum and minimum thresholds within which comfortable conditions occur in free-running buildings (O'Connor and Capon, 2015).

The most common standards used for evaluating conditions of thermal comfort are the BS EN ISO ISO 7730 Standard, the ANSI/ASHRAE 55 and the BS EN 15251 Standard. These are based on the heat-balance and the adaptive approach.

3.2.1 ISO Standard BS EN ISO 7730

The BS EN ISO Standard 7730:2005 (BSI, 2005) is based on the Predicted Mean Vote Method and it provides the equations for calculating the PMV and PPD indexes as well as tables for determining the PMV for set values of activity, clothing insulation and environmental parameters. Provisions for accounting for local discomfort are also expressed through the Draught Rate which is the percentage of people expected to feel discomfort by draught, vertical air difference, cool floors and radiant asymmetry. Buildings are classified to three categories according to the PMV/PPD achieved and the local discomfort rates. These are categories A ($-0.2 < PMV < +0.2$), B ($-0.5 < PMV < +0.5$) and C ($-0.7 < PMV < +0.7$) (BSI, 2005).

3.2.2 ANSI/ASHRAE Standard 55

The ANSI/ASHRAE Standard 55 (ASHRAE, 2010) provides a PMV-based method for mechanically conditioned buildings similar to BS EN ISO 7730. For naturally ventilated buildings, however, the adaptive approach to comfort is considered. The indoor comfort temperature in this case is defined with respect to the mean outdoor temperature:

$$T_{comf} = 0.31T_{m,o} + 17.8 \quad \text{Equation 3-2}$$

Where,

T_{comf} = optimal comfort temperature (°C)

$T_{m,o}$ = mean outdoor temperature (°C)

The monthly mean outdoor temperature is considered in the calculation of the comfort temperature but this is currently under discussion as the running mean outdoor temperature may also be considered in future. It is also examined in that case if the use of the same equation should be applied (Nicol et al., 2012, Nicol and Spires, 2013). A zone of temperatures that would be found acceptable by the 80 and 90 percent of the users is then determined from the T_{comf} (Equation 3-3) and can be seen in Figure 3-1.

$$T_{accept} = 0.31T_{m,o} + 17.8 \pm T_{lim} \quad \text{Equation 3-3}$$

Where,

T_{accept} = acceptable temperature limits (°C)

T_{lim} = range of acceptable temperatures, 2.5 °C for 90% and 3.5 °C for 80% acceptability

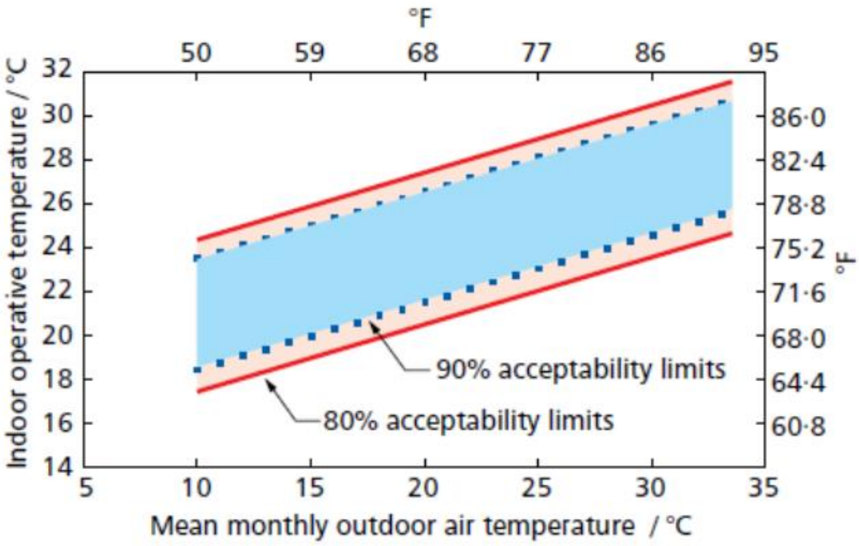


Figure 3-1: Ranges of acceptable temperatures for 80% and 90% acceptability (Nicol and Spires, 2013)

3.2.3 European Standard BS EN 15251

Similarly to the American ANSI/ASHRAE Standard 55, the European Standard BS EN 15251:2007 (BSI, 2007a) considers different approaches for indoor comfort levels of mechanically and naturally ventilated buildings. Criteria on comfort category based on the PMV-PPD indices are set for mechanically conditioned buildings as well as recommended maximum and minimum operative temperatures and building use. For naturally ventilated buildings the comfort temperature is determined in relation to the external temperature according to Equation 3-4 below (Nicol and Spires, 2013):

$$T_{comf} = 0.33T_{rm} + 18.8 \qquad \text{Equation 3-4}$$

Where,

T_{rm} = exponentially running mean of the daily mean outdoor temperature (°C) defined by Equation 3-5 below (Nicol and Spires, 2013):

$$T_{rm} = (1 - \beta)\,(T_{od-1} + \beta \cdot T_{od-2} + \beta^2 \cdot T_{od-3} \ldots.) \qquad \text{Equation 3-5}$$

Where,

β = constant (<1)

T_{od-1}, T_{od-2}: daily mean temperatures for the previous day, the day before etc.

In BS EN 15251:2007 buildings are classified in four categories based on their nature and specific comfort limits are set for mechanically conditioned (in terms of PMV ranges) and free running buildings (in terms of deviation of acceptable temperatures from the comfort temperature). The building categories with the respective limits are presented in Table 3-1 (Nicol and Spires, 2013).

Table 3-1: Categories of buildings in BS EN 15251:2007 and explanation of each category along with the limits of acceptable temperature and PMV for free-running and mechanically conditioned buildings

Category	**Explanation**	**Suggested acceptable temperature range (K)**	**Suggested acceptable PMV limits**
I	High level of expectation – recommended for spaces occupied by sensitive and fragile people	±2	±0.2
II	Normal level of expectation – recommended for new buildings and renovations	±3	±0.5
III	Moderate expectation level – recommended for existing buildings	±4	±0.7
IV	Values outside the criteria for the above categories – Should be considered accepted for part of the year	>4 or <-4	>0.7 or <-0.7

Based on the above criteria, the range and the limits of acceptable temperatures in relation to the running mean outdoor temperature for the different building categories are presented in Figure 3-2.

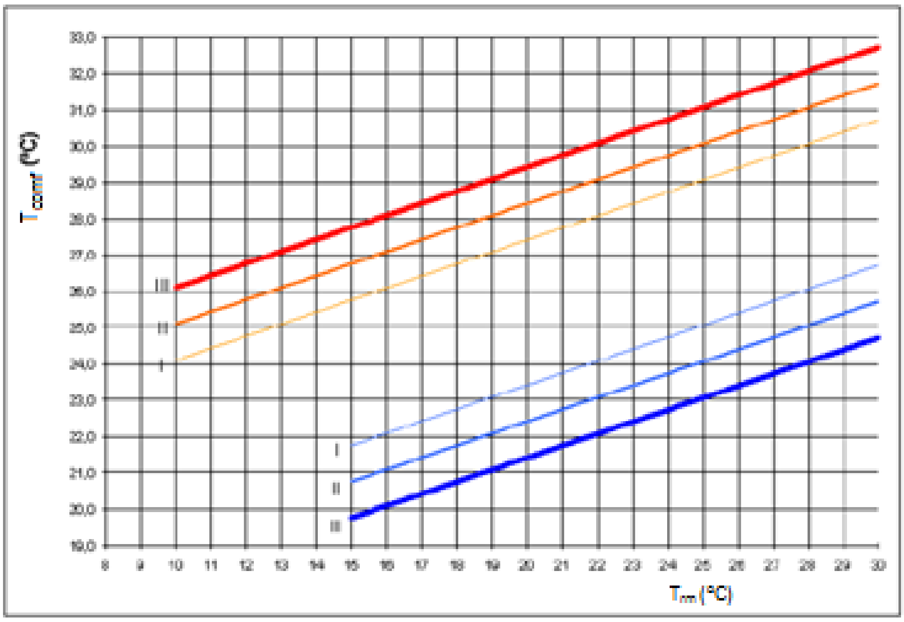


Figure 3-2: Limits of acceptable comfort temperature (T_{comf}) in relation to the running mean outdoor temperature (T_{rm}) for the different building categories (BSI, 2007a).

3.3 Tools and methodologies for assessing overheating in dwellings

Based on the above approaches on thermal comfort, static and adaptive, methodologies for assessing overheating in dwellings have been developed. These are used for compliance and design purposes. The main methodologies for assessing the risk of overheating in the UK are:

- The Standard Assessment Procedure methodology;
- The CIBSE guidance
- The Passivhaus Planning Package methodology

3.3.1 Standard Assessment Procedure

With regards to demonstrating compliance to building regulations, the propensity of overheating in a dwelling is investigated with the use of Appendix P of the Government's Standard Assessment Procedure (SAP 2012). The procedure presented in Appendix P provides a steady state calculation of predicted monthly indoor temperatures for the months June, July and August and takes into account the solar gains, the effective ventilation, the thermal capacity and the monthly mean external temperatures for the region where the dwelling is situated (DECC, 2014). A threshold temperature is calculated which is then used to assess the overheating propensity of the dwelling when compared to specific benchmark temperatures (Table 3-2).

Table 3-2: Overheating propensity relating to the monthly threshold temperatures

Threshold Temperature	**Likelihood of high internal temperature during hot weather**
< 20.5 ^{o}C	Not significant
≥ 20.5 ^{o}C and < 22.0 ^{o}C	Slight
≥ 22.0 ^{o}C and < 23.5 ^{o}C	Medium
≥ 23.5 ^{o}C	High

The dwelling is considered to have a non-significant or slight likelihood of high internal temperatures when the mean monthly internal temperatures calculated are lower than 20.5^{o}C or between 20.5^{o}C and 22.0^{o}C. If the monthly mean temperatures exceed 23.5^{o}C it is considered to have a high propensity for high internal temperatures, while it is classified as having medium likelihood if threshold temperatures are between 22.0^{o}C and 23.5^{o}C.

This methodology for assessing the propensity for a dwelling to suffer from high internal temperatures, even though is not affecting the SAP rating, it is used for demonstrating compliance to building regulations. A dwelling with a predicted low or medium risk of overheating is normally considered compliant while a high predicted risk of overheating would not normally be accepted Building Control (Diamond et al., 2015).

Due to the nature of SAP being a tool for compliance rather than a design tool, it is only able to provide a simplified approach to predicting the overheating risk of a dwelling. There is no provision in assessing the severity or the frequency of overheating and the use of monthly average temperature inputs does not take into account the effect of potential hot spells on the predicted indoor temperature. In addition, there is no provision for considering the effect of climate change and urban heat island effect (Mylona et al., 2015). Furthermore, little consideration is taken on the synergetic effects of the factors that contribute to overheating (Richards Partington Architects, 2012). The methodology has limited ability to account for and differentiate between the effects of adaptation strategies (Zero Carbon Hub, 2010).

3.3.2 CIBSE guidance

Guidance on the assessing the overheating risk in dwellings was given in the seventh edition of the 'CIBSE Guide A – Environmental Design' (CIBSE, 2007). Recommended design temperatures for the different zones of mechanically cooled as well as free-running dwellings are provided in Guide A. These are temperatures which are considered to be acceptable by the majority of occupants.

With regards to free-running dwellings it is accepted that these recommended design temperatures may not always be maintained due to the absence of a cooling system and that higher temperatures might occur. When the design temperatures are exceeded occupants are likely start to feel uncomfortable. A benchmark temperature was set, such that when it was exceeded the building or zone under consideration is said to have overheated. In addition, in order to account for the occurrence of overheating a benchmark frequency was also set accounting for the percentage of time when the aforementioned benchmark temperature is exceeded. When this percentage of time was exceeded, the building or the zone was said to be suffering from overheating (CIBSE, 2007). The recommended temperatures as well as the benchmark temperatures and the overheating criteria for free – running dwellings are presented in Table 3-3 below (CIBSE, 2007).

Table 3-3: Design temperatures and benchmark temperatures and criteria for assessing overheating in dwellings

	Winter Design Temperature (°C)	Summer Design Temperature (°C)	Benchmark Temperature (°C)	Overheating Criterion
Air conditioned dwellings				
Bathrooms	20-22	23-25	-	-
Bedrooms	17-19	23-25	-	-
Halls/stairs	19-24	21-25	-	-
Kitchen	17-19	21-23	-	-
Living Room	22-23	23-25	-	-
Toilets	19-21	21-23	-	-
Free-running dwellings				
Bedrooms	-	23	26	Benchmark should not be exceeded for more than 1% of occupied hours
Living areas	-	25	28	Benchmark should not be exceeded for more than 1% of occupied hours

The proposed criteria provided valuable guidance in assessing overheating by designers for several years. However, several problems associated with the use of a fixed benchmark temperature and a fixed percentage of time when this temperature was exceeded were identified (Nicol and Spires, 2013):

1. The suggested approach does not consider the adaptive thermal comfort model principle, according to which the temperatures that the users find comfortable are close to the indoor temperatures they are experiencing which, in turn, are related to the outdoor temperatures. Comfort temperatures rely on the external temperatures with recent temperatures experienced having greater effect on the thermal perception of the occupant than older ones.
2. It does not take into account the severity of overheating. The percentage of time when the threshold temperature is exceeded does not provide any information on how much it is exceeded. In that sense, temperatures that are by 1°C or 4°C higher than the threshold are assessed as having the same effect on occupant comfort.

3. The use of a threshold temperature makes the approach susceptible to systematic errors in simulations which may distort the distribution of the resulting indoor temperatures and provide misleading information on the comfort levels.
4. The use of occupied hours is susceptible to manipulations which may alter or even diminish the resulting levels of overheating.
5. Finally, Nicol and Spires (2013) argued that the use of a whole year might not be the most appropriate measure for assessing overheating as this might occur in shorter timescales.

As a result, the overheating criteria set in the 2006 version of the CIBSE guide A were superseded in the current, eighth edition of the guide (CIBSE, 2015b). Instead of providing a fixed value for the comfort temperature and a fixed maximum temperature threshold, overheating is assessed via the maximum temperature (based on the comfort temperature (Equation 3-4)) for free-running buildings that is calculated from the running mean of the daily mean outdoor temperatures is provided by the BS EN ISO 15251 European Standard.

$$T_{max}=0.33T_{rm} + 21.8 \qquad \text{Equation 3-6}$$

Where,

T_{max} = the maximum acceptable temperature (^{o}C)

T_{rm} = exponentially weighted running mean of daily mean outdoor temperatures

The assessment of the overheating potential of dwellings was now based on the following three criteria. Failing to meet two out of these three criteria results in characterising a building or a zone as suffering from overheating (Nicol and Spires, 2013):

1. The number of occupied hours when the operative temperature (T_{op}) exceeds T_{max} by more than 1 degree should not exceed 3% of the total occupied hours for the period May – September inclusive.
2. The severity of overheating is accounted for by the weighted exceedence (W_e) which for any day should be less than or equal to 6 (Equation 3-7).

$$W_e=(\sum h_e) \times WF = (h_{e0}\times0) + (h_{e1}\times1) + (h_{e2}\times2)+(h_{e3}\times3) \qquad \text{Equation 3-7}$$

Where,

W_e = weighted exceedance

WF = weighting factor. WF = 0 if ΔT ≤ 0 and WF = ΔT if ΔT > 0. ΔT is the difference between the actual operative temperature, T_{op}, and the maximum acceptable temperature, T_{max}, rounded to the nearest whole degree.

h_{ey} = number of hours when the WF = y

3. An upper limit temperature has been set that the operative temperature of a room shall not exceed. This is the absolute maximum temperature for a room and is 4 degrees higher than the comfort temperature (ΔT = 4 K)

In order to evaluate the performance of the dwelling according to the above criteria, the use of dynamic simulation software is required. Dynamic simulation models for building analysis take into account the building properties and environmental conditions as well as heat transfer mechanisms to which a building is exposed to, and calculate the response of the building under investigation in terms of resulting temperatures and/or resulting heating and cooling loads.

Two types of weather files have been approved by CIBSE and are commonly used in thermal performance analyses of buildings, the Test Reference Years (TRYs) and Design Summer Years (DSYs). TRYs are weather files which provide statistical representation of the past, constructed by using months from different years in order to produce one typical year for that period. DSYs are weather data sets for a complete year for which 'the average temperature of the summer months is at the centre of the upper quartile of rankings obtained from about 20 individual years' (CIBSE, 2007). When assessing the overheating risk of a dwelling at the design stage it is recommended by CIBSE that the DSY files are used, while TRY files are intended for calculating the energy consumption of the dwellings.

3.3.3 Passivhaus Planning Package (PHPP)

The risk of overheating is also taken into account during the Passivhaus certification process. In order for a property to achieve Passivhaus certification it is required that certain levels of thermal comfort are provided to the occupants. Overheating is defined in terms of a temperature threshold being exceeded for a set amount of time. A building is considered to suffer from overheating when the predicted internal temperature exceeds the threshold temperature of 25°C for more than 10%

of annual occupied hours (McLeod et al., 2010). In order to achieve certification this limit should not be exceeded. It is recommended that the 25^{o}C limit should not be exceeded for more than 5% of the occupied time so that high levels of comfort are guaranteed at summer; A dwelling is characterised as ‘Good’ when temperatures above 25^{o}C occur for 2-5% of the occupied time and as ‘Excellent’ when this is the case for 0-2% of occupied time (Diamond et al., 2015).

The overheating assessment is carried with the use of the PHPP. PHPP calculations consider monthly average values of temperature and solar radiation, solar gains and ventilation as well as the thermal capacity of the dwelling. Since monthly average climate data are used, the PHPP procedure has similar characteristics to the SAP methodology, i.e. it does not take into account the severity of overheating or the effect of short period with high temperatures, nor is it able to identify overheating occurring in short concentrated periods. In addition, the PHPP algorithm treats the building as a single zone and therefore overheating assessment of separate zones is not provided (Feist et al., 2007).

3.4 Evidence on overheating in UK dwellings

Evidence on overheating has grown significantly over the past years. Based on the above tools and methodologies, several monitoring and simulation studies have investigated this issue. These are presented below.

3.4.1 Monitoring studies

Despite the wide concern for the overheating risk of UK dwellings, there is relatively limited evidence from monitoring of existing dwellings, especially large scale studies. This is mainly due to the fact that overheating was not considered as an important issue for the housing industry so far. Beizaee et al. (2013) reported on the findings of a large scale survey conducted at a national level aiming to investigate the thermal performance of English houses. In total, valid data from 207 houses, 193 free-running and 14 heated, across the nine Government Office Regions of England were analysed. Monitored temperatures from the living room and the main bedroom in each house were evaluated based on the static (PMV-PPD indices) and adaptive criteria set by the BS EN 15251 standard. According to the static criteria it was found that despite the fact that the 2007 summer was cooler than usual, 4% of the living rooms and 21% of the bedrooms in all houses were found to have temperatures exceeding the respective recommended temperature thresholds.

When the adaptive criteria were considered, it was found that temperatures in most houses were within the comfort range and even below the lowest acceptable temperature limits. Beizaee et al. (2013) questioned the reliability and applicability of the BSEN 15251 standard for use in the assessment of dwellings as the method was based on data from studies in offices where users have less adaptive options than dwelling occupants. Flats were found to suffer the most from high temperatures, and especially top-floor flats, while detached houses were experiencing lower temperatures. With respect to the age, dwellings built after 1990 experienced the highest temperatures (due to higher insulation and airtightness levels) while lower temperatures were found in dwellings built before 1919. In terms of wall construction type, houses built with solid walls were found to have lower temperatures than those built with cavity walls and other construction methods (which would also be more highly insulated).

Another large scale study was conducted in summer 2009 where valid data from temperatures measured in living rooms and bedrooms from 230 houses in Leicester where analysed (Lomas and Kane, 2013). Again data were assessed with the use of the static and adaptive criteria set by the BS EN 15251:2007 Standard. Despite the fact that the 2009 summer was relatively cool with only a five-day heat spell a large number of dwellings were found to suffer from temperatures higher than the respective zone thresholds indicating that these zones were uncomfortably warm. Similarly to the findings of the 2007 study reported by Beizaee et al. (2013), flats were found to suffer more from elevated temperatures than other house types while detached houses presented the lowest temperatures. Considering the construction type, houses built with solid walls had the lowest temperatures compare to other built types while with respect to age houses constructed prior to 1919 were found suffer the least from high temperatures. Zones in modern houses built after 1980 were found to have the highest monitored temperatures.

Further evidence on the scale of the overheating problem was provided by another large scale study, the 2011 Energy Follow-Up Survey (EFUS) (Hulme et al., 2013). This Survey was conducted by the Building Research Establishment (BRE) on behalf of the Department of Energy and Climate Change (DECC) owing its name to the fact that it was conducted to a number of houses taking part at the 2010/2011 English Housing Survey. The analysis of overheating issues was based on interviews and temperature monitoring. A total of 2,616 households were interviewed as part of the 2011 EFUS; temperature sensors were installed 823 of these houses. Twenty percent of the interviewed households reported that were unable to keep comfortably cool temperatures in at least one room of their house. 39.4% of these residents reported that overheating occurred in parts of their houses for one to four days per week while 22.3% reported that overheating occurred every day in a typical summer (Hulme et al., 2013). End terrace houses were found to suffer the most from overheating in at least one room while bungalows were found to have the least problem. In consistency with the findings of studies mentioned previously modern dwellings built after 1975 were found to have high overheating potential, while dwellings built prior to 1919 had the lowest overheating risk. In addition, residents of houses with SAP rating higher than 70 reported increased risk of overheating. The analysis of the monitored temperatures showed that the mean temperature in houses where overheating was reported was by 0.5^{o}C to 1.5^{o}C higher than the other houses.

The report *"*Investigation into Overheating in Homes: Literature Review" (Department for Communities and Local Government, 2012) presented the findings from six studies (Wright et al., 2005, Summerfield et al., 2007, Firth et al., 2007, Firth and Wright, 2008, Wingfield et al., 2008, Mavrogianni et al., 2010, Makrodimitri and Riley, 2010, and Makrodimitri, 2010). These studies present similar findings; they suggest that overheating is already an issue in the UK housing stock and that it is a more prominent issue for purpose built flats, end terrace houses as well as newly constructed houses built after 1990. With regards to dwellings built to high levels of insulation and airtightness it is reported that there is significant risk of overheating although it was noted that the sample size of the monitored dwellings does not allow for drawing general conclusions. The report suggested that low energy houses were prone to overheating, especially lightweight constructions or massive constructions with internal insulation.

The Rowner Research Project developed by the Zero Carbon Hub and a number of project partners investigated the design and delivery of two blocks of flats, one built to comply with level 3 of the CfSH (Block B) through a fabric first approach and the other built according to meet the specifications of the proposed FEES (Block C). Both blocks were constructed to high levels of insulation and airtightness with masonry cavity wall construction, using thin-joint blockwork with full-fill blown-bead insulation (ZCH, 2014). In total, 24 flats of three typologies, large single aspect, small single aspect and large multi aspect flat comprised the two blocks.

The study was conducted from September 2012 until September 2013. Eleven flats were monitored, four in Block B and seven in Block C. With regards to the static criteria, most flats presented overheating with temperatures in only two out of the eleven properties not exceeding the temperature thresholds. Single aspect flats were found to suffer from higher temperatures (especially the small ones) compared to the multi aspect ones in the same floor which had the potential to achieve increased ventilation rates. The highest temperatures were observed in the top floor flats. Similar findings were reported in an occupant survey which however captured the users' perceptions of summer 2012.

Further evidence of overheating occurring in existing dwellings were provided by Richards Partington Architects (2012) and the NHBC Foundation (2012) for flats and houses built to high efficiency standards. Rodrigues and Gillott (2011) also monitored the performance of the BASF house, a level 4 of the Code for Sustainable Homes compliant low energy house built using MMC (ICF walls for the ground floor and SIP walls for the first floor) which incorporated a range of passive strategies for achieving thermal comfort such as shading, natural ventilation, high insulation levels, phase change materials, earth-air heat exchanger (EAHE). It was found that the bedrooms suffered from overheating while the conditions in the living areas were within the comfort bands. However, the occupants did not express any complaints about discomfort even though they stated that the conditions were warm.

3.4.2 Simulation studies

Data from monitoring studies on overheating is increasing over the past years. However, the main body of evidence is provided by simulation studies. Numerous studies have focused on the risk of high temperatures in UK dwellings and investigated the effectiveness of strategies to mitigate it.

Orme et al. (2003) investigated the potential overheating on well-insulated buildings through the use of dynamic thermal simulations. The performance of four building types was examined: detached house, semi-detached, town house and top floor flat. A series of measures with potential to reduce overheating (thermal mass, ventilation, shading and reduction of internal gains) were examined through a parametric analysis. The adaptation measures were found to reduce but not eliminate overheating. The study suggested that overheating can be reduced significantly when a combination of measures is applied. Thermal mass coupled with night time ventilation was shown to be the most effective measure. It was also suggested that good solar control should be applied to lightweight well-insulated buildings and that night time ventilation is beneficial to the performance of both heavy and lightweight constructions.

A report from Arup Research and Development and Bill Dunster Architects (2005) dealt with the performance of heavyweight and medium weight compared to lightweight dwellings for current and future climate. It was found that when no adaptation measures were considered, all three constructions presented overheating in the living room at some point in the future, with the heavyweight construction performing better. With regards to the bedrooms all three structures presented similar behaviour, with the lightweight structure performing slightly better. When ventilation and shading were considered, the heavyweight construction was found to perform better than the lightweight in all climates.

The performance of a series of typical dwelling types - a 19th century semi-detached house, a new-build two storey house with varying levels of thermal mass (low, medium and high), a 1960s flat and a new-build flat - was investigated by Hacker et al. (2005a). The study showed that increased levels of thermal mass resulted in improved thermal conditions in the living rooms of the houses. However, this was not the case in the bedrooms where the lightweight house was found to perform similarly to the medium and heavyweight one. When the use of shading and controlled ventilation was considered, the high thermal mass construction was found to perform better than the light-weight one in both the living room and the bedrooms. It was also shown that the new-build flat showed a similar performance for the living room with the 1960s flat but in the bedrooms it was found to present higher levels of overheating at night. This was attributed to the increased insulation and airtightness levels of new build flats which, in combination with the relatively high mass walls, resulted in retaining the heat in the interior. Again, when shading and ventilation were taken into account the performance of the new build flat was significantly improved, resulting in better performance levels than the 1960s flats.

Hacker et al. (2008) also investigated the performance of lightweight, medium weight, medium-heavy and heavyweight construction types in terms of overheating under future climatic conditions. The results suggested that structures with higher levels of thermal mass presented lower levels of overheating and that mechanical cooling would be required at some time in the future; this would be expected earlier for the lightweight construction and later for the medium and heavier constructions. The effect of thermal mass was more evident in the living spaces rather than the bedrooms and it was concluded that medium and heavy weight constructions offer the potential for higher performance in terms of thermal comfort and CO_2 emissions in a warming climate.

Peacock et al. (2010) examined the effects of climate, construction type and internal heat gains on the likelihood of overheating for climatic data of 2005 and 2030. The heavyweight construction presented the smallest amount of overheating, having however high heating demands due to the low levels of insulation. The study also highlighted that the use of passive ventilation appears to provide limited benefit for the London climate in the future as temperatures rise.

Kendrick et al. (2012) evaluated the thermal performance of a three bedroom semi-detached house built according to the Part L 2006 requirements under current and future climate scenarios. The study examined the performance of lightweight, medium-weight and heavyweight construction configurations representative of current UK practice as well as a very heavyweight configuration (which serves as an upper benchmark in terms of thermal mass). It was seen that heavyweight construction had reduced overheating in the living room, but the lightweight construction had a better performance in avoiding overheating in the bedrooms, as a result of its ability to cool down faster. Furthermore, it was found that the lightweight, medium-weight and heavyweight configurations do not appear to have large performance differences. This was in contrast with other studies and it was attributed mainly to the fact that the analysis considered common construction types; it was reported that common methods used in dwelling construction are not exactly heavyweight and hence they do not take fully advantage of the potential benefits of thermal mass. It was also suggested that lightweight modern methods of construction may present increased risk of overheating, but this is not much higher than the risk associated with traditional heavyweight constructions.

Gupta and Gregg (2012) investigated the effectiveness of several adaptation strategies for reducing overheating in future climatic conditions. Shading was found to be the most effective measure, followed by high albedo surfaces and external insulation. Combinations of adaptations strategies were also examined, however none was found to completely eliminate overheating. It was suggested that an adaptation analysis may be more effective when different climatic periods are taken into account along with different emissions scenarios and associated probabilities.

While numerous studies have examined the overheating potential in dwellings with common insulation levels, very few studies have investigated the propensity for overheating of super-insulated low energy houses. Rodrigues (2009) and Rodrigues and Gillott (2013) investigated the overheating propensity of the BASF house, a low energy house built with ICF Walls in the ground floor and SIP walls in the first floor, for the current and future climatic data.The house was found to suffer from overheating at the bedrooms. The performance of the house was also evaluated for the years 2020, 2050 and 2080. It was found to suffer from increasing levels of overheating as further timeslices in the future were considered; from 2050 onwards overheating was an issue for other areas of the house appart from the berooms.

The overheating potential of the Mark Group house, a super insulated steel frame house designed to achieve zero-carbon emissions, in current and future weather scenarios was examined by Rodrigues (2009) and Rodrigues et al. (2013b). The ‘as-built’ performance of the house and the effects of adaptation measures were assessed in these studies; adaptation measures included ventilation, shading and the use of the Earth-Air Heat Exchanger as well as increased levels of thermal mass. The findings of this study also suggest that the combined use of these strategies reduced but did not eliminate overheating. Only when the use of thermal mass with the combination of the rest adaptation measures was considered, the overheating to most zones (except the sunspace) was eliminated for the current weather scenario. The same analysis was performed for the 2020, 2050 and 2080 climatic conditions. It was found that significant overheating is likely to occur in all the zones of the house as a result of the increasing external temperatures and that a cooling strategy should be considered. Rodrigues et al. (2014) investigated in another study the potential impact of PCM, as additional thermal mass, on the energy performance of the Mark Group house. A number of simulations were performed where the application of different amounts (one and two layers) of PCM boards was examined initially at the sunspace and later on the bedroom ceilings as well. The potential of the PCM to reduce overheating was also compared to that of concrete when the external walls of the house were substituted with precast concrete panels. It was found that the PCM boards had a limited effect in reducing overheating compared to that of concrete; however it was suggested that this should be taken in context, since the amount of PCM considered was much lower than the amount of concrete when precast concrete walls are applied. The addition of an extra layer of PCM was not found to provide significant reductions. It was suggested that the use of PCM should be considered in conjunction with other mitigating strategies such as ventilation.

3.5 Tools and Methodologies evaluate thermal mass in dwellings

Numerous of the above studies highlighted the importance of thermal mass for mitigating the overheating risk of a dwelling. Its effect on the heating and cooling loads of a building and the indoor temperatures is the result of complex and interrelated interactions of the building fabric and the transient temperature fluctuations, the internal heat gains, ventilation and thermal storage effects. Accurate prediction and representation of heat flows and resulting temperatures can only be achieved with the use of dynamic thermal simulation models requiring the use of computer programs (CIBSE, 2015b). Balaras (1996) and ASHRAE (2009) provide the most common dynamic methods used for assessing the energy use and cooling load of a building along with the respective parameters for describing the effects of thermal mass. Dynamic simulation analysis requires significant levels of expertise and it can also have significant time and cost requirements.

However the use of thermal mass has significant implications in other aspects of building design (such as structural requirements, choice of heating and/or cooling system, ventilation strategy etc) and therefore its application should be considered at an early stage of the design process (CIBSE, 2015b). For this reason, simplified methods have been developed to assess its effectiveness in the thermal performance of dwellings, the most common of which is the CIBSE cyclic method (the admittance method). In addition, compliance and certification methodologies also provide tools to evaluate the levels of thermal mass in a building zone.

The following paragraphs present the most widely used criteria to evaluate the levels of thermal mass for design and compliance purposes, i.e. those recommended by CIBSE and the criteria used by SAP to demonstrate compliance with building regulations as well as those used by PHPP for certifying Passivhaus buildings.

3.5.1 CIBSE method for thermal mass assessment

With regards to assessing the effect of thermal mass on the resulting indoor temperatures, CIBSE developed the 'admittance method'. This is a simplified dynamic thermal model developed to allow the manual calculation of summer temperatures and cooling loads early at the design stage. The simplicity of this method lies with the fact that all the internal and external loads are treated as a sum of a steady state component and a sine wave with 24-hour period. Therefore it considers a single day repeated several times, hence the term 'cyclic model', until steady state conditions are achieved (CIBSE, 2015b). The environmental temperature is considered in the calculations to account for the combined radiant and conductive heat transfer. The thermal response of the building elements depends on their longwave emissivity, the surface heat transfer coefficient and the thermal properties of the structure (CIBSE, 2015b). Three main parameters are used to characterise the building elements and determine the thermal response of the space (CIBSE, 2007):

- Thermal admittance (Y-value) measured in W/m^2K is the rate of heat flow between the internal surfaces of the structure and the environmental temperature in the space for each degree of deviation of the space temperature about its mean value.
- Decrement factor (f) is the ratio of the rate of heat flow through the structure to the environmental temperature in the space for each degree deviation in external temperature about its mean value, to the steady rate of heat flow (U-value).
- Surface factor (F) is the ratio of the variation of radiant heat flow about its mean value readmitted to the space from the surface, to the variation of heat flow about its mean value absorbed by the surface.

The admittance method is simple and transparent and even though it is commonly applied by a simple code, it also allows the user to perform manual calculations and verify the code results. A code for calculating the cooling loads is provided in the seventh edition of the CIBSE Guide A: Environmental design (CIBSE, 2007). However, the cyclic nature of a single day repeated several times of the method does not allow for taking into account effects of rapid changes in loads or the effects of the long-term heat storage of the thermal mass over a hot period. Hence, it is not considered suitable for assessing the performance of building with high levels of thermal mass. Therefore users should be considerate of the above limitations when applying the admittance method.

3.5.2 Standard Assessment Procedure

Thermal mass in SAP is accounted for with the use of the Thermal Mass Parameter (TMP). The Thermal Mass Parameter is defined as the sum of the product of the area of each element with the respective heat capacity per unit area for that element, divided by the total floor area of the dwelling (Equation 3-8) (DECC, 2014).

$$TMP=\frac{\sum(\kappa_i \cdot A_i)}{TFA} \qquad \text{Equation 3-8}$$

Where

κ_i = heat capacity per unit area for each element i (KJ/m^2·K)

A_i = area of each element i (m^2)

TFA = total floor area (m^2)

The calculation of the Thermal Mass Parameter takes into account all external walls, floors and roofs (including party walls and party floors/ceilings) as well as both sides of internal walls and intermediate floors/ceilings. The heat capacity per unit area (κ) is calculated for each element with the use of Equation 3-9 (DECC, 2014):

$$\kappa=\sum(d_j\cdot \rho_j\cdot c_j) \qquad \text{Equation 3-9}$$

Where,

d_j = thickness of layer j (m)

ρ_j = density of layer j (kg/m^3)

c_j = specific heat capacity of layer j (kJ/kg·K)

The calculation of the κ – value takes into consideration those layers of the construction element that are included within a depth measured from the surface of the element in contact with the heated spaced that extents to whichever occurs first:

- Halfway through the total thickness of the element
- A layer of insulating material (defined as having thermal conductivity equal to or less than 0.08 W/m^{2}K)
- 100mm depth

Indicative values of heat capacity are also provided for typical constructions.

Indicative TMP values of 100, 250 and 450 kJ/m^2·K corresponding to low, medium and high thermal mass constructions are provided for design assessments where constructions have not been precisely defined (DECC, 2014).

The Thermal Mass Parameter is taken into account in the Appendix P calculations of the temperature threshold that determines the likelihood of overheating during hot weather described above.

3.5.3 Passivhaus Planning Package

The effect of thermal mass on the resulting temperatures to assess overheating risk is also taken into account by the Passivhaus Planning Package (PHPP). The effective thermal capacity is set in the 'Summer' Worksheet of the PHPP software and is calculated as follows (Feist et al., 2007):

$$c = 60 + n_{heavy} \cdot 24 \ \mathrm{Wh/(m^2K)} \qquad \text{Equation 3-10}$$

Where,

c = effective thermal capacity (Wh/m^{2}K)

n_{heavy} = massive surface of a typical room (walls, floors,ceiling). The number of massive surfaces may not be more than six ($0 \leq n_{heavy} \leq 6$)

A minimum level of thermal capacity is 60 Wh/m^{2}K for a lightweight construction, while a value of additional 24 Wh/m^{2}K is considered for each thermally heavyweight surface. Alternatively fixed values for lightweight, medium and heavyweight constructions of 60 Wh/m^2K, 132 Wh/m^2K and 204 Wh/m^2K respectively are proposed to the user (Feist, 2007). As the building is treated as a single zone model, a single value of the level of thermal mass is required for the calculation (Lewis, 2014).

3.6 Future Warming Climate – Climate Change Projections

The issue of overheating becomes more important when considering the projected climate change and it was seen that many studies investigated the performance of dwellings in the future. Mean daily temperature will rise, with the South of England likely to face the highest risk. The UK is expected to face hotter and drier summers as well as warmer and wetter winters, while extreme weather events are likely to occur more often (Gething, 2010, Gething and Puckett, 2013). With regards to building performance it can be estimated that the heating demand will decrease while the cooling demand will increase. Future weather files are used in dynamic building simulation software to evaluate the occurrence of high internal temperatures in the future. These are based on climate change projections published by the Department for Environment, Food and Rural Affairs (DEFRA). The main climate projections used in building simulations are the UK Climate Projections (UKCP09) and the previous UK Climate Impacts Programme (UKCIP02).

3.6.1 UK Climate Projections (UKCP09)

In order to assess the possible effects of the expected changes in climate, the Department for Environment, Food and Rural Affairs (DEFRA) published the latest UK Climate Projections (UKCP09). The UKCP09 climate projections follow a probabilistic approach of the potential climatic changes under three emissions levels scenarios: low, medium and high (Hacker et al., 2009). For each of these scenarios monthly, seasonal and annual climate averages are provided for a 25km grid as well as specific aggregated administrative and river-basin areas. The projections were based on the baseline period 1961-1990 and regard seven overlapping thirty-year periods from 2010 to 2099 (UK Climate Projections, 2009a).

The probabilistic nature of the UKCP09 projections is associated with the fact that different outcomes are assigned with different degrees of probability based on the Cumulative Distribution Function (CDF), with each value in the CDF representing the probability of change being less than a specific value (Jenkins et al., 2009). For example 50% probability is the central estimate of change being as likely to be or not to be exceeded, 10% probability represents changes which are very likely to be exceeded while 90% probability are changes which are very likely not to be exceeded. An example of a CDF is given in Figure 3-3 below.

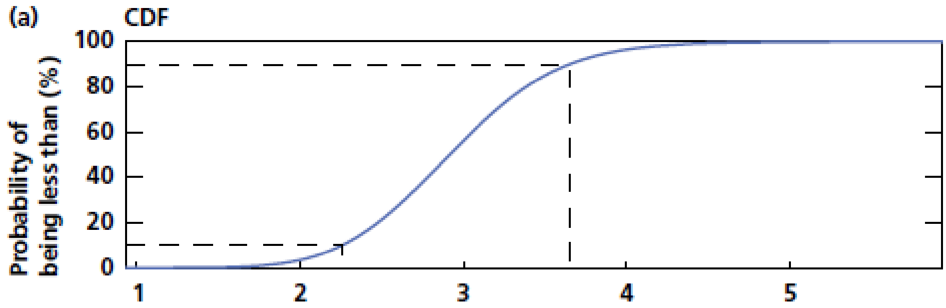


Figure 3-3: Typical example of Cumulative Distribution Function of temperature change for a hypothetical timeslice, month, location and emissions scenario (Jenkins et al., 2009).

In order to transform the UKCP09 climate projections into finer temporal and spatial scales, the UKCP09 Weather Generator (WG) is used, a downscaling tool which provides probabilistic daily or hourly values of the weather variables for 5km grid squares. The Weather Generator produces time series of statistically plausible hourly and daily weather data based on recorded data and random number sampling (UK Climate Projections, 2009b).

While the UKCP09 projections and the associated output from the weather generator provide the most recent sets of climatic data, they are not suitable for building energy modelling as they do not include certain variables such as wind speed and direction, and the Weather Generator typically provides 3000 synthetic future years representing 100 plausible daily future climate time series for each year of a 30-year period (Mylona, 2012). For this reason, several projects were funded by the Engineering and Physical Sciences Research Council (EPSRC) under the 'Adaptation and Resilience to a Changing Climate Coordination Network' (ARCC CN) to deliver methodologies for transforming the UKCP09 data so that they would be deemed suitable for integration to the existing simulation software (ARCC CN, 2012):

- COPSE: "Coincident Probabilistic climate change weather data for a Sustainable built Environment"
- Low Carbon Futures: "Decision support for building adaptation in a low carbon climate change future" (LCF)
- PROCLIMATION: "The use of probabilistic climate scenarios in building environmental performance simulation"
- PROMETHEUS: "The use of probabilistic climate data to future proof design decisions in the buildings sector"

A detailed review of the methodologies as well as description of associated benefits and limitations considering their use in building simulation is provide by Mylona (2012).

The PROMETHEUS project offers DSYs and TRYs for three time periods and the different emissions scenarios for multiple locations for increased probabilities (10%, 33%, 50%, 66% and 90%) while COPSE provides a single DSY and TRY file for each time period; this reduces the computational time required, but does not allow for the assessment of multiple risks. PROCLIMATION suggested the use of single year for the TRY rather than constructing a typical year from the different months, while LCF provided a regression equation to calculate the indoor temperatures from weather data which allowed for performing overheating risk assessments for multiple uncertainties and probability ranges thus reducing the computational requirements (Mylona, 2012).

In addition, CIBSE produced future DSY files incorporating the UKCP09 probabilistic projections for three areas of London (urban, semi-urban and rural) for the three time periods 2020, 2050 and 2080 for 10%, 50% and 90% probability and for different emissions scenarios: low emissions for 2020, low and medium emissions for 2050 and all three emissions scenarios in 2080 (CIBSE, 2013).

3.6.2 UK Climate Impacts Programme (UKCIP02)

UK climate projections UKCP09 replaced the previous UK Climate Impacts Program projections (UKCIP02) which followed a deterministic approach towards the projected change in climate. In the case of the UKCIP02 projections, a specific value of a predicted change in climate was provided rather than predicted range of possible changes with respective probabilities as is the case with the UKCP09 projections. UKCIP02 Projections were based on four different scenarios of potential future greenhouse gas emissions levels: low, medium-low, medium – high and high. The predicted climate changes were provided on a 50-km grid for three 'timeslices' which were 30-year periods named after the central decade. These were the 2020s for the period 2011-2040, the 2050s for 2041 to 2070 and the 2080s for the period 2071 – 2100. These 30-year projections were also based on the 1961-1990 baseline period (Hacker et al., 2009).

The UKCIP02 climate change predictions are provided in monthly averages of values for a number of variables. Four methods for downscaling the average values into smaller intervals, suitable for thermal building simulation, e.g. hourly values, were developed (Hacker et al., 2009):

- Dynamical downscaling, a physics-based model which simulates all the dynamic processes taking place. The output usually is in daily values with hourly values obtained through interpolation.

- Analogue scenarios that relate similarities of the resulting climate change for a location with existing data from another geographical location. Alternatively the ‘temporal analogue’ treats extreme weather series in the current climate as average series in future climate.
- Time series adjustments (‘morphing’). An existing time series of weather observations is adjusted by being ‘shifted’ and ‘stretched’ in order to account for average future changes in weather variables.
- Stochastic models (‘weather generators’). These are statistical models which account for relationships between climate variables and produce plausible weather time series

The morphing method was used by CIBSE as it was suitable to develop future Test Reference Years and Design Summer (from existing TRY and DSY files) for the 2020s, 2050s and 2080s timeslices. This method was found particularly useful as it was a simple and straightforward method and the industry was already familiar with the use of DSY and TRY files. Furthermore, the morphing method was found to offer higher degree of confidence regarding the accuracy or resulting time series (Hacker et al., 2009).

The main advantages offered by the UKCP09 projections compared to the UKCIP02 are the finer spatial resolution (Figure 3-4) and the probabilistic nature of climate change which accounts for uncertainties in predictions. Uncertainty derives from different but plausible predictions offered from different climate models. The UKCP09 projections were based on a large ensemble of variants of the Met Office Hadley Centre global model together with 12 other international global models while predictions in UKCIP02 were based on the Met Office Hadley Centre model (Jenkins et al., 2009).

Direct comparison between the two methodologies is therefore not applicable in most of times. In a report by the UK Climate Impacts Programme and the Scottish Climate Change Impacts Partnership (UKCIP and SCCIP (no date)) the changes in several climate variables (mean winter and summer temperature and mean winter and summer precipitation) from the two projections (for 10%, 50% and 90% probability) for the two common scenarios were compared (high emissions and low emissions) for the different Administrative regions. It was found that in most cases the UKCIP02 were in the lower part of the UKCP09 distribution and that in some cases they were close to the central estimate.

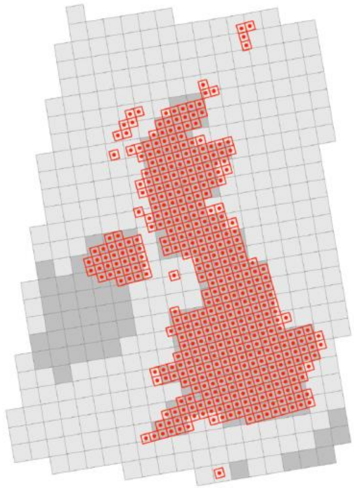


Figure 3-4: UKCP09 grid (red cells) in comparison to the UKCIP02 grid (grey cells). The red dots are the values of the underlying UKCP02 cells (UKCIP and SCCIP, no date))

3.7 The Nottingham climate

Local weather conditions are the main driver of a building's thermal response and therefore climate data are central to the thermal performance analysis. All the monitoring studies carried during the course of this project, presented in Chapter 4 to Chapter 7, investigated the performance of buildings located in Nottingham. For this reason, information on the region's climatic conditions is presented below.

Nottingham is the largest city of the East Midlands region of England, part of the wider district Midlands. Due to its location at the centre of England, the climate of Midlands is characterised as intermediary from the south of England to the north in terms of temperatures and from Wales to the east of England in terms of rainfall (Met Office, 2015a). The annual average temperature in the East Midlands varies between 8.5°C and 10°C (CIBSE, 2015b). The mean annual temperature for Nottingham was 9.8°C for the climate period 1981 – 2010 with a mean maximum of 13.4°C and mean minimum temperature of 6.1°C. Temperatures over the year vary significantly with average maximum ranging from 6.6°C to 21.3°C and average minimum temperatures from 1.1°C in February to 12.1°C in July. The average total amount of rain over a year reached 709.4mm on average for the period 1981 – 2010 with 124.2 days with rainfall more than 1mm. The annual average number of sunshine hours was 1440.1 hours and the number of frost days was 42.9 days. The climate data for Nottingham were taken from the Watnall weather station which is the nearest climate station to the city (53.005N, -1.250W) at an altitude of 117 meters above sea (Table 3-4) (Met Office, 2015b).

Table 3-4: Mean monthly values for the Nottingham climate

Month	Max Temp (°C)	Min Temp (°C)	Days of air frost (days)	Sunshine (hours)	Rainfall (mm)	Days of rainfall (mm)	Monthly mean wind speed at 10m (knots)
Jan	6.6	1.3	10.2	54.7	61.2	11.8	8.6
Feb	7.0	1.1	10.6	73.2	47.2	10.0	8.5
Mar	9.7	2.8	5.3	104.2	49.5	11.1	8.2
Apr	12.5	4.3	2.2	141.0	53.8	9.9	7.5
May	16.1	7.1	0.1	181.6	51.8	9.3	7.1
Jun	18.9	10.0	0.0	170.6	62.5	9.2	6.4
Jul	21.3	12.1	0.0	191.1	57.6	9.2	6.2
Aug	21.0	12.0	0.0	180.1	62.0	9.4	6.1
Sep	17.9	10.0	0.0	131.2	58.6	9.4	6.4
Oct	13.7	7.1	0.7	99.4	71.2	11.2	7.1
Nov	9.4	3.9	4.2	63.7	65.7	11.8	7.3
Dec	6.7	1.6	9.7	49.2	68.6	12.1	7.7
Annual	13.4	6.1	42.9	1440.1	709.4	124.2	7.2

According to the UKCP09 climate change projections, by 2050 the region will experience a 2.5°C increase of the mean summer temperature and a 2.2°C increase of the mean winter temperature considering 50% probability level and the medium emissions scenario. The projected increase of the mean daily maximum and minimum temperatures in the summer is 3.3°C and 2.7°C respectively. Annual precipitation is expected to remain unchanged in 2050 with a 50% probability. However, seasonal variations are expected to occur with summer mean precipitation projected to drop by 15% while winter mean precipitation to increase by 14 % (UK Climate Projections, 2009a).

Apart from the predicted future changes, climate change appears to have already affected current weather conditions with extreme phenomena occurring at an increased rate over the last years. The Local Climate Impacts Profile (LCIP) for Nottingham, a project coordinated by Climate East Midlands with advice from UK Climate Impacts Program to identify areas of vulnerability to climate change, identified nine key weather events occurring over the period 2000 – 2010 (Climate East Midlands and Nottinghamshire County Council, 2011):

- Two heat waves (August 2003 and July 2006);
- Two severe winter events (February 2009 and January 2010);
- Two flooding events (June 2007 and June 2008);

- Two storms (July 2006 and January 2007); and

- One event of storm and flood in November 2000

3.8 Conclusions

In this chapter, the basic concepts relevant to the work of this thesis were discussed. The concepts of thermal comfort and overheating and the main methodologies to define and assess them were discussed. Research evidence from monitoring and simulation studies that overheating is an issue of increasing importance of UK dwellings that is likely to become more prominent in the future were also presented.

Despite the fact that evidence on the overheating risk of dwellings is growing, there is still limited evidence on the thermal performance of super-insulated dwellings with very high levels of airtightness. Large-scale monitoring studies investigated the general performance of the housing stock, focusing mostly on the age and type of housing and the construction type which are more likely to overheat. Even though they provided evidence on the scale of overheating across the building stock, the vast majority of UK houses are not built to high energy performance standards. These studies identified the trend of modern houses to present higher indoor temperatures. Smaller scale studies investigated the performance of well-insulated houses and flats and reported overheating problems. However, these are limited and most of them do not allow for comparison of different construction types.

Simulation studies provide more flexibility and allow for examining different variables such as construction type, dwelling type and insulation levels. They also allow for investigating the future performance of dwellings. Numerous simulation studies suggested that thermal mass has the potential to reduce the levels of overheating to a certain extent.

Based on this, the concerns regarding the thermal performance of MMC presented in Chapter 2 appear to be justified. However, a report published by the NHBC Foundation suggests that designers tend to overestimate the ability of thermal mass to mitigate overheating as they often include in the simulations unfeasible assumptions such as ideal use of the ventilation strategy or high ventilation rates that are not possible to be found in practice (NHBC Foundation, 2012). In addition, Kendrick et al. (2012) argued that many simulation works tend to use construction types that are not usually met in practice and therefore they are overestimating the effectiveness of thermal mass.

Significant scope for further research exists therefore in order to assess the overheating propensity of dwellings built with MMC to high energy efficiency standards and evaluate the effectiveness of thermal mass to regulate internal temperatures. The following chapters investigate this matter with the use of whole building dynamic simulations and monitored data of ambient temperatures. In Chapter 4, a parametric analysis examined the thermal performance of Nottingham H.O.U.S.E. a timber frame low-energy building under varying levels of thermal mass. In Chapter 5, the overheating risk of two dwellings of similar design, one built with timber frame construction and one with modern masonry construction is evaluated again though the analysis of monitored and simulated data. The study then focuses on the performance of building elements, rather than whole house performance, through monitoring the heat flows and surface temperatures in situ (Chapters 6 and 7) as well as under fixed conditions in a laboratory setting and through Finite Element Analysis (Chapter 8).

CHAPTER 4. THE NOTTINGHAM H.O.U.S.E CASE STUDY

In Chapter 2 it was demonstrated that there are wide concerns on the use of Modern Methods of Construction in relation to their thermal performance and their increased risk of overheating. These concerns are based on the lack of thermal mass associated with most MMC; thermal mass has been found to be an effective strategy to mitigate overheating in many simulation studies (Orme and Palmer, 2003, Orme et al., 2003, Hacker et al., 2005a, Arup Research and Development and Bill Dunster Architects, 2005, Hacker et al., 2008, Rodrigues, 2009, Peacock et al., 2010, Kendrick et al., 2012, Gupta and Gregg, 2012, Rodrigues et al., 2013a, Rodrigues et al., 2014, Sougkakis et al., 2014, Rodrigues et al., 2015). It has been suggested however that these concerns, although reasonable, may be unjustifiable since there is not enough evidence on the actual performance of houses built with MMC to support this statement (Rodrigues, 2009).

In addition, growing research evidence suggests that there is a difference between the design and the as-built performance of new UK buildings. This is commonly called the 'performance gap' (Zero Carbon Hub, 2014a). The performance gap may compromise the efforts to achieve the national carbon targets discussed in Chapter 2 and also affects client satisfaction and the reputation of the building industry (Cutland Consulting Limited, 2012). Therefore, it has been treated as an issue of high priority by the government and industry and a target has been set for 2020 that at least 90% of new houses should meet or exceed the design energy and CO_2 performance levels (Zero Carbon Hub, 2015a). Gathering further evidence for the underperformance of dwellings to identify the causes and inform the industry and the government so that appropriate measures and training are taken is considered critical in tackling the performance gap (Cutland Consulting Limited, 2012).

These issues highlight the need for additional studies reporting on the actual performance of MMC. The work presented in this chapter is in line with this requirement. A pilot study was conducted where the actual as built performance of the Nottingham H.O.U.S.E., a super-insulated timber frame house, was evaluated in terms of fabric construction quality and risk of overheating. The study sought to assess whether the design requirements have been met in practice and identify causes of potential underperformance. In addition, as a response to the concerns on the risk of MMC to suffer from elevated temperatures, a parametric study was conducted to evaluate the use of non-traditional lightweight elements, i.e. elements other than brick, masonry and concrete that are not commonly used by designers, as potential solutions to increase the levels of thermal mass and mitigate overheating.

In the first paragraphs, the context required to assist the reader in evaluating the work presented in the rest of the chapter is set. Here, the concept of the Nottingham H.O.U.S.E., the design features and construction specifications of the building are presented. This information is inextricably linked to the analysis and introducing these to the reader is required in order to evaluate the performance of the building.

The following sections of the chapter comprise the main body of the analysis which was arranged in two autonomous but interlinked parts. The first part reports on the results of a pilot study conducted to assess the as-built performance of the building. This study involved a series of diagnostics tests performed to evaluate the quality of the fabric construction and investigate whether the design specifications were met in practice or not. The ability of one of the most commonly used MMC worldwide, namely timber frame construction, to deliver housing at the highest energy efficiency standards was investigated in this section. In addition, it was sought to identify potential areas of underperformance of the construction and review whether these could be avoided in practice at the scale of mass production.

The second part of the analysis was simulation based. A parametric simulation study designed to assess the overheating risk of the house under varying levels of thermal mass was conducted and the findings of this study are presented here. The study investigated the potential to use non-traditional materials and building elements to increase the levels of available thermal mass in the house.

Several useful conclusions were derived from the studies, which together provided a holistic view of the dwelling's thermal performance. These are discussed in the final section of this chapter. In addition, drawing from the experience gained from the analysis the author underpinned some of the limitations of the studies and proposed actions for improving the procedure as well as suggestions for further work.

4.1 Scope and Aim

The work presented in this chapter aimed at evaluating the Nottingham H.O.U.S.E. as a proposed solution for low-carbon housing of high construction quality that is able to deliver high standards of thermal comfort and energy efficiency. The main aims of the analysis were:

- To evaluate the as-built performance of a highly insulated building constructed with timber frame construction;

- To investigate the ability of timber frame construction to meet the stringiest energy efficiency targets and evaluate its overheating potential;
- To investigate the potential of thermal mass to help regulate internal temperatures; and
- To assess the use of non-traditional lightweight materials to provide additional levels of thermal mass to a building and reduce the risk of overheating

4.2 Methodology

The thermal performance of the building was assessed both in-situ and through the use of dynamic simulations.

<u>In situ assessment</u>

The actual as-built performance and construction quality of the building fabric were assessed during a pilot study involving a series of non-destructive tests and a monitoring study. These were:

Whole House Heat Loss Test (coheating) to determine its Heat Loss Coefficient (HLC). The test was performed according to the protocol determined by the Leeds Metropolitan University (Johnston et al., 2013). The test procedure involves heating the building under investigation to a steady increased temperature, significantly higher than the mean external temperature (usually 25 ^{o}C) with the use of electrical heaters and monitoring the internal and external temperatures, as well as the power consumption of the heaters. The HLC is determined by plotting the daily average electrical consumption, Q, against the daily average Delta – T values (Difference between the average internal and average external temperature, ΔT) (Johnston et al., 2013).

However, this calculation does not account the effect of solar gains and usually leads to an underestimated value for the HLC. There are two commonly used methods to account for the influence of solar radiation, multiple regression analysis and Siviour Analysis. In the former method, the relationship of the electrical consumption data (power input) against the solar radiation,S, and the Delta-T (ΔT) is determined. The result is a solar corrected value of the power input. This is then plotted against the daily average ΔT values and a new HLC that accounts for solar gains is obtained. In the Siviour analysis, a linear regression is performed between the values of Q/ΔT in the y-axis and S/ΔT in the x-axis. The resulting line has a slope that determines the solar aperture, R, and a y-intercept that determines the new HLC (also accounting for the solar gains) (White, 2014)

U-value analysis of the external wall and roof were determined by measuring the heat flux and the temperature on these elements during the co-heating test. The results were analysed according to the criteria set by the BS ISO 9869-1:2014 on the in-situ measurement of thermal resistance and thermal transmittance (BSI, 2014):

- Test duration exceeding 72 hours
- Deviation between the R-value obtained at the end of the test and the R-value obtained 24h before is not larger than ±5%
- The deviation between the R-value obtained from the first time period with a duration of INT(2 x D_T/3) days and the R-value obtained from the last time period of the same duration does not exceed ± 5 %. (D_T is the duration of the test in days and *INT* is the integer part)

The air permeability of the house was assessed through a Blower Door Test according to the approved procedure provided by the Air Tightness and Measurement Association that is based on the BS EN ISO 13829: 2001 'Standard Thermal Performance of Buildings -Determination of air permeability of buildings - Fan pressurisation method' (BSI, 2001, ATTMA, 2010). The process involves applying a differential pressure with the use of a door fan and measuring the required airflow to achieve that pressure difference. The air permeability may be determined though pressurisation or depressurisation of the building. A series of measurements are taken at different pressure steps. The air permeability of a building is then determined and expressed as the volume of air in m^3 that leaks through the envelope per m^2 of envelope per hour at a pressure of 50Pa ($m^3/(m^2h)$@50Pa).

Overheating analysis through monitoring actual temperatures, external and internal, over the summer period. As the Nottingham H.O.U.S.E is used as an office building, the analysis of elevated temperatures considered the static criteria for thermal comfort and overheating in offices set by the Chartered Institution of Building Services Engineers (CIBSE). According to these criteria, 25^{o}C is a comfortable temperature for offices and overheating occurs when temperatures exceed 28^{o}C for more than 1% of occupied hours (CIBSE, 2007)

Thermal Imaging Analysis was conducted to determine potential areas of thermal bridging and air leakage. Thermal imaging is a valuable diagnostics tool for evaluating the performance of the building fabric by visualizing the surface temperature of the building. It is a quick and non-destructive method to identify areas of thermal anomalies, such as where insulation may be interrupted by structural elements, compromised by moisture or poor installation or even missing and/or air leakage might occur.

Thermographic surveys are most commonly used for qualitative analysis. The proposed method for conducting such analysis and identify irregularities in the thermal envelope is set out in BS EN ISO 13187:1999 'Thermal performance of buildings - Qualitative detection of thermal irregularities in building envelopes – Infrared method' (BSI, 1999). However, there are cases where thermal imaging can be used for quantifying certain properties of the constructions investigated (Pearson, 2011).

Parametric study

After assessing the as-built performance of the building, the second stage of the analysis involved investigating the overheating potential of the house under varying levels of thermal mass. The parametric study was conducted with the use of whole building dynamic simulation software. The use of non-traditional lightweight materials on the walls and ceilings to provide additional levels of thermal mass to the house was considered and the performance of these materials was compared to that of concrete, a material used commonly in heavyweight constructions.

The non-traditional building elements examined were Rigidur H, a gypsum fibreboard developed by British Gypsum that combines gypsum, water and cellulose fibres from recycled paper, and Alba®balance 23 and Alba®balance 26, two plasterboard types developed by Rigips AG that contain PCM microcapsules with 23°C and 26°C phase change temperature respectively (British Gypsum, 2012, Rigips Saint Gobain, 2012). Various layers of Rigidur H and Rigips PCM plasterboards were considered in the walls and ceiling of the building and their performance was compared against to that of concrete. The overheating potential was evaluated in terms of occurrence of elevated temperatures above specific temperature thresholds.

4.3 The simulation software

Dynamic thermal simulation analysis investigates the response of the building to external and internal thermal loads based on heat transfer calculations performed. It is used in several applications where is required to demonstrate compliance with building regulations on energy performance and certification purposes, to assess the expected energy consumption and CO_2 emissions of specific design options (energy modelling) and to evaluate the thermal conditions with regards the thermal comfort of users (CIBSE, 2015a). In addition, several software packages also allow for analysis of daylight and ventilation levels, although the use of specialised software is recommended for these applications.

Dynamic simulations were performed using commercial software EDSL Tas, one of the most commonly used software by industry and research in dynamic thermal analysis applications. It was developed in the UK by Environmental Design Solutions Limited, a company with more than twenty years of experience in building simulation software (EDSL, 2015a). Tas consists of three main components (EDSL, 2015b):

- 3D Modeller, the program where the building model is created and information on its location and orientation is provided. Rendered views of the building geometry are available by the 3D Modeller and shading calculations are undertaken. The model is then extracted to the Building Simulator
- Building Simulator. All the necessary inputs for the simulations are provided by the user in this component. Through the use of databases the appropriate weather file, construction materials for the building elements, internal conditions and occupancy schedules are assigned to the model.
- Results Viewer. When all the parameters are assigned to the model and the simulations are performed, results may be viewed in the Results Viewer. Results are provided for the zone air temperature (dry and resultant), mean radian temperature, surface temperatures, humidity, condensation risk, space loads (sensible and latent), energy consumption and plant size (EDSL, 2009).

Based on the heat balance method, Tas provides a snapshot of the thermal condition of the building every hour. It may be used for predicting the performance of a dwelling over a whole year or under extreme design conditions (EDSL, 2009). The sensible heat balance for a zone is determined through a combination of the energy balance of the air with the surrounding surfaces and the energy balances of the external surfaces. The heat balance is then solved for every hour to determine the zone temperature, the thermal load and the surface temperature of the building elements. A latent heat balance for every zone is also solved for each zone accounting for latent heat loads, moisture and humidification/dehumidification plant. Heat transfer through conduction, convection and radiation as well as internal heat gains and solar gains are considered in the heat balance of zones. The co-ordination method, derived from the ASHRAE response factor method is used to determine conduction heat transfer from external surfaces (EDSL, 2009, ASHRAE, 2013).

Validity of Tas to perform building energy simulations is well established. The software has completed all performance tests required by ASHRAE 140-1 (2004) ASHRAE 140-1 (2007) and it is compliant with BS EN ISO Standards 13791, 13792, 15255 and 15265. In addition, it has been approved as compliant for EPC and Part L 2013 assessments in England and Part L 2014 assessment in Wales (EDSL, 2015c). It has been widely used by researchers in the field of building thermal performance ((Rodrigues, 2009, Kendrick et al., 2012, Wang et al., 2013, Rodrigues et al., 2014, Amoako-Attah and Jahromi, 2015, Tubelo, 2016, Kiamba, 2016) to mention a few). The ability of the software to produce accurate results was also demonstrated in a study by conducted by EDSL and Mitsubishi Electric, where an office building fitted with a Mitsubishi MULTI R2 recovery system was simulated. Results showed good agreement between simulated and monitored results (CIBSE Journal, 2013). Jankovic (2012) characterised it as a very useful dynamic simulation tool with the 'right combination of software complexity and user interaction'.

4.4 House Design

The Nottingham H.O.U.S.E. (Home with Optimised Use of Solar Energy) is a two storey L-shaped "starter home" and it was developed to provide an affordable solution for a first residence for a couple or a new family. The house was designed as semi-detached or as part of a terrace, with the L-shape providing an external courtyard when joined with other houses. However, the house has been built as a detached house at the Creative Energy Homes (CEH) site at the University Park Campus, University of Nottingham. The Creative Energy Homes project is a unique research project which involves monitoring seven dwellings built with different MMC and at various specifications aiming "to stimulate sustainable design ideas and promote new ways of providing affordable, environmentally sustainable housing that are innovative in their design" (Gillott et al., 2010a, Rodrigues et al., 2014). A view of the house as currently built at the CEH site is presented in Figure 4-1 below and the plans of the ground and first floor are provided in Figure 4-2.

Figure 4-1: Exterior view of the Nottingham H.O.U.S.E.

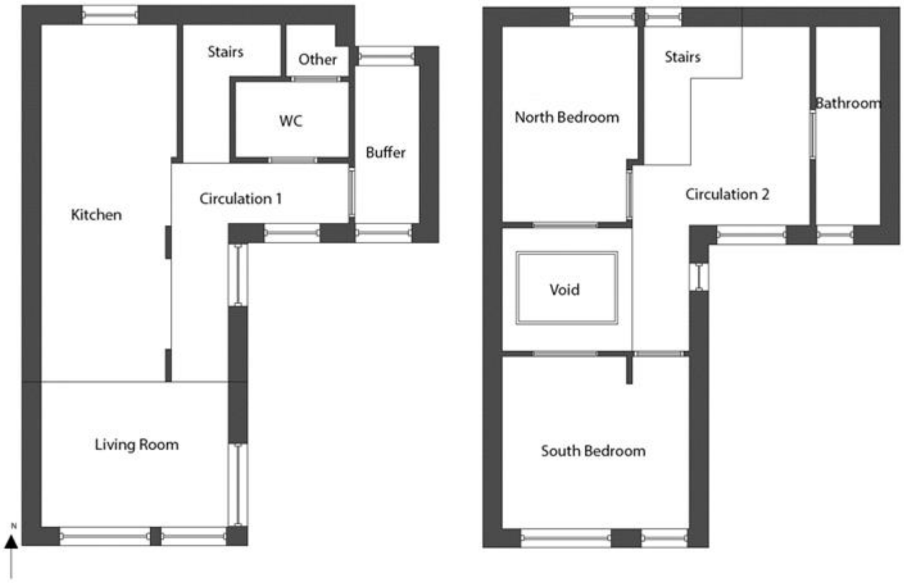


Figure 4-2: Plans of the ground floor (left) and the first floor (right) of the Nottingham H.O.U.S.E.

The Nottingham H.O.U.S.E. was designed by students at the Department of Architecture and Built Environment at the University of Nottingham to enter the Solar Decathlon 2010 competition in Madrid and aspired to provide a solution for the deployment of affordable houses built to zero-carbon standards. The original design was further refined by industry partners under the coordination of the members of the academic staff. The main aims of the project team were to provide a solution to the modern issues of the housing industry; a house which is easily repeatable and able to achieve the high energy efficiency standards at a reasonable cost.

The house was built using volumetric MMC; it consists of eight fully prefabricated timber cassette panel structures, filled with glasswool insulation, transported and assembled on-site. This approach made the construction process very fast and flexible; this can be demonstrated by the construction record of the building. The house was firstly assembled in Nottingham. It was then moved to London for the Ecobuild exhibition in March 2010, before being transported and assembled in Madrid in June 2010 for the Solar Decathlon 2010 competition. Since 2012 it has been permanently installed at the University Park campus (The University of Nottingham, 2016b). This is an excellent demonstration of the ease of deployment and the flexibility of the house.

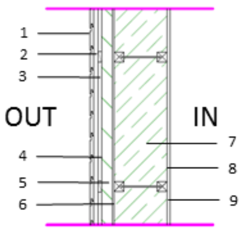
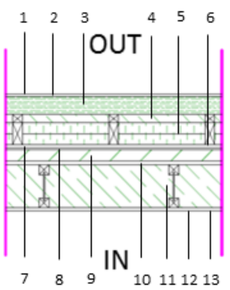
Fabric First approach was central in the design of the Nottingham H.O.U.S.E. The design was based on the principles of the Passivhaus Standard, i.e. very high levels of insulation, minimization of thermal bridging and high levels of air tightness (a value not higher than 0.6 ACH is required for certification). The targets that need to be met in order for a building to be certified as Passivhaus were presented in Table 2-4. The house also aimed at achieving level 6 of the CfSH.

A typical section and build-up of the external walls and the roof is presented in Table 4-1. The design U-values of the opaque building elements, were:

- External walls: 0.10W/m^{2}K
- Floor: 0.10W/m^{2}K
- Roof: approximately 0.075 W/m^{2}K (originally built with a U-value of 0.13W/m^{2}K in London and Madrid. Further insulation was added in the permanent installation in the CEH site)

In order to minimize the heating requirements, high levels of solar gains utilization through the use of large glazed surface areas in the South façade were also adopted. External shading was provided to avoid unwanted solar gains during the summer period. The North façade has considerably smaller proportion of glazed areas in order to minimize heat losses during winter. North facing windows were considered for increasing the levels of natural lighting and for delivering cross ventilation. The house compact footprint also contributed towards reduced heat consumption.

Table 4-1: Sections and build-up of the external walls and roof

EXTERNAL WALL		OUT 1. 18 mm Thermowood cladding 2. 20x50 horizontal HW battens at 400 mm centres 3. 16x50 vertical SW battens at 600 mm centres 4. Breather membrane 5. 50 mm ISOVER RKL Façade insulation (glasswool) 6. 9 mm sheathing ply 7. 245 mm I joists filled with insulation Isover Multimax 30 8. Vario airtight membrane 9. 12.5 mm Rigidur IN
ROOF		OUT 1. Sarnafill roofing membrane 2. 12 mm ply 3. 80 mm Hofatex sarking board 4. Glass fibre insulation installed (average 37.5 mm) 5. 100 mm (2x50) rigid insulation batts 6. 12mm ply 7. Roof membrane 8. 10 mm ply 9. 50 mm insulation Isover Roofine P35 (glasswool) 10. 15 mm ply 11. 195 mm I joists in filled with insulation Isover Multimax 30 (fibreglass wool) 12. Vario airtight membrane 13. 15 mm Rigidur IN

In order to increase the levels of comfort during the summer, both natural and mechanical ventilation were adopted. Natural ventilation is provided by means of cross-ventilation and stack ventilation by opening the roof window above a double-height space that has been considered in the dining area. Provision for this space was taken for connecting the ground floor with the first floor as well as assisting natural ventilation. Mechanical ventilation is also provided when the external conditions are not ideal for opening the windows. Preheating the incoming air through heat recovery reduces the thermal load of the building. The system is also equipped with a HEPA technology filter to deliver increased levels of air quality (Saint-Gobain, 2014).

During the Solar Decathlon 2010 competition in Madrid, a Passive Downdraught Evaporative Cooling (PDEC) system was installed at the double height space above the dining area. Nozzles were positioned just below the roof window providing water mist that evaporated and cooled the incoming air. The performance of the system in the climate of Madrid was assessed by Ford et al. (2012). The PDEC system was removed when the building was permanently erected at the CEH site, at the University of Nottingham Park Campus.

In order to minimize the electricity consumption of the house and reduce further the internal heat gains, low-energy lighting and low energy appliances provided by NEFF were used. Solar thermal collectors to deliver hot water and photovoltaic panels to produce electricity, both provided by SONNENKRAFT, were also fitted as part of the zero carbon strategy.

4.5 Assessing the as-built performance of the Nottingham H.O.U.S.E.

The Nottingham H.O.U.S.E. was designed according to well-established low-carbon principles to achieve the highest standards of energy efficiency and emissions reductions. The timber frame volumetric construction method was not only able to meet the stringent requirements on energy efficiency at the design stage but also contributed towards achieving great flexibility in building installation and fast erection times.

Despite being designed as a dwelling, the house has been used as an office building by staff members at the Department of Architecture and Built Environment. The building has been a valuable living research facility; It was not only a unique project for the students to be actively involved in the design and construction of a low-energy super-insulated house but also offered the opportunity to undertake significant research on the performance of low-carbon buildings.

4.5.1 Results

The results of the study are presented in the following paragraphs:

Whole House Heat Loss Test: The coheating test was conducted for a period of eleven days, from the 15th to the 25th of February 2014. The first three days were considered as the fabric thermal saturation period and therefore the analysis accounted for eight days of monitoring data. The daily average values of the monitored data are presented in Table 4-2. The resulting Heat Loss Coefficient was found to be 70.02 W/K. This figure was based on raw data and did not account for heat gains from solar radiation and therefore the solar corrected HLC was calculated using linear regression and it was found to be 77.26W/K. Siviour Analysis was also performed and the HLC was found to be 86.31 W/K (Figure 4-3). The fabric heat losses were then calculated by deriving the infiltration losses calculated according to the methodology of the Standard Assessment Procedure (SAP) from the HLC values and using the actual weather data recorded at the time of the test. The total fabric heat loss of the building was 68.4 W/K according to the solar corrected data or 76.93W/K according to the Siviour analysis. The total fabric heat losses predicted by SAP were 77.19W/K.

Table 4-2: Daily average data recorded during the coheating test

Date	Average Temperature Difference (°C)	Average daily power input (W)	Average daily solar irradiance (W/m^2)	Solar/ΔT (W/m^2K)	Power/ΔT (W/K)
18/02/2014	16.55	1302.96	17.31	1.05	78.73
19/02/2014	16.96	1209.08	28.69	1.69	71.30
20/02/2014	15.92	1029.92	31.75	1.99	64.69
21/02/2014	19.56	1161.08	52.14	2.67	59.37
22/02/2014	17.51	1115.75	73.72	4.21	63.73
23/02/2014	14.01	1274.88	15.56	1.11	90.97
24/02/2014	15.63	1151.38	30.71	1.96	73.67
25/02/2014	16.72	1146.46	48.92	2.93	68.56

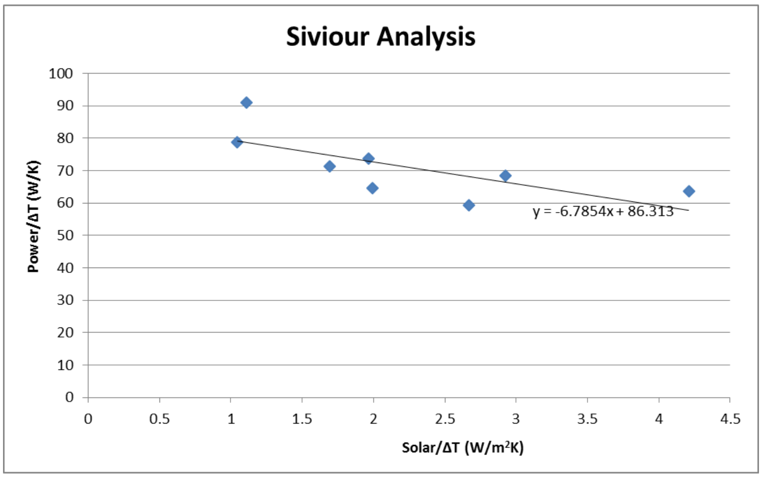


Figure 4-3: Plot of the Siviour Analysis

U-value analysis: The external wall U-value was found to be approximately 0.12W/m^{2}K and the roof U-value was 0.08 W/m^{2}K. These values were by 20% and 6.66% higher than the design U-value of these elements. The criteria set by BS ISO 9869-1:2014 (BSI, 2014) for the calculation of the R-values are presented in Table 4-3. The calculated U-values for the wall and roof over time and the stabilization when the criteria were met are presented in Figure 4-4 and Figure 4-5. The results of the analysis suggest that even though very high insulation levels were achieved in practice, the design U-values were not met. It is worth mentioning that due to equipment restrictions, one heat flux sensor was installed in each building element in the centre position between the timber framing. The calculated U-values correspond to this part of the wall where insulation is uninterrupted by frame. The actual U-value of the wall is slightly higher due to the thermal bridging occurring on the I-joists. After the completion of the coheating test, a heat flux sensor were installed on the frame and the insulation part of the wall, to determine the framing effect. It was found that the heat flux at the joists was approximately 30-40% higher than the heat flux on the middle section between the joists.

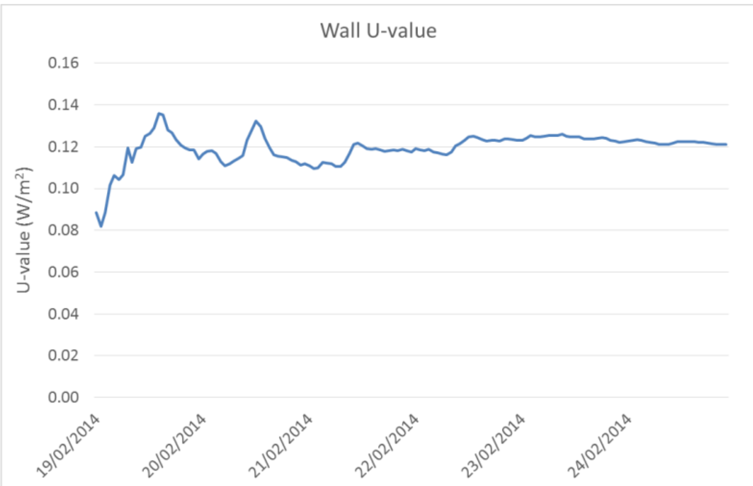


Figure 4-4: U-value of wall obtained with the average method of BS ISO 9869-1:2014

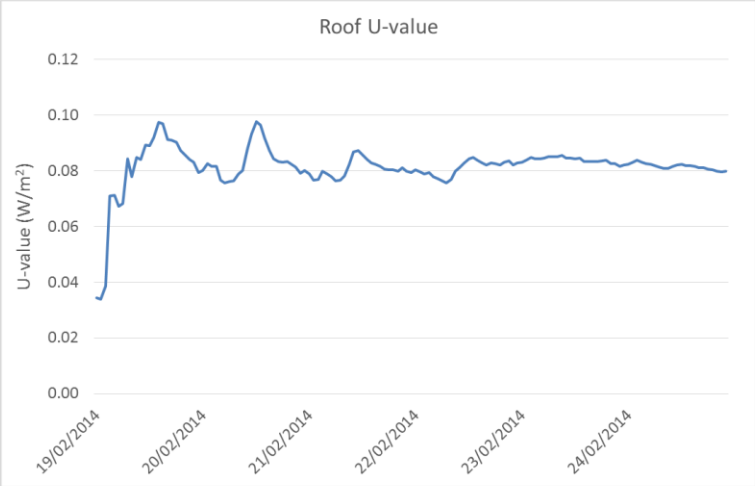


Figure 4-5: U-value of roof obtained with the average method of BS ISO 9869-1:2014

Table 4-3: Compliance of the R-value calculation to the BS ISO 9869-1:2014 criteria

Criterion 1: Test duration > 72h		
Test duration: 19.02.2014 – 24.02.2014		
Criterion 2: Deviation of R-value at the end of the test and the R-value obtained 24h before ≤ ±5%		
Date	Wall R-value (W/m^2K)	Roof R-value (W/m^2K)
19.02.2014 – 24.02.2014	8.26	12.52
19.02.2014 – 23.02.2014	8.16	12.20
Relative difference	1.23%	2.62%
Criterion 3: Deviation between R-value at the first and second INT(2 x D_T/3) periods ≤ ±5%		
Date	Wall R-value (W/m^2K)	Roof R-value (W/m^2K)
19.02.2014 – 22.02.2014	8.11	12.19
21.02.2014 – 24.04.2014	7.94	12.63
Relative difference	-2.10%	3.61%

Air permeability: The air permeability measured with the Blower Door Test was 2.7 $m^3/(m^2h)$. This figure is well below 10$m^3/(m^2h)$ required by the UK building regulations and is considerably better than 5 $m^3/(m^2h)$ that is the normal airtightness value for mechanically ventilated dwellings (ATTMA, 2010). However, this value is still far from the best practice value of 1$m^3/(m^2h)$ and the Passivhaus requirement of 0.6 ACH (in the case of the Nottingham this was approximately 0.75$m^3/(m^2h)$). All figures refer to 50 Pa pressure.

Thermal Imaging Analysis: The thermographic survey of the building was conducted during the coheating test and survey identified areas of thermal bridging in the corners and the junctions between the external walls and the roof and floor or ceiling (Figure 4-6a). These were found to be limited in the area of the junction, suggesting continuity of insulation. However areas of possible air leakage or areas where insulation had been damaged were also identified in these junctions (Figure 4-6b). Thermal bridging and air leakage was also found around the windows and doors or even through the frame (Figure 4-6c and Figure 4-6d).

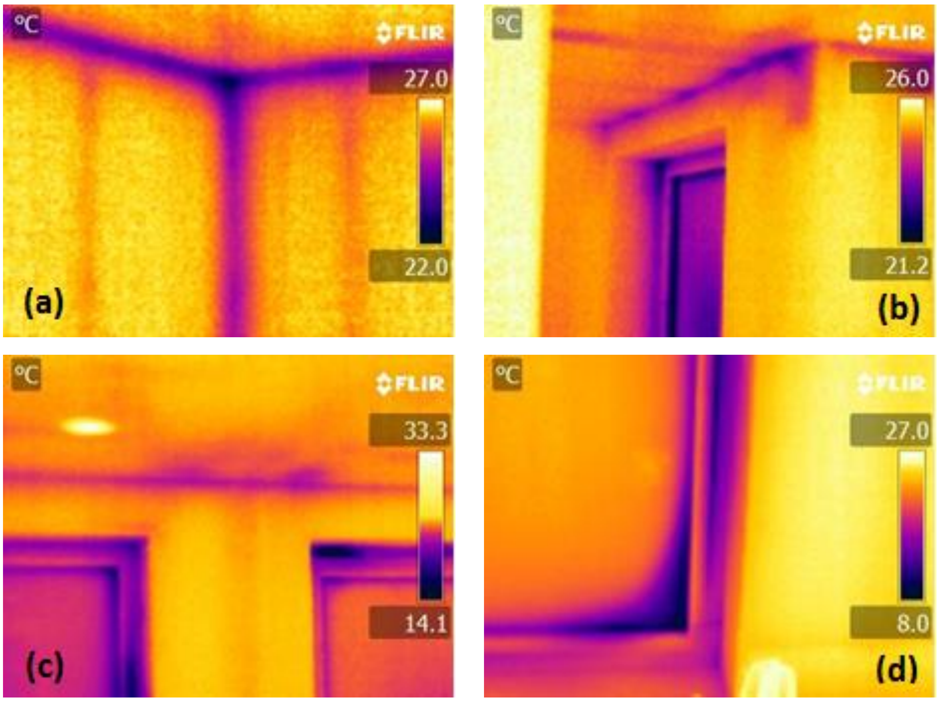


Figure 4-6: Areas with thermal bridges and possible air leakage and/or missing insulation

Overheating analysis: The ambient temperatures were recorded with Tinytag TGU 4500 and TGU 4017 sensors (accuracy of approximately 0.45°C in environmental conditions met in office buildings and the reading range was -40°C to +85°C (Gemini Dataloggers Ltd, 2016)). The floor plans of the building and the location of the sensors can be seen in Figure 4-7. The sensors were placed at a height of 1.5m above floor level. External temperature data was provided from the weather station installed 20m from the building on the CEH site.

Figure 4-7: Floor Plans and location of the tinytag sensors (Left: Ground Floor, Right: First Floor)

Zone temperatures were monitored from December 2013 onwards and the building was opened on July 2014. The overheating analysis considered the 3 month summer period, from July (when the building was first opened) to September 2014. The peak external temperature during the period investigated was 28.53°C and the average external temperature was 12.88°C. During this period, the percentage of time when temperatures exceeded the 25°C comfort and the 28°C overheating limit in the three zones used as office spaces are presented in Table 4-4. The temperature profile for these three zones and the external temperature for the same period is presented in Figure 4-8.

Table 4-4: Monitored temperatures in the offices

	External	First Floor North	First Floor South	Ground Floor
<18 °C	31.1%	0.0%	0.0%	1.2%
18-25 °C	63.5%	78.8%	76.0%	75.9%
25-28 °C	5.0%	18.6%	19.1%	17.5%
>28 °C	0.3%	2.6%	4.9%	5.4 %

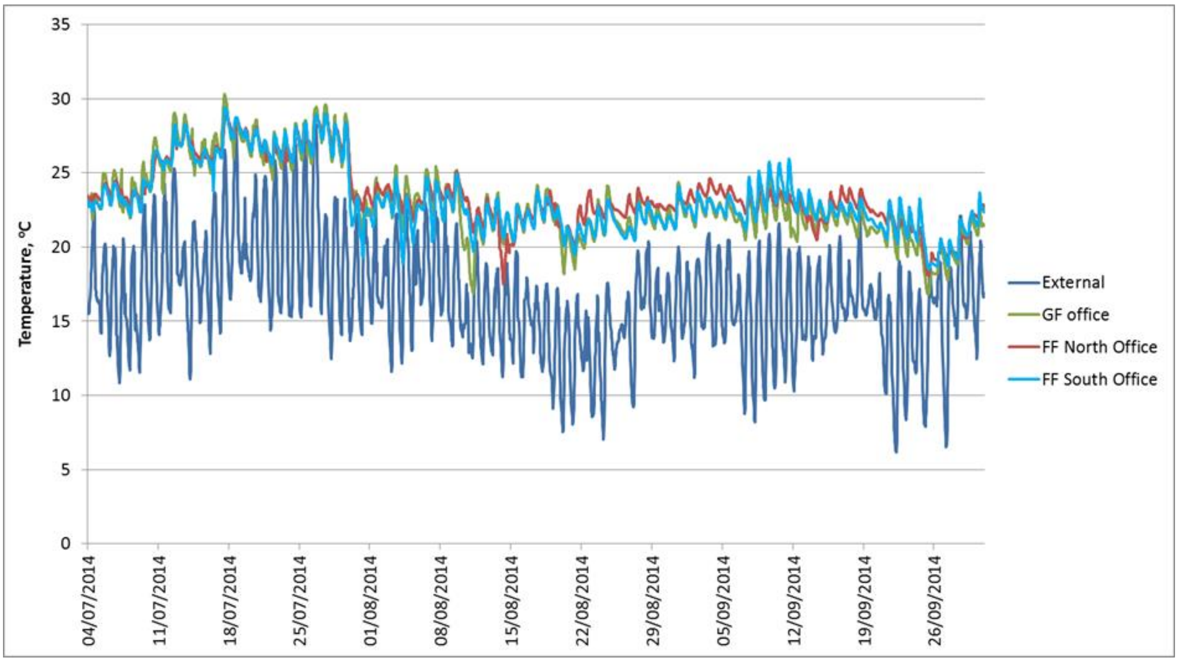


Figure 4-8: Temperatures monitored in the Nottingham H.O.U.S.E. during July and September 2014

A brief look at the results suggest that all three areas investigated suffer from overheating; recorded temperatures exceed the 28°C threshold by 2.6% and 4.9% in the north and south offices of the first floor respectively and by 5.4% in the ground floor one. In addition, the 25°C comfort limit is exceeded for 18.6% of the time in the north, 19.1% in the south office of the first floor and for 17.5% of the time in the ground floor office. The maximum recorded temperatures for the same period for the three selected areas were: 28.9°C in the north office, 29.4°C in the south office and 30.3°C in the ground floor office.

However, these figures should be taken in context. The actual occupancy of the offices was not monitored and the building was not fully occupied during most of the summer period. Therefore, the high temperatures observed were mainly due to the fact that the building windows and doors were kept closed for most of the time during unoccupied periods. The large south oriented glazing areas maximised the solar gains and the high levels of insulation and airtightness resulted in the heat being trapped inside the building.

A short study was conducted between the 25th of July and the 8th of August 2014 to evaluate the effect of the window opening on the internal temperatures. The zone has two large south facing windows, of which one is fixed and the other is openable. In addition, a fixed opening located at the internal wall, opposite the south facing windows, facilitates the air movement providing access to the adjacent void space beneath the roof window (Figure 4-9). Ventilation is therefore provided through cross ventilation from the south facing window and the roof window; the door, when opened, also contributes to increased cross ventilation rates.

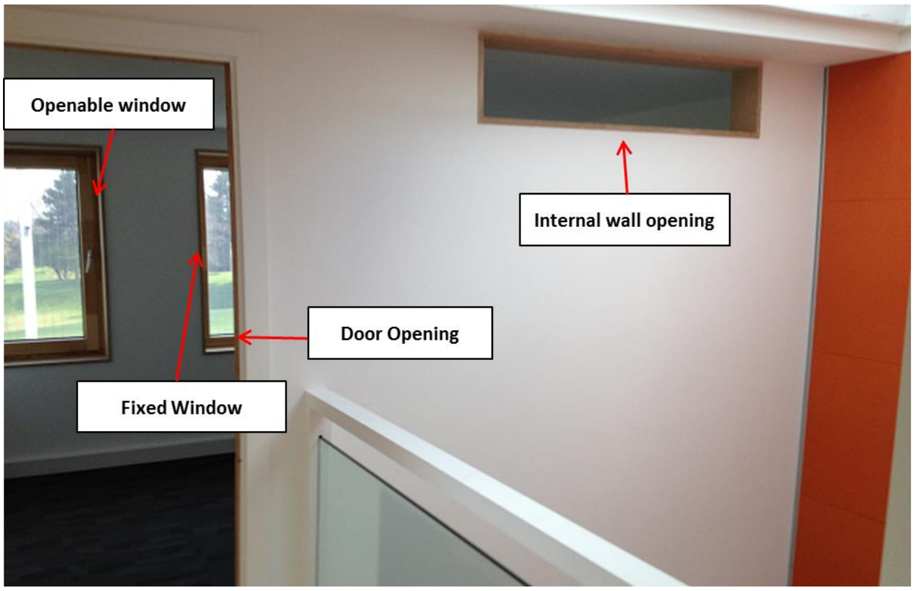


Figure 4-9: Openings in the South Office zone of the Nottingham H.O.U.S.E.

The window opening pattern of the first floor south office was controlled by the author and the resulting temperatures were monitored. The periods when the three openings contributing to the ventilation of the space were open, i.e. the south facing openable window, the roof window and the door were recorded in order to investigate the effect of ventilation on the zone temperatures. These are presented in Figure 4-10. Each day is divided in two periods, daytime and night time (D and N in Figure 4-10). The period when each opening was kept open is shown in green and the periods when the openings were shut are shown in red.

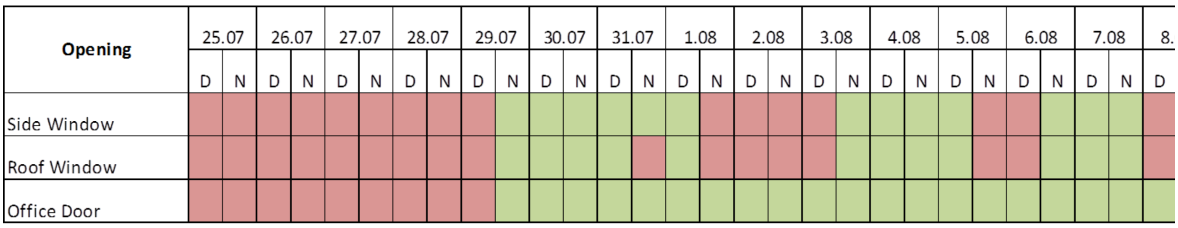


Figure 4-10: Opening schedule of the South Office windows and door

During the study three distinct opening patterns were examined:

- Pattern 1: All windows and door were closed
- Pattern 2: All windows and door were kept open
- Pattern 3: Windows were closed and door was open

The temperature profile of the monitored zone during this period can then be seen in Figure 4-11. Similarly to the previous convention, days when the office doors and windows were kept closed are shaded red and days when they were opened are shaded green. It is apparent, that when all windows and the door were closed (Pattern1), the temperature remained high even though the external temperature had already dropped a few days earlier (Box A). When the windows and door were opened (Pattern 2) the internal temperature dropped to comfortable levels very fast. It can also be seen that keeping the door open and the windows closed (Pattern 3) was not adequate to reduce the zone temperatures. The importance of cross ventilation can also be seen at the night of the 31st of July when the roof window was kept closed due to rain forecast for that night. It is clear that the temperature only slightly dropped during that night despite the fact that the external temperature drops significantly (Box B). One-sided ventilation provided by the south window was not able to cool down significantly the zone temperature.

From the above study, it can be concluded that the building's thermal response to ventilation was fast. Although initial findings showed increased occurrence of elevated temperatures, it is believed that under normal conditions of occupation however, overheating would not likely occur, at least not to a great extent. The ventilation strategy (cross ventilation and night time cooling) appeared to result in significant reduction of the zone temperature.

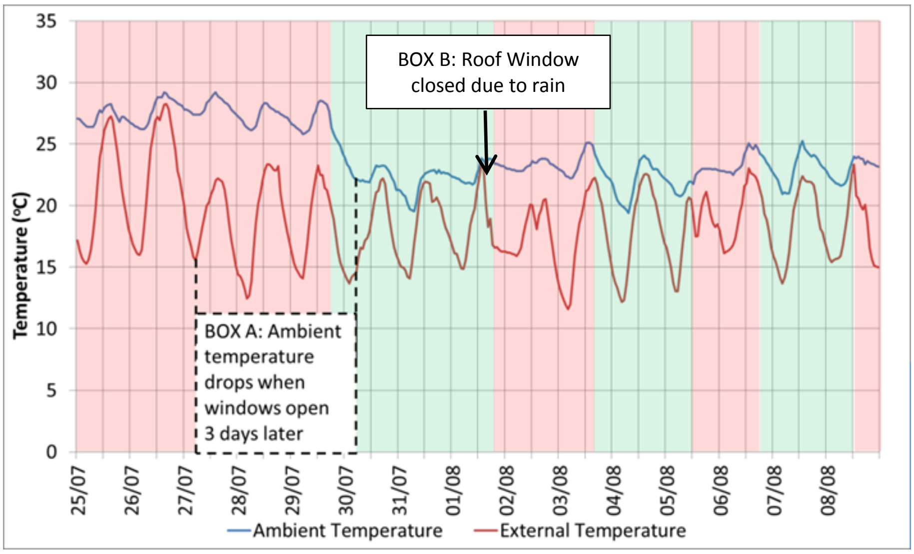


Figure 4-11: External and internal temperatures monitored and window opening schedule (red shade: closed, green shade: open)

4.5.2 Discussion

The study of the as built performance of the Nottingham H.O.U.S.E. highlighted some areas of underperformance. Nevertheless, these are considered reasonable to be addressed by industry when considering mass production of prefabricated housing and some of them may be attributed to the unique nature of the building being developed as a student project.

The in-situ calculation of the U-value of the walls and roofs was found to be 20% and 6.66% higher than the design values respectively, suggesting the inputs in SAP regarding the material specifications may have led to overestimated performance. However, the actual fabric heat loss was determined and it was found to be very close to the theoretical value determined by SAP using design values for the thermal transmittance of building elements. The fabric was found to perform in practice as predicted or better. This could be attributed to the fact that SAP calculations considered the worst possible values for thermal bridging.

Thermal bridges and areas of damaged/missing insulation and air leakage were identified in the junctions of the different building elements which compromised the thermal performance of the building but these were not extensive. Some of these junctions can be avoided through the use of careful design of details but were mainly caused by poor construction. The fact that the building was built by a group of inexperienced students and was moved to different locations prior to its final installation in the Creative Energy Homes site might have caused damage in the fabric and the junctions between the different elements. In any case, it is apparent that careful design in construction details, skilled workforce on-site and rigorous supervision are required for achieving the high energy efficiency standards in practice. It is considered that these improvements can be applied on mass produced prefabricated houses and that low energy standards can be met on large scale.

The air permeability of the construction is significantly lower than what was required by the Building Regulations but higher than required for achieving Passivhaus certification. With regards to the overheating risk of the dwelling, it was found that the building suffers from overheating, but this can be attributed mainly to the fact that the building was closed for most of the time. Monitoring the effect of ventilation in the south office indicated that the room would down shortly after the windows were opened. This highlighted the importance and value of occupancy monitoring towards identifying areas when the construction does not manage to meet the design specifications.

4.6 Parametric Study

The second part of this study presents the findings of a parametric simulation study conducted to evaluate the overheating risk of the Nottingham H.O.U.S.E. and the potential to mitigate it through the use of additional levels of thermal mass provided by non-traditional lightweight elements.

A model of the house was built in EDSL Tas (Figure 4-12) and a series of dynamic simulations were performed to evaluate its performance using the CIBSE weather file for Nottingham. The house was modelled as a dwelling rather than office building and it was divided in zones according to the expected use of areas: buffer space, WC, circulation areas, stairs, kitchen, living room, south and north bedroom, bathroom, void and other (plant room). These can be seen in Figure 4-2.

The analysis considered additional layers of material mounted on the walls and ceilings, increasing from 1 to 3 layers. The available wall area was 260m^2 and the ceiling area was 80m^2. A base case was used as benchmark where the walls and ceilings were finished with 1 layer plasterboard (Case0-Plast). Then the performance of Rigidur H was investigated considering 1 to 3 layers (Cases 1-Rig to 3-Rig). The wall mounted layers of Rigidur were 10mm thick and the ceiling layers were 12.5mm. In addition, for reasons of comparison, the performance of equal amounts (10mm on the walls and 12.5mm on the ceiling) of high density concrete mounted on the walls and ceilings was examined (Cases 1-Con to 3-Con). The typical build-up of the different constructions and the thermal properties of the materials used is presented in Appendix A.

Figure 4-12: Model of the Nottingham H.O.U.S.E. developed in EDSL Tas

The effectiveness of Phase Change Materials in regulating the internal temperatures was also examined. The BASF Micronal® PCM utility (Beta) in EDSL Tas enabled the performance of the Rigips

Alba®balance 23 (melting point at 23°C) and Alba®balance 26 (melting point at 26°C) plasterboard to be investigated. Alba®balance 23 has latent heat storage capacity of 300 KJ/m^2 while the respective value for the Alba®balance 26 is 330 KJ/m^2. The performance of each PCM board was investigated using one and two layers on the walls and the ceilings of the house with the thickness of each layer being 2.5cm. Table 4-5 provides a summary of the properties for the materials used in this analysis (EDSL, 2010, British Gypsum, 2012, Rigips Saint Gobain, 2012). A summary of the different cases examined and the associated quantities are presented in Table 4-6.

Table 4-5: Material properties

	Density (kg/m^3)	**Specific Heat (J/kgK)**	**Conductivity (W/mK)**	**Latent Heat storage capacity (KJ/m^2)**
Plasterboard	960	837	0.16	-
Rigidur H	1200	1100	0.2	-
Concrete	2100	840	1.4	-
Alba®balance 23	1000	1132	0.27	300
Alba®balance 26	1000	1132	0.27	330

Table 4-6: Summary of cases examined

Case	**Material**	**Layers**	**Volume (m^3)**	**Mass (kg)**
Case0 - Plast	Plasterboard	1	3.60	3,451.46
Case1 - Rig	Rigidur H	1	3.60	4,314.33
Case1 - Con	Concrete	1	3.60	7,550.07
Case2 - Rig	Rigidur H	2	7.19	8,628.65
Case2 - Con	Concrete	2	7.19	15,100.14
Case3 - Rig	Rigidur H	3	10.79	12,942.98
Case3 - Con	Concrete	3	10.79	22,650.22
Case1 - Alb23	Alba balance 23	1	6.10	6,104.88
Case1 - Alb26	Alba balance 26	1	6.10	6,104.88
Case2 - Alb23	Alba balance 23	2	12.21	12,209.75
Case2 - Alb26	Alba balance 26	2	12.21	12,209.75

4.6.1 Simulation Assumptions

The following assumptions were considered for the simulations:

Weather: The CIBSE Design Summer Year Weather Data (DSY) for Nottingham based on the year 2002 was used. This is the recommended climatic file for performing overheating analysis by CIBSE (CIBSE, 2007).

The following internal gains were assumed:

Occupants: It was considered that two people (adults) live in the house. Heat gains from the occupants were assumed to be 100W per person, 65W sensible and 35W latent. This value was considered to represent an average for residential activity and it was based on recommendations made by ASHRAE for occupant gains in non-residential spaces for different levels of activity (ASHRAE, 2013).

Apertures: All the window types were set to open during the daytime when the occupants were in the house, that is from 6 am until 8 am and again from 6pm to 11pm and were kept closed at night for reasons of security, privacy and noise, as the analysis assumed the dwelling in an urban setting. The bedroom windows were set to start opening when the resultant temperature in the respective bedroom exceeded 23°C and were fully open when the temperature reached 25°C. The non-bedroom windows were set to start open when the resultant temperature of the adjacent zone reached 25°C and were fully open at 26°C. All the windows were also set to close when the outside temperature exceeded the internal or when the wind velocity exceeded 3m/s.

The MVHR system was set to start providing fresh air when the temperature in the house reached 25°C and fully supply the required ventilation rate when the temperature reached 26°C. Ventilation rate was set to 1 ACH and it was available on a 24-hour basis. Mechanical ventilation was working supplementary to natural ventilation during occupancy hours and as the main ventilation system for the rest of the day.

Equipment and appliance gains: The equipment gains in the living room were caused by the operation of a TV, a hi-fi system, a computer and the use of mobile phone chargers summing up to a total energy consumption of 0.65kWh per day. The appliances contributing to the kitchen heat gains were a kettle, a microwave oven, a cooker, a washing machine, a dishwasher and a fridge each running at different hours producing total daily energy consumption of 2.45kWh. The equipment and appliance gains are given in detail in Table 4-7 .

Table 4-7: Equipment and appliance gains

Room	Equipment	Power (kW)	Usage	Frequency	Energy use per day (kWh)
Living Room	Hi-fi	0.04	When on	1 hour/day	0.04
	TV	0.15	When on	2 hours/day	0.30
	PC	0.09	When on	3 hours/day	0.27
	Chargers	0.02	When on	2 hours/ay	0.04
	Total daily energy use in Living Room				0.65
Kitchen	Kettle	3	1.5 boil	4 times/day	0.60
	Microwave	0.8	when on	0.5 hours/day	0.40
	Cooker with hob	0.8	when on	0.5 hours/day	0.40
	Washing machine	0.95	per one hour cycle	once weekly	0.14
	Dishwasher	1	per one hour cycle	twice weekly	0.29
	Fridge	226	kWh per year		0.62
	Total daily energy use in Kitchen				2.45

4.6.2 Results

The study aimed at investigating the effect of different materials with varying levels of thermal mass on the building's thermal environment with a focus on the resulting internal temperatures. Since the main focus of the study were the resulting temperatures and not the assessment of the thermal comfort of occupants, the static criteria by CIBSE (rather than the adaptive) were used for assessing overheating, i.e. the temperature should not exceed 28^{o}C in living spaces and 26^{o}C in the bedrooms for more than 1% of the occupied time (CIBSE, 2007). In addition, since the overheating occurrence in terms of number of occupied hours may lead to varying results according to the selected occupancy pattern (Nicol and Spires, 2013), the overheating risk was also assessed considering both occupied hours and 24-hour schedule (whole year performance). Furthermore, the maximum temperatures over the whole year were also determined and a degree-hour approach, estimating the degree-hours when the two thresholds were exceeded, was followed. This offered better insight on the ability of thermal mass to regulate temperatures.

Overheating occurrence during occupied hours

Results were analysed for the main areas of the house i.e. the living room, the kitchen and the two bedrooms. Table 4-8 presents the zones examined with the available area of thermal mass in these zones, i.e. the area of walls and ceiling. At this stage of the analysis the overheating occurrence during the occupied hours for each zone was examined. The percentage of occupied time when temperature in each zone exceeded 26^{o}C and 28^{o}C is presented in Figure 4-13 and Figure 4-14 and in detail in Table 4-9.

Table 4-8: Areas of available thermal mass (walls and ceiling) per zone

Zone	**Area (m^2)**
Living Room	25.00
Kitchen	41.74
South Bedroom	47.62
North Bedroom	40.44

With regards to overheating during occupied hours it can be seen that the bedrooms practically do not present any overheating, since the temperature in the south bedroom exceeds 26^{o}C by only slightly more than 1% (from 1.03% to 1.20%); the temperature in the north bedroom does not exceed 26^{o}C by more than 1% of occupied time in any case.

Regarding the living spaces, the kitchen presents overheating with the temperatures being higher than 28^{o}C for 4.84% of occupied hours in Case0-Plast. Increasing the levels of thermal mass reduced the occurrence of overheating in that zone, however it was not eliminated. Concrete appeared to be slightly more effective than Rigidur H and Alba®balance 26 was found to be more effective than Alba®balance 23.

In the living room overheating was observed to a small degree (1.92% of occupied hours in Case0-Plast) which was reduced with the addition of thermal mass and eliminated when two layers of Alba®balance 26 are used (Case2–Alb26). Again, concrete was found to have a better performance than Rigidur H and Alba®balance 26 was more effective than Alba®balance 23.

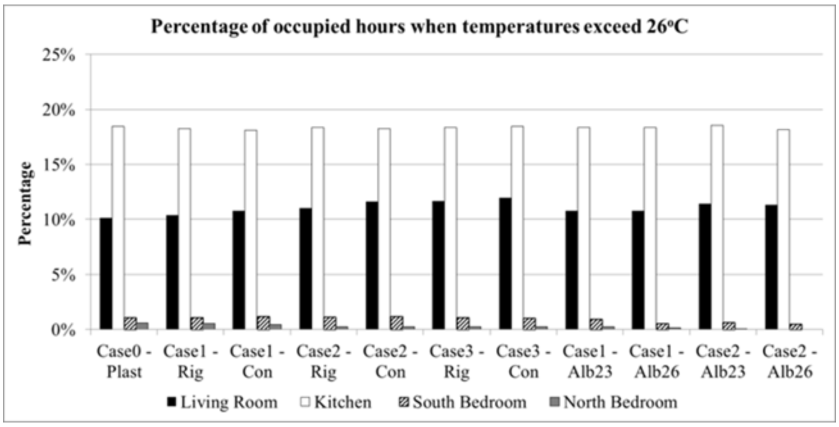


Figure 4-13:Percentage of occupied time when temperature exceeds 26 °C

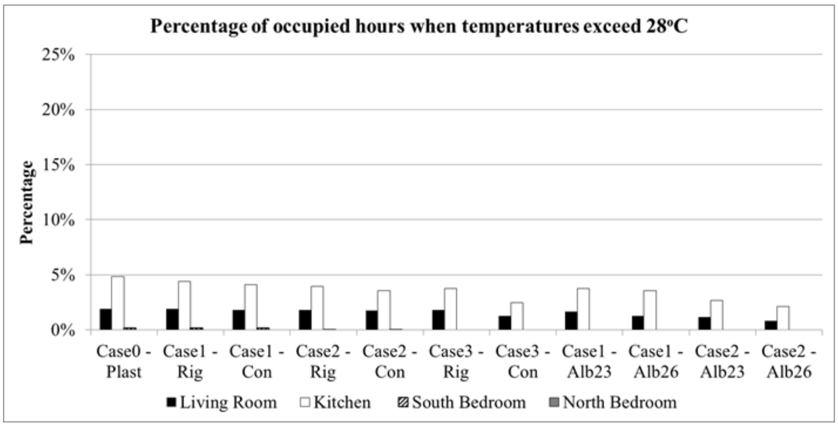


Figure 4-14: Percentage of occupied time when temperature exceeds 28 °C

Table 4-9: Percentage of occupied time when temperatures exceed 26°C and 28°C

	Living Room (%)		Kitchen (%)		South Bedroom (%)		North Bedroom (%)	
	>26	>28	>26	>28	>26	>28	>26	>28
Case0 - Plast	10.14	1.92	18.45	4.84	1.06	0.14	0.58	0.00
Case1 - Rig	10.41	1.92	18.26	4.38	1.10	0.14	0.55	0.00
Case2 - Rig	11.05	1.83	18.36	3.93	1.13	0.07	0.27	0.00
Case3 - Rig	11.69	1.83	18.36	3.74	1.10	0.00	0.27	0.00
Case1 - Con	10.78	1.83	18.08	4.11	1.20	0.14	0.45	0.00
Case2 - Con	11.60	1.74	18.26	3.56	1.16	0.03	0.27	0.00
Case3 - Con	11.96	1.28	18.45	2.47	1.03	0.00	0.24	0.00
Case1 - Alb23	10.78	1.64	18.36	3.74	0.92	0.00	0.24	0.00
Case2 - Alb23	11.42	1.19	18.54	2.65	0.62	0.00	0.07	0.00
Case1 - Alb26	10.78	1.28	18.36	3.56	0.55	0.00	0.14	0.00
Case2 - Alb26	11.32	0.82	18.17	2.10	0.48	0.00	0.00	0.00

Overheating occurrence over the whole year

The overheating occurrence over the whole year was investigated at this stage of the simulation study. The performance of each material in reducing overheating was also examined at this stage in terms of number of layers and material mass applied. When taking into account the occurrence of elevated temperatures over the whole year, significant levels of overheating were observed in the living room, the kitchen and the south bedroom, while overheating was also observed in the north bedroom albeit to a smaller degree. The results of the whole year analysis are presented as percentage of time the temperature exceeds 26^{o}C and 28^{o}C in Figure 4-15 and Figure 4-16 and in detail in Table 4-10.

It is apparent that in all cases the living room suffered the most from overheating followed by the kitchen and the south bedroom, while the north bedroom presented the lowest levels of overheating. The performance improvement in terms of temperatures exceeding 26^{o}C, achieved by using one layer of Rigidur H instead of one layer of plasterboard (Case1–Rig over Case0-Plast) ranged from 0.6% to 16.5% in the zones under consideration. The respective performance improvement in terms of temperatures exceeding 28^{o}C ranged from 6.6% to 28.6%. The addition of one and two extra layers of Rigidur H (Case2–Rig and Case3–Rig) decreased further the overheating occurrence in the zones examined and practically eliminated it in the north bedroom.

Table 4-11 presents the performance improvement achieved from adding extra layers of Rigidur H in the zones under investigation, regarding occurrence of temperatures exceeding 26^{o}C and 28^{o}C.

In addition, the performance of concrete and the two PCM boards was investigated. The relative performance of concrete against Rigidur H, namely the materials that act as thermal mass by storing sensible heat, and the relative performance of the two PCM boards, Alba® balance 23 and Alba® balance 26 which have the ability to store latent as well sensible heat is presented in Figure 4-12.

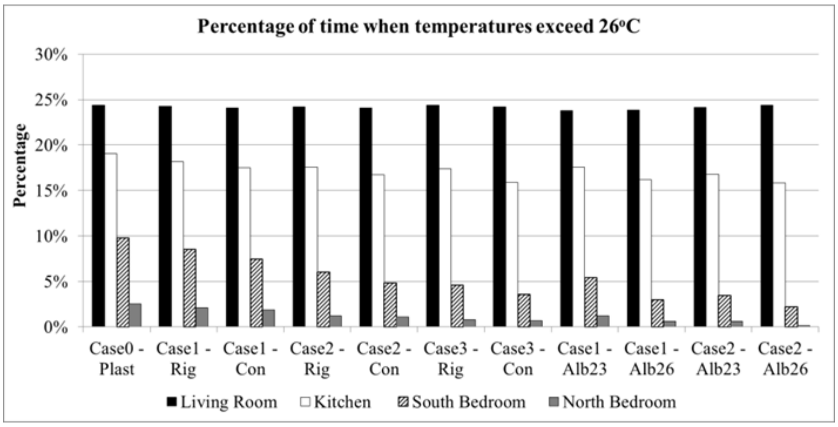


Figure 4-15: Percentage of time (whole year) when temperatures exceed 26 °C

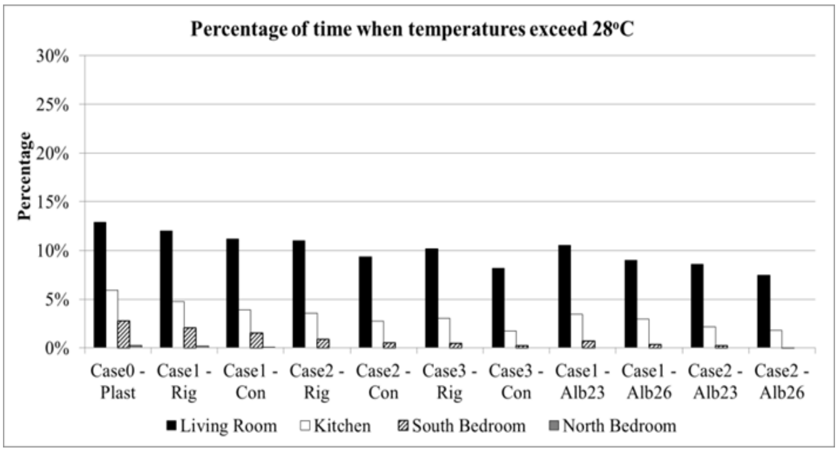


Figure 4-16: Percentage of time (whole year) when temperatures exceed 28 °C

Table 4-10: Percentage of time (whole year) when temperatures exceed 26 °C and 28 °C

	Living Room (%)		Kitchen (%)		South Bedroom (%)		North Bedroom (%)	
	>26	>28	>26	>28	>26	>28	>26	>28
Case0 - Plast	24.4	12.9	19.1	5.9	9.8	2.8	2.6	0.2
Case1 - Rig	24.3	12.0	18.2	4.7	8.5	2.1	2.1	0.2
Case2 - Rig	24.1	11.2	17.5	3.9	7.4	1.6	1.9	0.1
Case3 - Rig	24.2	11.0	17.6	3.6	6.0	0.9	1.2	0.0
Case1 - Con	24.1	9.4	16.7	2.7	4.8	0.5	1.1	0.0
Case2 - Con	24.4	10.1	17.4	3.0	4.6	0.5	0.8	0.0
Case3 - Con	24.2	8.2	15.9	1.7	3.6	0.2	0.7	0.0
Case1 - Alb23	23.8	10.5	17.6	3.4	5.4	0.7	1.2	0.0
Case2 - Alb23	24.1	8.6	16.8	2.2	3.4	0.2	0.6	0.0
Case1 - Alb26	23.8	9.0	16.2	3.0	3.0	0.4	0.6	0.0
Case2 - Alb26	24.4	7.5	15.8	1.8	2.2	0.1	0.1	0.0

Table 4-11: Performance comparison of plasterboard against Rigidur in different quantities

	Living Room (%)		**Kitchen (%)**		**South Bedroom (%)**		**North Bedroom (%)**	
	>26	>28	>26	>28	>26	>28	>26	>28
Case1-Rig over Case0-Plast	0.6	6.6	4.8	19.7	13.3	25.9	16.5	28.6
Case2-Rig over Case1-Rig	0.2	8.7	3.3	24.3	29.5	55.6	42.2	100.0
Case3-Rig over Case2-Rig	-0.8	7.6	1.0	15.9	23.3	47.5	36.1	-

Table 4-12: Performance comparison of concrete against Rigidur H and Alba®balance 23

	Living Room (%)		Kitchen (%)		South Bedroom (%)		North Bedroom (%)	
	>26	>28	>26	>28	>26	>28	>26	>28
Case1-Con over Case1-Rig	0.8	7.0	3.6	17.1	12.4	23.9	11.8	60.0
Case2-Con over Case2-Rig	0.5	14.7	4.9	24.2	19.3	40.0	11.1	-
Case3-Con over Case3-Rig	0.7	19.7	8.7	43.2	22.6	50.0	13.0	-
Case1-Alb26 over Case1-Alb23	-0.3	14.5	7.7	13.6	45.1	49.2	50.5	-
Case2-Alb26 over Case2-Alb23	-1.1	12.8	5.9	16.8	36.2	63.2	78.2	-

Concrete was found to be more effective than Rigidur H in reducing the overheating occurrence in all zones. This was particularly the case when increased thickness of material was used and when higher temperature was considered. For example when three layers of material were considered, the performance improvement of using concrete instead of Rigidur H (Case3-Con over Case3-Rig) ranged from 0.7% to 22.6% in terms of temperatures exceeding 26°C. Regarding the 28 °C threshold the respective improvement achieved from using concrete over Rigidur H ranged from 19.7% to 50.0%.

However, care should be taken when interpreting these results; the absolute values of performance should also be taken into account. The higher values of improvement refer to already low percentages of overheating. For example, the relative improvement of Case3-Con over Case3-Rig was found to be 50% in the south bedroom for the 28°C threshold. However, the actual overheating reduction was just 0.3% (from 0.5% to 0.2%). With regards to the performance of the PCM boards, it can be seen that Alba®balance 26 resulted in reduced overheating occurrence in most zones compared to Alba®balance 23 when the 26°C threshold was considered and in all zones for the 28 °C limit.

Effect of material thickness on overheating occurrence

The effect of the thickness of Rigidur H, concrete and the two PCM boards on the overheating occurrence over the whole year in the living room, the kitchen and the south bedroom was also investigated. As the levels of overheating in the north bedroom were very low and practically eliminated, this zone was omitted from further analysis. Figure 4-17 to Figure 4-19 present the percentage of time when temperatures exceeded 26°C and 28°C for the different number of layers applied in the living room, the kitchen and the south bedroom.

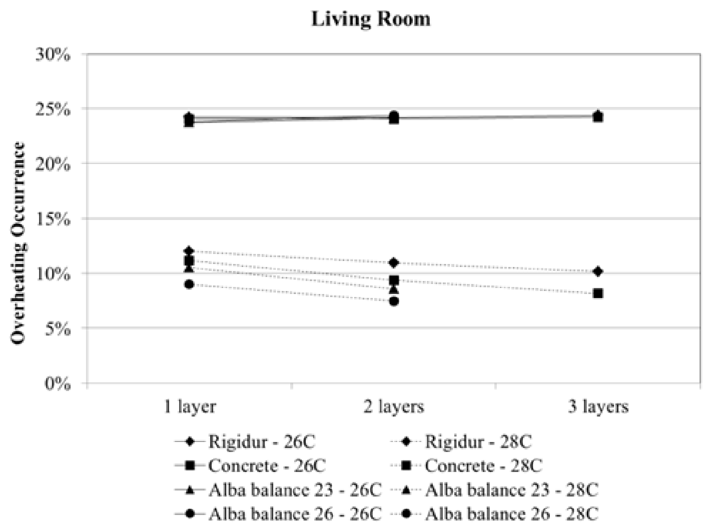


Figure 4-17: Overheating occurrence for different layers of material in the living room

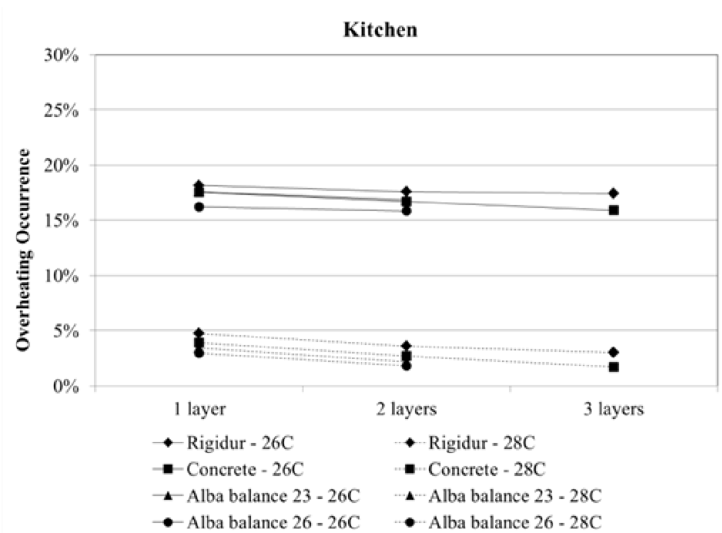


Figure 4-18: Overheating occurrence for different layers of material in the kitchen

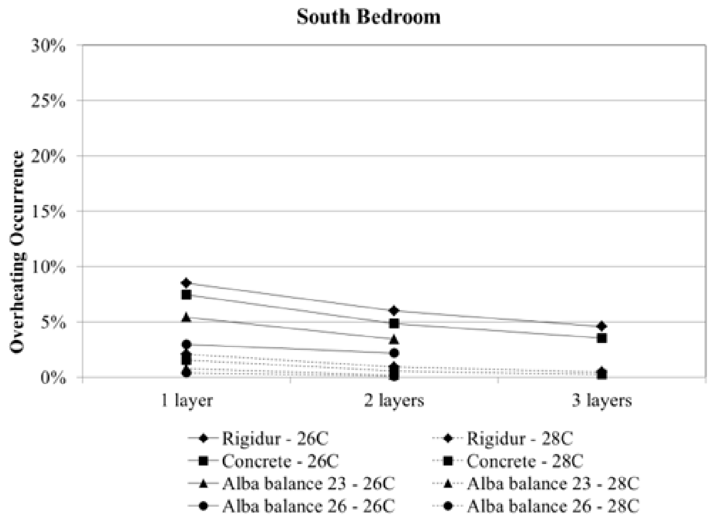


Figure 4-19: Overheating occurrence for different layers of material in the south bedroom

The performance of the materials was investigated considering both thresholds in all zones. In the living room all materials were found to have similar performance in terms of temperatures exceeding 26 ^{o}C; increasing the layers of the material did not practically change the overheating occurrence. Regarding the 28 ^{o}C benchmark, it is apparent that increasing the layers of thermal mass did reduce the percentage of time when temperatures exceeded it. Concrete appeared to be slightly more effective than Rigidur H. The occurrence of temperatures higher than the 28^{o}C threshold for concrete were 11.19%, 9.37% and 8.15% considering one, two and three layers respectively; the corresponding values for Rigidur H were 12.03%, 10.98% and 10.15%. The PCM boards were in turn more effective than concrete, with Alba®balance 26, resulting in the lowest percentage of overheating. Overheating occurrence was 9.01% and 7.48% considering one and two layers of Alba®balance 26 against the occurrence of 10.54% and 8.57% for one and two layers Alba®balance 23.

In the kitchen, increasing the layers of the material resulted in a decrease in the occurrence of temperatures exceeding 28 ^{o}C. Again, concrete appeared to have a more significant effect in mitigating overheating than Rigidur. The temperatures exceeded the 28^{o}C overheating threshold for 3.93%, 2.72% and 1.71% of time considering one, two and three layers of concrete. The respective frequencies for Rigidur H were 4.74%, 3.58% and 3.01%. The Alba®balance 26 was found to be the most effective considering both thresholds with 2.97% and 1.80% overheating occurrence for one and two layers.

In the south bedroom the results also indicated that concrete was more effective in coping with high temperatures than Rigidur H. The effectiveness of both materials seemed to drop with the increase of the number of layers applied. The frequency of temperatures higher than 28^{o}C was

1.56%, 0.55% and 0.24% for one, two and three layers of concrete against 2.05%, 0.91% and 0.48% for the same number of Rigidur H layers). The PCM boards were found to be significantly more effective and again the Alba®balance 26 had the best performance with just 0.38% and 0.08% occurrence considering one and two layers respectively.

Effect of material mass on overheating occurrence

Concrete was found to perform better than Rigidur H in all zones. Rigidur H has higher specific heat than concrete, however concrete has much higher conductivity and much higher density. For the same material thickness, the mass of concrete is by 75% larger than the respective amount of Rigidur H. It can be concluded, therefore, that concrete has the ability to store more heat which can be absorbed and released easier compared to Rigidur H. Alba®balance 26 also performs better than Alba®balance 23 which was expected to a certain degree, as its latent heat storage capacity is by 10% higher.

Furthermore, it appears that the temperature ranges occurring in the house, are more favourable for the Alba®balance 26 board. It should be noted that the PCM boards are thicker than the layers of Rigidur H and concrete. In order to account for the different densities and thicknesses of the materials, the results were also compared against the material mass available. Figure 4-20 to Figure 4-22 present the performance in terms of material mass for the same zones.

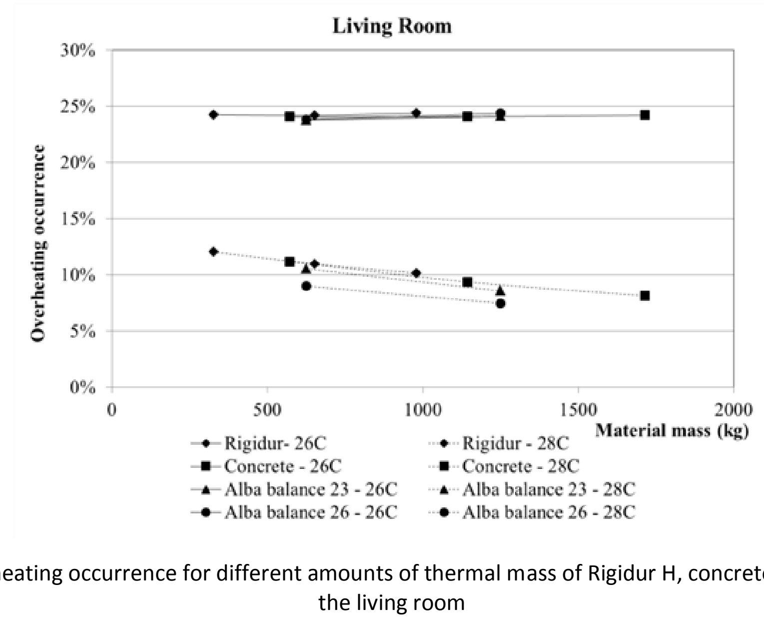


Figure 4-20: Overheating occurrence for different amounts of thermal mass of Rigidur H, concrete and PCM boards in the living room

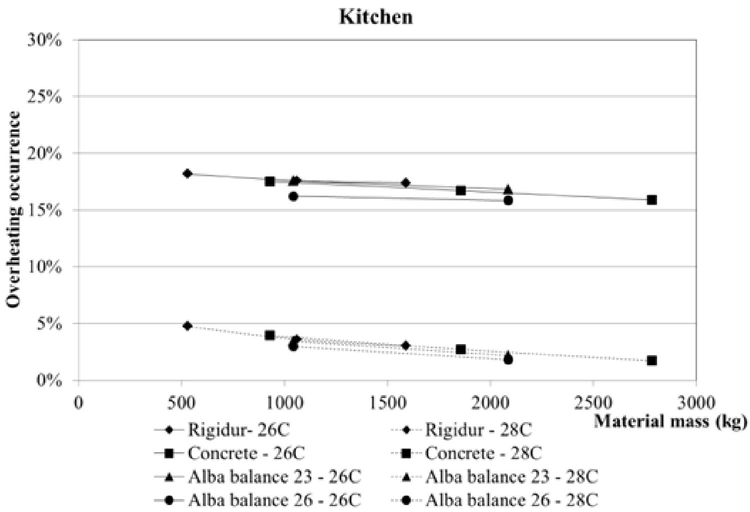


Figure 4-21: Overheating occurrence for different amounts of thermal mass of Rigidur H, concrete and PCM boards in the kitchen

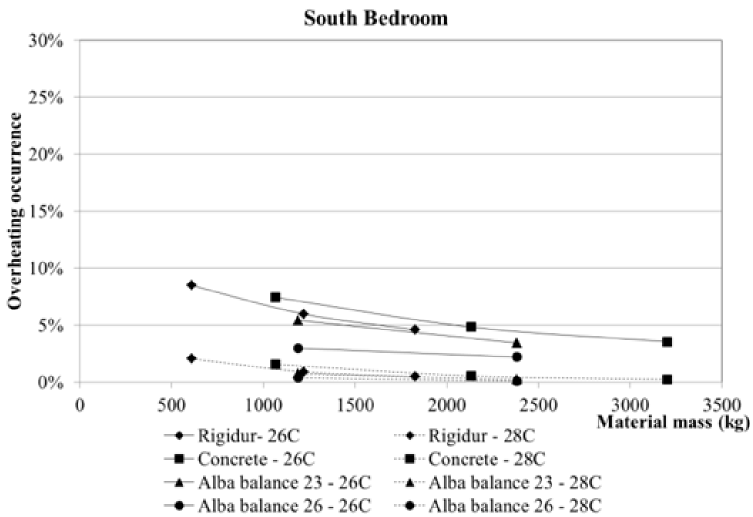


Figure 4-22: Overheating occurrence for different amounts of thermal mass of Rigidur H, concrete and PCM boards in the south bedroom

For the same levels of material mass, Rigidur, concrete and Alba®balance 23 presented quite similar performance in the living room and kitchen, where increased internal gains occurred. Alba®balance 26 was found to have slightly better performance in reducing only the 28^{o}C occurrence in the living room and the occurrence of temperatures higher than 26^{o}C and 28^{o}C in the kitchen. In the south bedroom, Rigidur H was found to be more effective than concrete in the south bedroom for the same amounts of mass. Again, Alba®balance 26 board was found to be the most effective.

Peak temperatures and degree hours

As it is widely accepted that the number of hours of exceedance of specific temperatures is not an accurate measure for assessing overheating, the effect of thermal mass on the peak internal temperatures of the dwelling was also investigated. The maximum temperatures for each case in the zones examined are presented in Table 4-13. It can be seen that the maximum temperature observed in each zone was reduced when the levels of thermal mass were increased. Concrete, again appears to be more effective than Rigidur H in reducing the peak temperature and Alba®balance 26 is found slightly more effective than Alba®balance 23 in all zones. The relative performance of each material in reducing the peak temperatures, in terms of material mass, is presented in Figure 4-23.

Table 4-13: Maximum temperature in each zone

	Living Room (°C)	**Kitchen (°C)**	**South Bedroom (°C)**	**North Bedroom (°C)**
Case0-Plast	35.47	33.61	32.46	29.53
Case1 - Rig	34.80	33.11	31.69	29.05
Case1 - Con	34.18	32.62	31.14	28.74
Case2 - Rig	33.86	32.24	30.35	27.98
Case2 - Con	33.00	31.52	29.79	27.72
Case3 - Rig	33.26	31.63	29.64	27.44
Case3 - Con	32.29	30.82	29.10	27.21
Case1 - Alb23	33.65	32.05	30.09	27.95
Case1 - Alb26	33.54	31.94	29.88	27.53
Case2 - Alb23	32.49	30.94	29.01	27.14
Case2 - Alb26	32.37	30.80	28.71	26.50

In addition, a degree hour approach was followed in order to evaluate the magnitude of overheating for the different cases examined. The degree hours of exceeding 26°C and 28°C were calculated for the three zones by multiplying the temperature difference between the indoor temperature and the temperature threshold when the respective temperature threshold was exceeded times the number of hours that the threshold was exceeded. These are presented in Figure 4-24. The results of the degree-hour approach demonstrate the ability of thermal mass to reduce overheating in a manner that the 'number of hours' approach was not able to do. For example, in the living room it was observed that the use of different materials and the use of additional layers of these materials did not change the percentage of time when temperature exceeded 26°C. However, based on the results presented in Figure 4-24 it can be concluded that increasing the material layers and applying different materials reduces the magnitude of overheating since the degree-hours above 26°C are decreasing. This suggests that even though the number of hours temperatures exceed 26°C may remain stable, the temperatures were reduced to a certain degree.

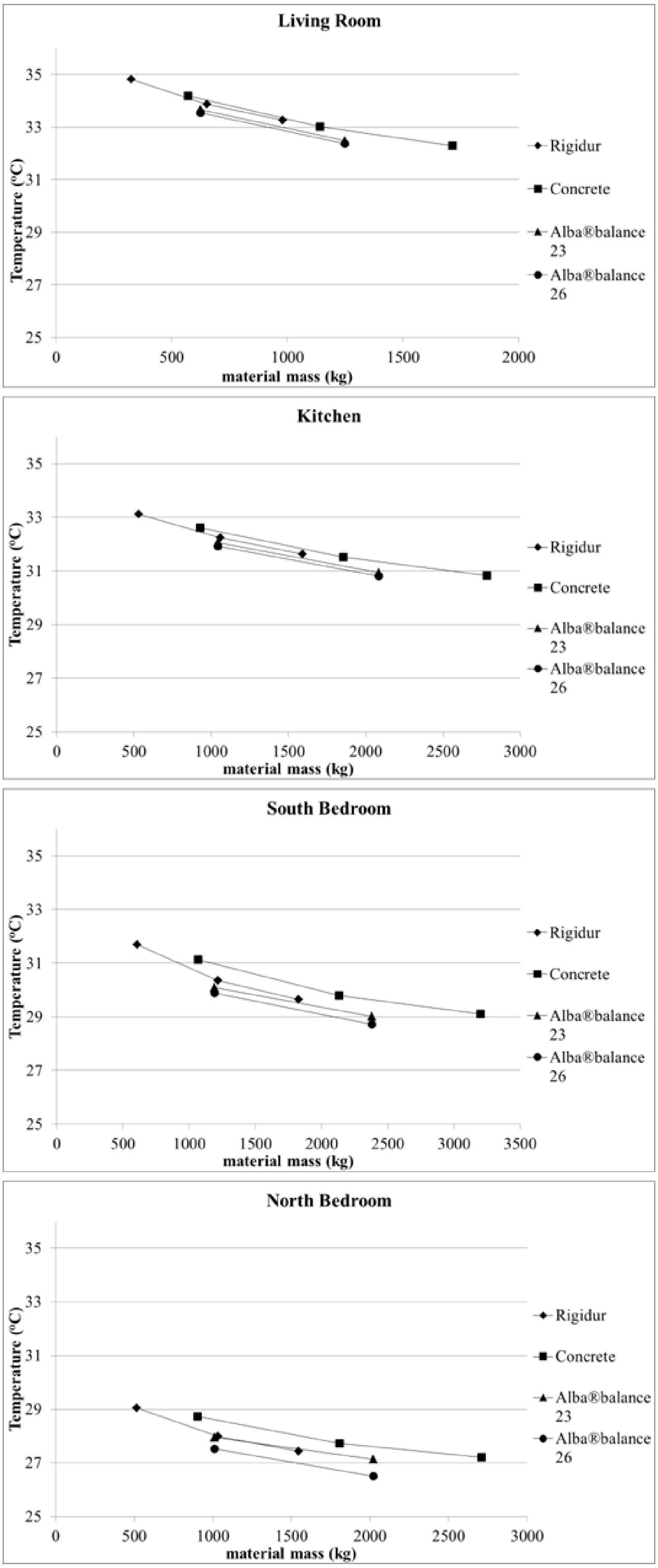


Figure 4-23: Reduction in maximum temperatures in each zone for different

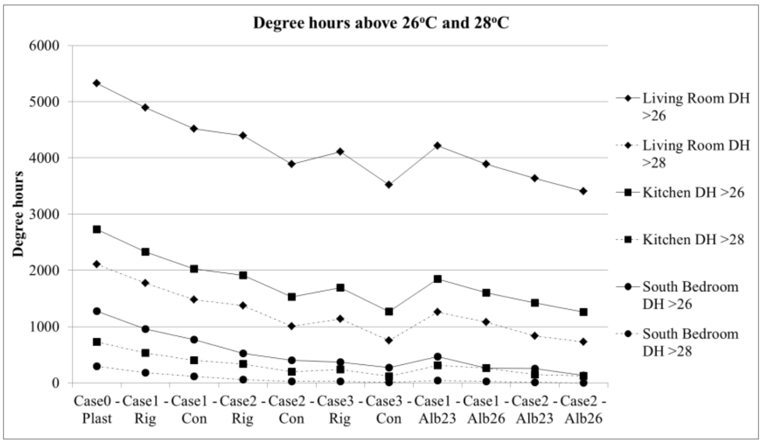


Figure 4-24: Degree-hours above 26 ºC and 28 ºC

4.6.3 Discussion

The parametric study assessed the overheating potential of the Nottingham H.O.U.S.E. in terms of temperatures exceeding 26ºC and 28ºC during both the occupied hours and over the whole year. The analysis showed that the Nottingham H.O.U.S.E. may suffer from overheating in some areas, considering both occupied hours and whole year occupancy. The results of the whole year analysis presented higher levels of overheating. The use of additional layer of Rigidur H reduced the percentage of time when the temperature exceeded 26ºC and 28ºC to a certain degree in most zones. Concrete with the same thickness as the layers of Rigidur H examined, was found to be slightly more effective at reducing overheating. However, this should be considered in the context of the mass of material used. The mass of concrete is 75% higher than the mass of Rigidur H. In addition, Rigidur H boards are much simpler to integrate to a wall than concrete. The PCM boards in most cases achieved lower levels of overheating, with the Alba®balance 26 board being more effective than the Alba®balance 23 board.

The results also demonstrated the ability of thermal mass to reduce the maximum temperatures observed in each zone. Again, peak temperatures were lowered when additional material layers were considered. Furthermore, the degree-day approach provided evidence that the overheating magnitude was reduced even in cases when the number of hours of overheating did not appear to be affected

4.7 Conclusions and suggestions for further work

The work presented in this chapter investigated the thermal performance of the Nottingham H.O.U.S.E. a super-insulated timber frame house and reported on the findings of two studies: a pilot study conducted to evaluate actual as-built performance of the house, and a parametric study that examined the overheating risk of the house under varying levels of thermal mass.

The pilot study involved a series of non-destructive tests commonly used in research and industry applications to evaluate fabric performance. Each test is a valuable building diagnostics tool but it is only able to provide information on a specific element or characteristic of the construction; conducting the range of tests provided a holistic approach to evaluating the as-built performance of the building. Findings from one test were able to complement and verify the results of other and together they were able to inform on areas of underperformance and improvement of the design and construction.

The pilot study identified specific areas of underperformance. The wall and roof U-values were found to be slightly higher than the design values and the air permeability, even though was significantly lower than the required value by Building Regulations, it was still higher than the design value required for Passivhaus certification. Thermal bridges and areas of air leakage were also identified through thermographic survey. The Heat Loss Coefficient however, was found to be close to theoretical one probably because SAP calculations considered the worst possible values for thermal bridging.

Despite the fact that the house failed to meet some of the design specifications, this was mainly attributed to the fact that it was constructed by inexperienced students and it had been installed and moved to several locations prior to its permanent location at the Creative Energy Homes site. Careful design, experienced construction operatives and rigorous supervision during all stages of development may eliminate these issues. Therefore, it is reasonable to assume that in the industrial setting of mass production of buildings, these are issues that can be easily addressed. Therefore, it is believed that timber frame construction is able to deliver high quality low carbon houses.

With regards to the overheating potential, the performance of non-conventional materials in terms of their ability in reducing the occurrence of elevated temperatures in the Nottingham H.O.U.S.E. was examined through the parametric study. Rigidur H, a high-density fibreboard, and two PCM boards, the Rigips Alba®balance 23 and Alba®balance 26 were examined. Rigidur H is an affordable and easy to handle solution which could be easily mounted in most MMC systems in order to provide additional levels of thermal mass without adding too much weight on the structure. PCM boards are also a widely considered alternative to provide extra levels of thermal mass for little weight addition to the structure and are also suitable for most MMC systems. In order to enable comparison the analysis also explored the addition of thermal mass through the use of concrete.

Overheating was reduced in most cases but not eliminated completely. Concrete was found to be slighty more effective than Rigidur H in terms of material thickness with improved performance of up to approximately 43%; however in terms of material mass Rigidur H was more effective. PCM boards were consistently more effective with Alba®balance 26 (up to approximately 17% compared to Alba®balance 23) being resulting to the lowest levels of overheating. Compared to the base case an improvement of up to almost 70% was achieved with the use of the different materials. The results of the analysis indicate that the use of Rigidur and, to a greater extent, the PCM boards have potential to regulate the internal temperatures and it is believed that their careful use in combination with other passive technologies is useful to mitigate overheating in highly insulated UK dwellings.

The findings of the parametric study were valuable in assessing the potential effectiveness of different solutions to regulate internal temperatures. However, this was a hypothetical study since the cases examined were proposals and are not commonly met in modern construction; especially the cases where three layers of material were considered. In addition, the Nottingham H.O.U.S.E. has been operating as an office building and not as dwelling which was the assumption of the simulation study. Therefore, there was no way to calibrate the file before performing the analysis. Validity of the study was demonstrated through the validity of the software to perform such analysis. It is suggested that when possible monitored data should be used to calibrate the simulation file.

Both these issues are addressed in the following chapter where the performance of two commonly used construction methods, timber frame and modern masonry cavity wall is assessed. These methods were used in the Green Street development, a housing project of energy efficient low carbon dwellings located in the Meadows area of Nottingham. Two houses one for each construction method were monitored for a period of approximately three years. The construction performance was assessed through the analysis of in-situ monitored temperature data and simulations.

CHAPTER 5. THE GREEN STREET CASE STUDY

In the previous chapter the findings of the parametric study suggested that the addition of thermal mass was an effective strategy to help reduce the frequency of elevated temperatures in a timber frame super-insulated dwelling. Non-traditional lightweight materials were examined as potential solutions to increase the levels of thermal mass in MMC constructions and they were found to have a beneficial effect on the house performance. Although the study led to valuable findings in terms of proposing alternatives to reduce the overheating risk of offsite construction, it did not assess commonly used construction methods that are widely used by the industry. Kendrick et al. (2012) suggested that many simulation studies tend to evaluate the overheating risk of dwellings by considering constructions that are not often met in practice and that commonly used masonry constructions in the UK do not fully benefit from the high levels of thermal mass.

The work presented in this chapter addresses this particular issue, namely investigating the behaviour of commonly used constructions. The performance of two low carbon houses with high levels of insulation and similar design was investigated. Both houses were located in the Green Street development, in the Meadows area of Nottingham. The external walls of these dwellings were built with two different construction methods, modern masonry cavity wall construction and timber frame construction, while the floor and roof were of the same construction. This provided an excellent testing facility to investigate the effect of the external wall construction on the internal temperatures experienced by the occupants. The aim of the work presented here is to evaluate the effect of the wall construction on the resulting temperatures and investigate whether timber frame would have higher overheating risk than masonry construction due to lower levels of thermal mass.

The analysis reports on the findings from two studies, a monitoring and a simulation based study. Again, the relevant context is given in the first section. Here, the design features and construction details of the two houses are presented. Information on the Nottingham climate can be found in Section 3.7 and is not repeated here.

In the second section, a monitoring study is presented. This involved the recording and analysis of temperatures experienced by the occupants in different zones of the two dwellings. The duration of the monitoring study was approximately three years and aimed to investigate the performance of the two methods under actual operative conditions. Several useful conclusions derived from the study were discussed along with its limitations. These limitations led to the simulation analysis presented in the third section.

The simulation analysis investigated the performance of one house considering both construction methods. The analysis was conducted for the current and future climatic conditions. Climate resilience is high in the housebuilding industry agenda and therefore the future performance of the construction methods is of particular interest in order to determine whether one method would be more suitable than the other.

Finally, the findings of the monitoring study and the simulations are summarised and discussed. The limitations of the analysis are also defined and suggestions for improvement and further work are made in this final section.

5.1 The Green Street Development

Located in the Meadows area of Nottingham, the Green Street development exemplifies sustainability in construction, design, and performance. The scheme which ranked as one of the best residential developments in the UK Property Awards, consists of a series of 38 low energy affordable houses proposed by the Nottingham based architects Marsh Grochowski and developed by Blueprint Regeneration (Igloo, 2013).

The development transformed the traditional urban street in a disadvantaged area of Nottingham with low-value dwellings of similar design into a contemporary one with a series of energy efficient modern houses built on both sides. Each house has a compact plan that includes three to four bedrooms and ensures the quality of space through a sufficient functional layout and storage areas. Enclosed backyards, large roof terraces as well as individual car garages are supplemented for each unit so as not to compromise the privacy of residents.

The parameters of sustainability integrate environmental design strategies with green technologies from planning to implementation. This is represented by electricity production through photovoltaic panels, wood pallet boilers, whole-house heat recovery and ventilation. In addition, the selected location, orientation, and internal details were designed to enhance light penetration throughout the house.

Adhering to the Fabric First approach, all properties were designed and constructed to reach ‘A’ rated Energy Performance Certificates as well as Code for Sustainable Homes Level 4. With very low infiltration rates equal to $3m^3/h/m^2$ at a pressure of 50Pa, highly insulated envelope (Roof 0.11 W/m^2K, Wall 0.13 W/m^2K, Ground Floor 0.15 W/m^2K and windows 1.2 W/m^2K), and high levels of air tightness, the designer has surpassed the requirements set by Building Regulations (Rodrigues et al., 2012).

The sustainability strategy also involved material sourcing, with the red bricks being locally made in Leicester and all timber being FSC approved (Igloo, 2013). The construction was implemented in three phases. Starting in 2011, the initial phase (Phase 1) adopted the timber frame method for the external walls. However, masonry construction was used for the external walls of the houses of Phase 2 and Phase 3 (Figure 5-1).

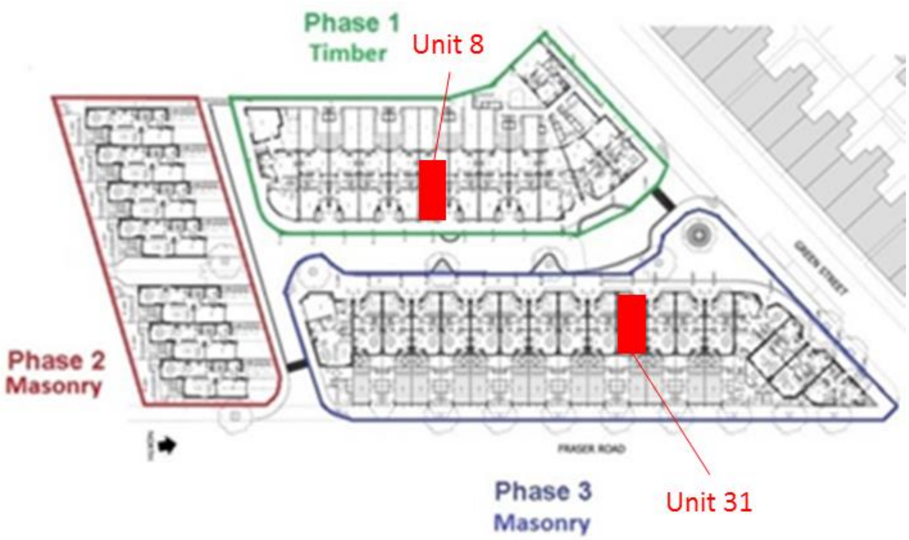


Figure 5-1: Green Street construction phases and location of houses

5.1.1 House Designs and construction methods

Both properties monitored, Unit 8 and Unit 31, are three storey terraced houses and are located at the opposite sides of the street (Figure 5-1). Although the two dwellings have similar plot and design, they differ in the interior layout and functional distribution. In addition, their external walls were built with different construction methods. Unit 8 was constructed as part of Phase 1 of the development. Therefore, the external walls were of timber frame construction. Unit 31 was built during the third phase of the construction process with the use of masonry cavity walls

The construction method of the two dwellings differs only in terms of the external walls specifications. The roof and floor in all houses is the same. The typical roof and floor build-up is given in Table 5-1.

Table 5-1: Typical build-up of the roof and floor constructions

Roof build-up	Floor build-up
OUT • Single ply roof finish • Cut to fall 152 mm Kingspan Thermataper TT47 LPC/FM insulation • Vapour check • 18mm plywood deck • 220mm timber joists with • 50 mm Kingspan Kooltherm K& insulation between joists at high level below deck • 12.5 mm Plasterboard and skim IN	OUT • 150 mm deep Fastfloor prestressed T beams spanning between walls with • lightweight insulated panels between the beams • C35 concrete structural topping with thickness 75 mm and reinforced with A98 mesh. • Tiles IN

Information on the design of the two dwellings, the differences between them and the construction details is given below.

Unit 31 - Masonry

Unit 31 (masonry) is a three-storey terraced house with west orientation and its main axis lying on the west–east axis. In the ground floor are the living room and the kitchen as well as guest toilet and a small storage room. The first floor comprises an en-suite master bedroom, a guest bedroom, a spare bedroom which serves as an office and dressing room, and the main bathroom. In the second floor there is the home office with terraces on both sides. The external view of the building along with the floor plans and the room distribution and orientation is presented in Figure 5-2.

Unit 31 was built with masonry cavity wall construction. Two types of cavity walls were built; on the ground floor brick and block construction and at the upper floor level block and block finished externally with render. The typical built up of the two cavity walls is presented in Table 5-2:

Table 5-2: Build-up of the masonry cavity wall variations

Brick and block cavity wall (ground floor)	Block and block cavity wall (first floor)
OUT • 103 brick • 150 mm cavity with 100 mm partial fill insulation • 100 block • 60 mm (overall thickness) plasterboard faced insulation to inner face IN	OUT • 90 mm block with approx.. 15 mm render • 150 mm cavity with 100 mm partial fill insulation • 100 block • 60 mm (overall thickness) plasterboard faced insulation to inner face IN

Figure 5-2: External view and floor plans for Unit 31 (masonry) (plan views developed in EDSL Tas)

<u>Unit 8 - timber frame</u>

Unit 8 (timber frame) is also a three-storey terrace house. Similarly to Unit 31 its main axis lies within the east-west direction. However, as it is situated at the opposite side of the street it has east orientation. The entrance is adjacent to an indoor garage. The ground floor also comprises the kitchen and dining area, a guest toilet, entrance hall and a small storage space. In the first floor are the living room, two bedrooms and the main bathroom whereas in the second floor is the master bedroom and a hallway. The external view of the house and the floor plans are shown in Figure 5-3 below.

Three different variations of the timber frame construction were used for the walls of Unit 8. The external walls of the ground floor were constructed with a brickwork outer leaf, while the walls above the brickwork at the first floor were rendered. In addition, a slight variation of the rendered type was used at the second floor for the wall facing the terrace. The build-up of the three wall variations is provided in Table 5-3.

Table 5-3: Build-up of the timber frame wall variations

External wall with outer brick layer	**External wall with render finish (above brickwork)**	**External wall with render finish facing the terrace**
OUT	OUT	OUT
• 102.5 mm brickwork outer leaf • 50 mm cavity • 55mm Kingspan Thermawall TW55 • 9 mm OSB sheathing • 140 mm Timber frame wall infilled with: • 100 mm Kingspan Thermawall TW 55 • 40mm cavity • Vapour control layer • 25 mm vertical timber beads • 12.5 mm Plasterboard and 2.5 mm skim	• 15 mm Weber render • 90 mm blockwork • 50 mm cavity • 55 mm Kingspan Thermawall TW55 • 9 mm OSB sheathing • 140 mm Timber frame wall infilled with: • 100 mm Kingspan Thermawall TW 55 • 40mm cavity • Vapour control layer • 25 mm vertical timber beads • 12.5 mm Plasterboard and 2.5 mm skim	• 15 mm Weber render • 10 mm cement bonded particle board • 25 mm drainage zone between battens • 70 mm Kingspan Thermawall TW55 • 9 mm OSB sheathing • 140 mm Timber frame wall infilled with: • 120 mm Kingspan Thermawall TW 55 • 20mm cavity • Vapour control layer • 25 mm vertical timber beads 12.5 mm Plasterboard and 2.5 mm skim
IN	IN	IN

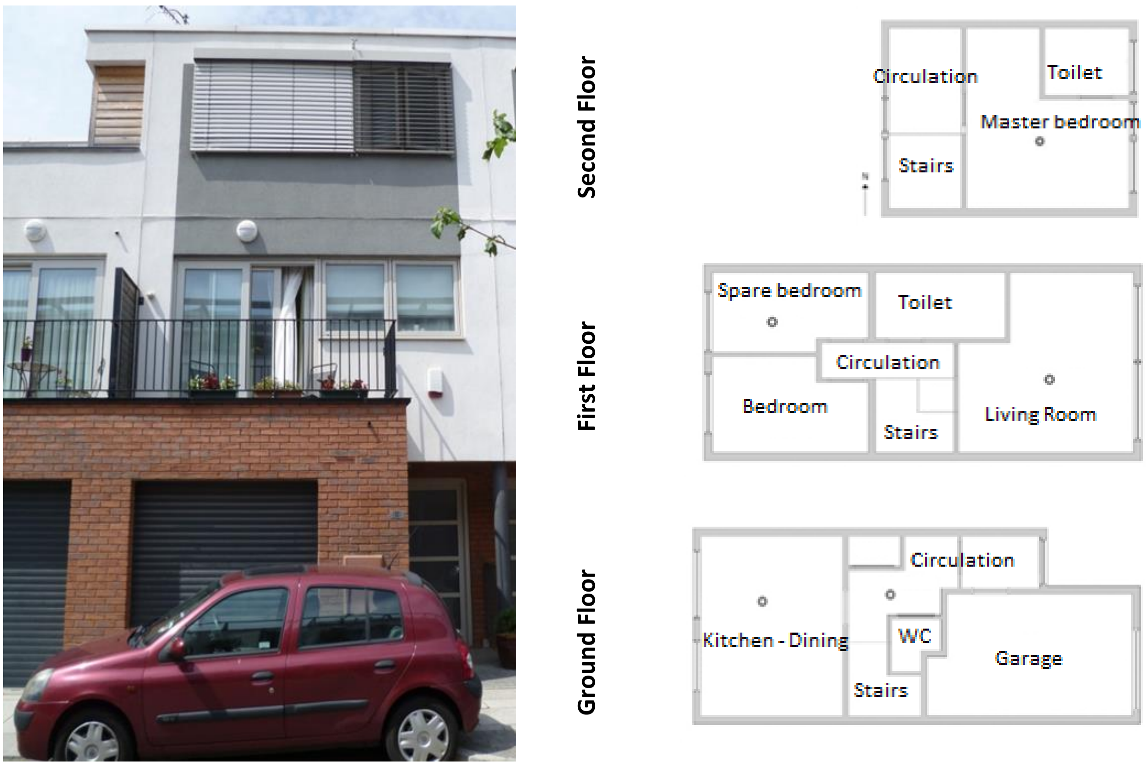


Figure 5-3: External view and floor plans of Unit 8 (timber) (plan views developed in EDSL Tas)

In summary, the design of the houses is similar with small differences mainly in the room layout and the orientation is directly opposite; Unit 8 has east and Unit 8 west orientation. Both houses have similar urban setting with both overshadowed by rows of terrace houses.

The two houses chosen for investigation incorporate both comparable methods of building construction making it an ideal testing ground reflecting the goal of the research.

5.2 Monitoring Study

Results from a three-year monitoring period are presented in this section. The analysis considered temperatures recorded in the zones of the two dwellings from December 2012 until the end of October 2015. Temperature data were collected by the author from September 2013 until the end of October 2015 for Unit 31 (masonry) and from July 2014 until the end of October 2015 for Unit 8 (timber frame). Data presented from December 2012 until the September 2013 for Unit 31 were collected from Dr. Faidon Nikiforiadis as part of a climate resilience research project (Rodrigues and Nikiforiadis, 2013), while data for Unit 8 for the period December 2012 – July 2014 were included in the work of Bailey (2015).

5.2.1 Scope and Aim

The scope of the study was to investigate the thermal performance of the two dwellings with respect to the occurrence of elevated temperatures. Whole year data were reviewed and analysed but particular focus was on the summer period when the two buildings were on free-running mode and elevated temperatures were most likely to occur.

The aims of the study were:

- Determine whether overheating was an issue in any of the two dwellings during the period of the monitoring
- Investigate whether the method of construction of the external walls would have an effect on the internal temperatures as a result of the different levels of thermal mass.

It was mentioned in Chapter 3, that significant research has been conducted on the ability of thermal mass to regulate internal temperatures and mitigate overheating. However, the vast majority of this research was simulation based with only a limited number of monitoring studies reporting on the real life performance of the houses (Department for Communities and Local Government, 2012). The need for reporting on the actual building performance and the value of such studies has been highlighted (Rodrigues, 2009, Zero Carbon Hub, 2015a). Therefore this study is considered timely and in line with the requirement for further monitoring studies.

5.2.2 Methodology

External temperatures and internal room temperatures in several rooms of Unit 8 and Unit 31 were monitored. Internal temperatures were recorded with the use of Tinytag TGU 4500 and TGU 4017 sensors (Figure 5-4). The reading range of these sensors was -40^{o}C to +85^{o}C with an accuracy of approximately 0.45^{o}C in environmental conditions met in dwellings (Gemini Dataloggers Ltd, 2016). The external temperature was recorded with the use of a Tinytag TV4500 sensor (reading range -25^{o}C to +50^{o}C for temperature with an accuracy of 0.4^{o}C) as well as a weather station installed at close proximity to the site for reasons of data consistency. Recordings were taken every five minutes. The location of the rooms monitored in each dwelling is presented in Figure 5-5.

Despite the fact that the two houses were of similar design and situated in the same development, there were significant differences between them in terms of room arrangement. Zones which are regularly used by the occupants, such as the living room and the bedrooms, were either located at different floors of the two houses or had a different orientation, or both. This can be seen clearly in Table 5-4. Therefore, direct comparison of specific zones was not expected to lead to conclusive evidence regarding the effect of the construction method on the resulting zone temperatures, as these would be greatly affected by the different design features. The only zone that could be directly compared was the spare bedroom which in both houses is situated in the west facing side at the first floor. Nevertheless, this is a zone which is not used on a regular basis by the occupants

Figure 5-4: Left: Tinytag sensors used for recording internal temperatures (TGU 4500 and TGU 4017), Right: External temperature sensor (TV 4500) (Gemini Dataloggers Ltd, 2016)

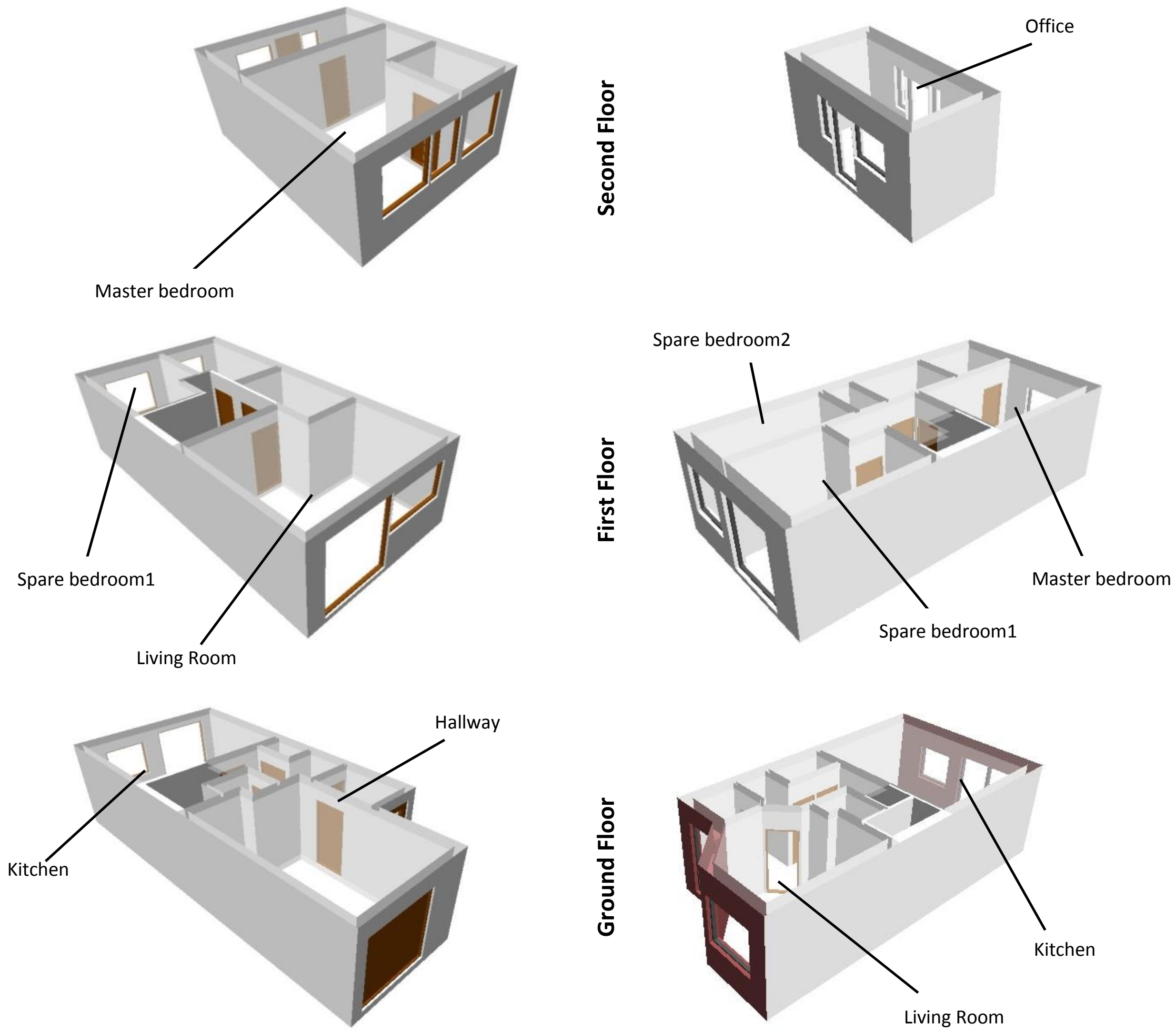


Figure 5-5: Exploded view of the location of sensors in Unit 8 (left) and Unit 31 (right) in each floor (rendered views developed in EDSL Tas)

For this reason, the average whole house temperature was found to be more appropriate instead to compare the performance of the two dwellings. The use of average temperatures tackled the problems arising from the different orientation and room location. As a result the main body of the analysis was performed considering the average house temperatures of the two dwellings. However, for purposes of qualitative assessment of the temperature conditions met in commonly used zones, the analysis also considered the thermal performance of the living room and the master bedroom in Unit 8 (timber) and Unit 31 (masonry). These zones were selected as being representative of a living space and a bedroom zone in the two dwellings that are regularly occupied.

Table 5-4: Rooms in Unit 8 and Unit 31 where the temperatures were monitored.

Unit 8 (timber)			Unit 31 (masonry)		
Room	Floor	Orientation	Room	Floor	Orientation
Kitchen-Dining	Ground	West	Kitchen-Dining	Ground	East
Living Room	First	East	Living Room	Ground	West
Master Bedroom	Second	East	Master Bedroom	First	East
Spare Bedroom	First	West	Spare Bedroom	First	West
Circulation	Ground	East	Guest Bedroom	First	West
			Office	Second	East - West

The performance of the houses and zones was assessed in terms of:

- Temperature profiles;
- Peak temperatures;
- Average and maximum fluctuation of internal temperature; and
- The CIBSE static criteria

The CIBSE static criteria for overheating in bedrooms and living spaces were used to evaluate temperatures in the different zones. These criteria were presented in Chapter 3 (Table 3-3). For ease of access, these criteria are summarised here in Table 5-5.

Table 5-5: CIBSE static criteria for assessing overheating (CIBSE, 2007)

Room	**Design Temperature (°C)**	**Benchmark Temperature (°C)**	**Overheating criterion**
Bedrooms	23	26	Benchmark temperature should not be exceeded for more than 1% of occupied hours annually
Living areas	25	28	Benchmark should not be exceeded for more than 1% of occupied hours annually

5.2.3 Results

<u>Whole house average temperatures</u>

Due to the long duration of the monitoring period (December 2012 – October 2015), there have been some periods of missing data mostly from the zones of Unit 8 (timber) due to issues regarding the battery and memory capacity of several sensors. In order to evaluate the performance of the two houses on an annual basis using the CIBSE static criteria, recorded data for a full year period were required. A complete dataset of recorded temperatures from all zones of both houses over a whole year has been achieved for the period October 2014 – October 2015.

The analysis of additional data from the previous years was also considered useful despite the fact that these data were not complete annual datasets. Their use facilitated in verifying the findings of the initial analysis. Since the main focus of this work is the overheating potential of dwellings, the data from the summer periods of 2013 and 2014 were also analysed.

Analysis of the data from the 11month period December 2012 – November 2013 have been presented by Sougkakis et al. (2014) and the conclusions may be considered as complimentary to the analysis presented here.

In summary, periods of available data in the two houses as well as the periods of reported data are presented in Figure 5-6 below:

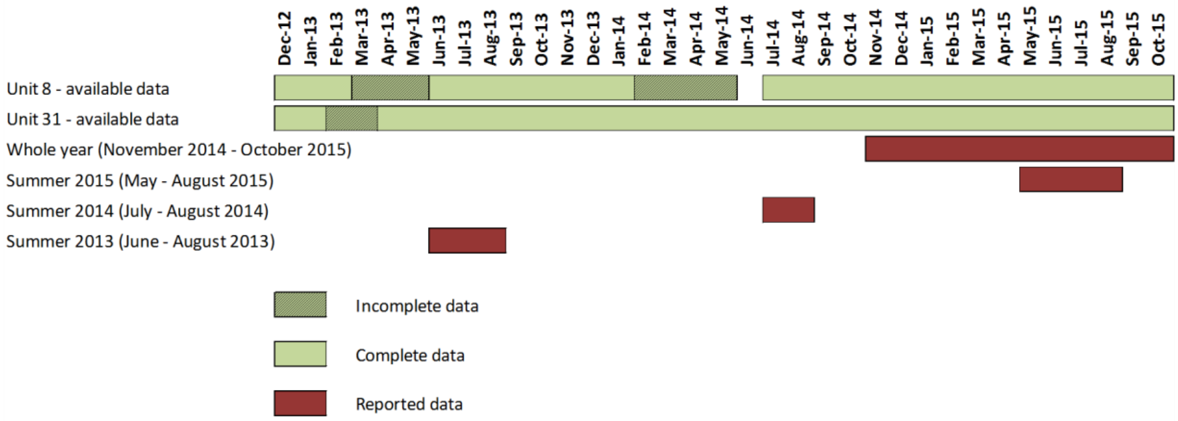


Figure 5-6: Timeline of periods of monitoring and reported data

<u>Temperature Profiles</u>

Whole year period: November 2014 – October 2015

The average house temperatures recorded over the complete year period spanning from November 2014 until October 2015 are presented in Figure 5-7. The annual monitoring period will be treated to consist of a heating period (when the heating system in both houses was expected to be working) and a cooling (non-heating) period for simplification, although it is understood that there will be periods where both or neither will be required. As the energy consumption and the operation of the building system controls were not monitored, it was not possible to identify the exact period when the heating system was turned on and off in each house. For reasons of consistency the heating period was considered to be from October until May. The non-heating period was from May until September 2015. The non-heating period is marked in Figure 5-7 between the two orange lines.

It can be seen that in general, temperatures in Unit 31 (masonry) appear to be more stable than in Unit 8 (timber). This appears to be particularly the case during the heating period when the temperatures in Unit 8 appear to have a much larger fluctuation around the set temperature than the temperatures in Unit 31. Average indoor temperature in Unit 31 appear to fluctuate daily around a mean of 20-21°C with a daily maximum of not more than 22°C and the daily minimum not falling below 18°C for most of the time during the heating season. On the other hand, indoor temperatures in Unit 8 (timber) are changing more rapidly with lower daily minimum values and higher maximum values. Similar findings were reported by Sougkakis et al. (2014). However, the temperature profile during the heating season were the result from the use of the heating system and the respective thermostat settings rather than the effect of the construction type.

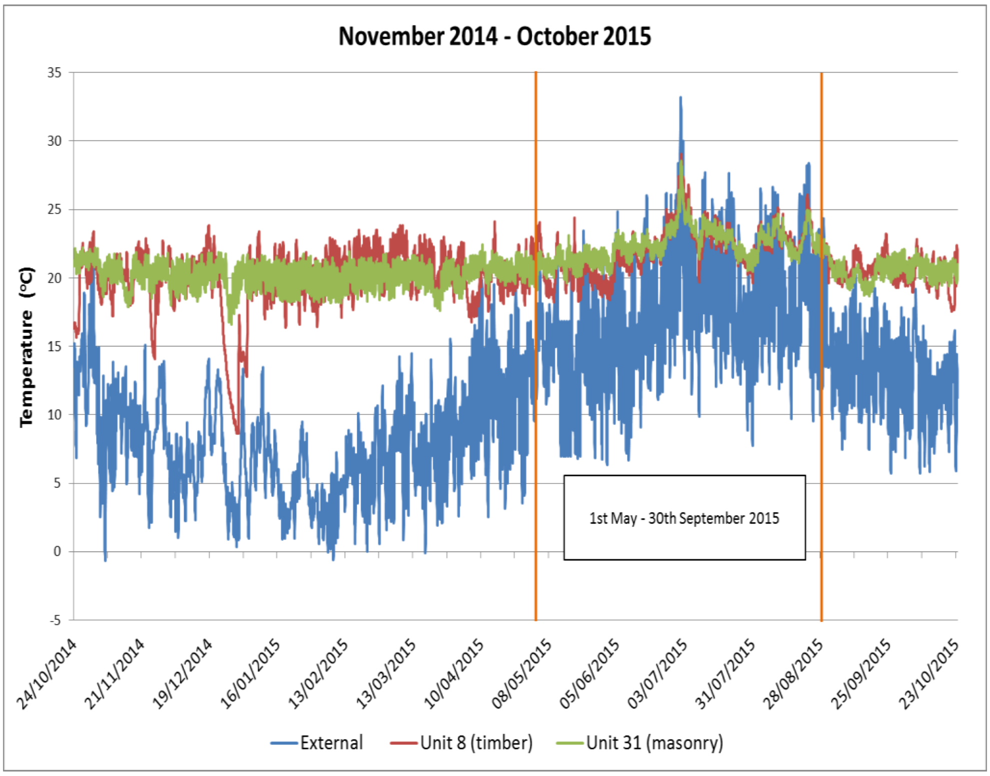


Figure 5-7: Average temperatures for Unit 31 (masonry) and Unit 8 (timber) and external temperature for the period October 2014 - October 2015

During the cooling period temperatures in the two houses appear to follow a very similar pattern of peaks and lows for most of the time. Peak temperatures in Unit 31 (masonry) are slightly lower than the peak temperatures recorded in Unit 8 (timber) and the temperature fluctuation around the mean daily temperature is found to be lower for the largest period of time.

However, there are periods of time when the temperatures in Unit 31 (masonry) are higher than the temperatures in Unit 8 (timber). These are found during a few weeks of May and in the last weeks of September. This can be attributed to the fact that the external temperature during May and during the end of September was lower than it was during the summer months, June – August. This suggests that possibly the heating system had been set into operation at least in one of the houses if not both and that the indoor temperatures were the result of space conditioning rather than being regulated by the building envelope. For this reason, only the summer months are considered at the following stages of the analysis. Period 2 of the analysis focuses on the summer months of 2015 in order to ensure that only data when no heating was used were examined, i.e. data from May and September were omitted.

Summer 2015: June – August 2015

The temperature profiles of the houses and the external temperature from the 1st of June 2015 until the 30th of August of 2015 were examined and presented in Figure 5-8. It can be seen that temperatures in Unit 31 are almost consistently lower than the respective temperatures in Unit 8, with lower peaks and lows. This is not the case only for several days during this period. The temperatures in Unit 8 are lower only in those periods when the external temperature drops rapidly. This could be considered as the result of the faster response of the timber construction to the external temperature drop and suggests that masonry construction appears to have potential to regulate internal temperatures through buffering and attenuation of external temperatures.

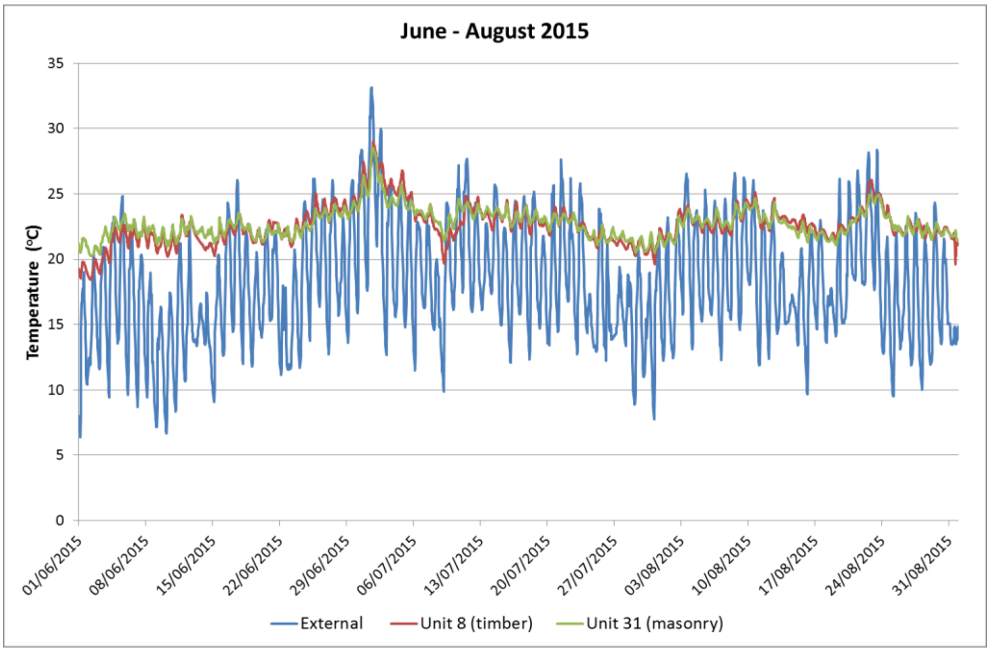


Figure 5-8: Average temperatures for Unit 31 and Unit 8 and external temperature for the period June – August 2015

The resulting temperatures during the hottest week of the summer, 29th of June until 6th of July 2015 are presented in Figure 5-9. During that week, significant external temperature variations were observed; external peak temperature rose from approximately 26°C to more than 33°C in two days. The following day a high of 30°C was reached, while at that same night the temperature dropped to almost 12.5°C. During that sudden temperature increase, temperature in Unit 8 (timber) reaches higher peak than in Unit 31 (masonry). During the hottest day, however, the difference is marginal (approximately 0.5°C). However, in the following day, temperature in Unit 31 remained at lower levels than in Unit 8 and that was the case for the rest of the week when the temperature in Unit 8 was constantly lower by approximately 1 to 2°C. The response of the two constructions to the external temperature excitations was similar; slightly higher temperature gradients were observed in Unit 8 (timber) while peak temperatures were reached either simultaneously or slightly earlier in Unit 31 (masonry). However, lower temperatures were reached earlier in Unit 8 (timber). In general, higher temperatures were observed almost consistently in Unit 31 (timber).

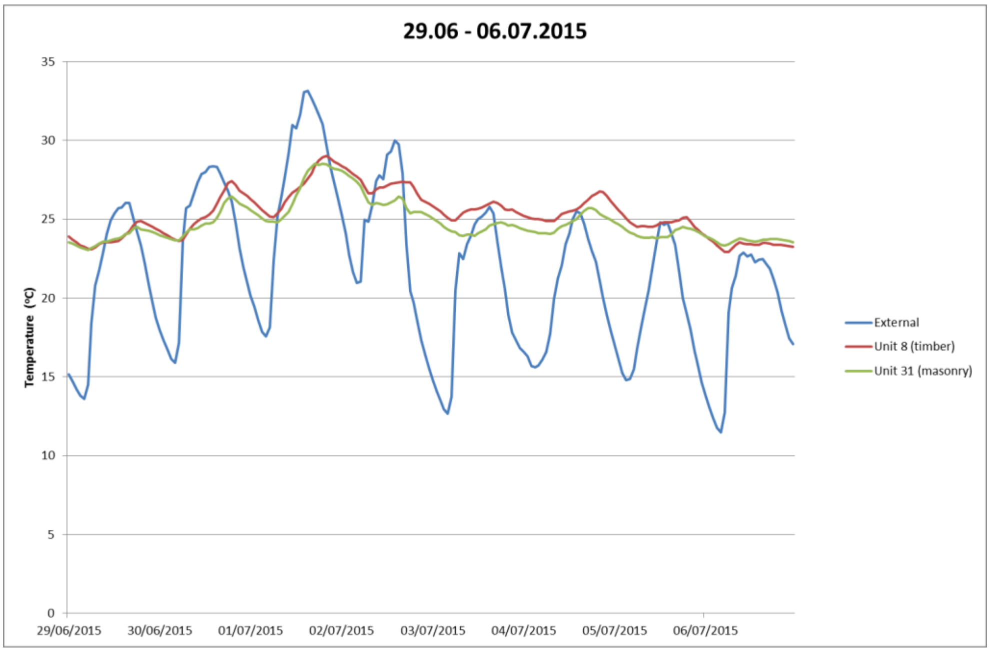


Figure 5-9: Average temperature for Unit 31 and Unit 8 and external temperature for the hottest week of summer 2015

Summer 2014: July - August 2014

Due to missing data from Unit 8, the analysis over the summer period of 2014 was limited to the months July and August. Data from September were also available but these were omitted from the analysis, in order to ensure that the temperatures were not the result of the use of heating system. The temperature profiles of the two houses for this period are presented in Figure 5-10.

Similarly to the findings the summer 2015 data, temperatures in Unit 31 (masonry) in general appear to present lower peak values and smaller diurnal variation than in Unit 8 (timber). Although the difference in peak temperatures is not great, it does however verify the pattern seen also in summer 2015. This is particularly the case in days of elevated external temperatures. There are some few-day periods when the peak temperatures are lower in Unit 8. Again, this appears to be the case when the outside temperature drops suggesting that the thermal mass of the masonry construction is acting as a buffer to that temperature drop.

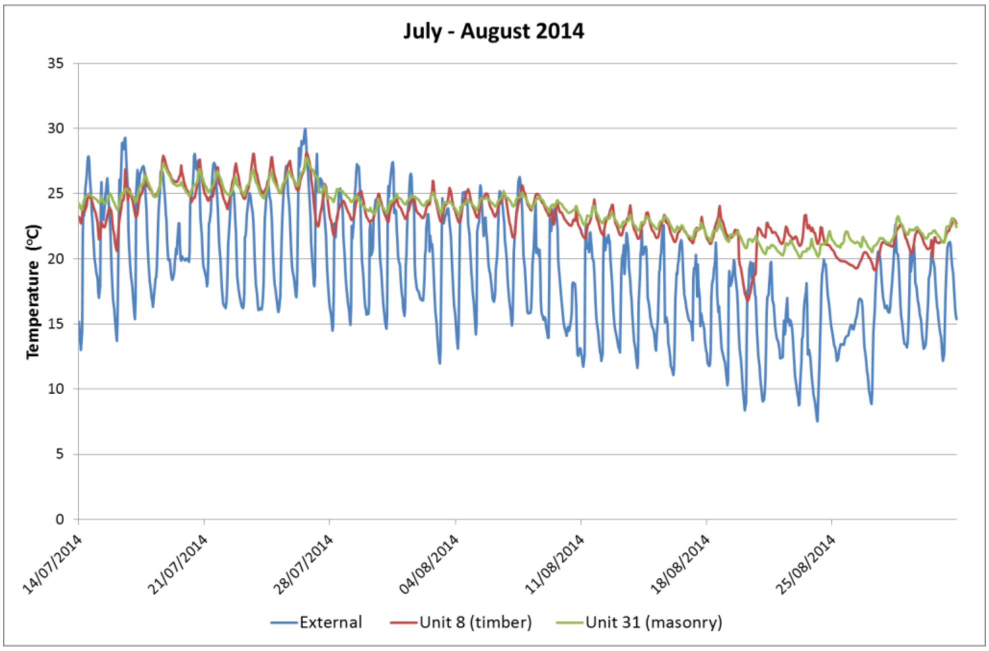


Figure 5-10: Average temperatures for Unit 31 and Unit 8 and external temperature for the period July – August 2014

Summer 2013: June - August 2013

Similar conclusions can be derived from the temperatures recorded over the June – August 2013 summer period. It can be seen that almost consistently Unit 8 (timber) presents higher peak temperatures and higher temperature fluctuations than Unit 31 (masonry), while there are a few days when the two houses perform equally (Figure 5-11). When the external temperature is dropping rapidly, the temperature in Unit 31 remains somewhat higher than in Unit 8, which was the case in the other two cooling periods examined. The data from summer 2013 showed the same patterns observed in the periods of summer 2014 and 2015. This highlighted the importance of the duration of the monitoring study. Examining the temperature profiles provided a visual representation and a qualitative assessment of the internal conditions in the houses. The three summer periods examined showed the same trends and increased the confidence in the observed interpretations. A quantitative analysis of the recorded data is presented in the following paragraphs.

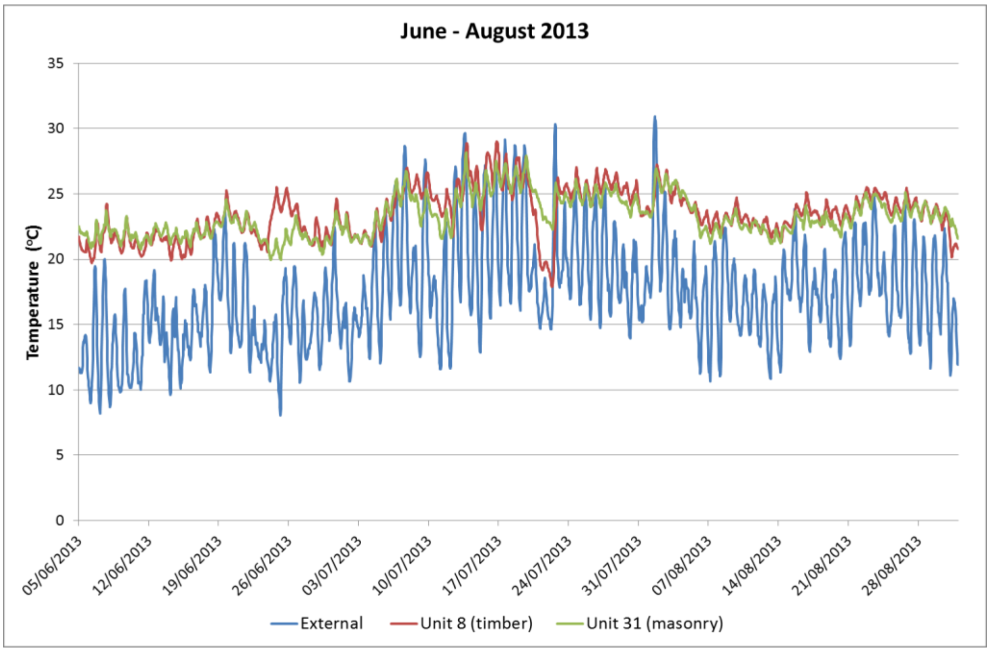


Figure 5-11: Average temperatures for Unit 31 and Unit 8 and external temperature for the period June – August 2013

<u>Peak temperatures and diurnal temperature fluctuations</u>

The investigation of the temperatures recorded in the two dwelling over three consecutive cooling periods (in spite of data for missing for certain periods of time) has showed that temperatures in Unit 31 (masonry) were almost consistently lower than Unit 8 (timber). The maximum temperatures experienced in the two dwellings over the three summer periods when temperatures where recorded are presented in Table 5-6. Maximum temperature was always higher in Unit 8.

Table 5-6: Maximum temperature in Unit 8 and Unit 31 experienced over the period examined

Period	**Maximum Temperature in Unit 8 (timber)**	**Maximum Temperature in Unit 31 (masonry)**
June – August 2015	29.02	28.53
July – August 2014	28.15	27.77
June – August 2013	28.99	28.15

The analysis of the average and the maximum diurnal variation in temperatures also highlighted the ability of the masonry construction to regulate the indoor temperature conditions. These are presented in Table 5-7. Both average and maximum daily temperature variation are lower in Unit 31 in all three summer periods examined.

Table 5-7: Maximum and average temperature fluctuation in Unit 8 and Unit 31 over the three periods examined

	Unit 8 (timber)		**Unit 31 (masonry)**	
Period	**Maximum fluctuation (°C)**	**Average Fluctuation (°C)**	**Maximum fluctuation (°C)**	**Average fluctuation (°C)**
June – August 2015	5.33	1.51	3.71	1.29
July – August 2014	6.25	2.42	2.57	1.29
June – August 2013	8.36	2.07	4.18	1.66

<u>Static criteria</u>

In order to investigate further the indoor temperatures experienced by the occupants the CIBSE static criteria were used. These were discussed in Section 3.3.2 (Table 3-3) and are presented in Table 5-5. The main zones of the two dwellings were analysed, namely the living room, the kitchen and the master bedroom.

The frequency of temperatures exceeding the overheating threshold temperatures over the period October 2014 – October 2015 are presented in Table 5-8 and Table 5-9 for the main zones of Units 8 and 31 respectively. The percentage of time the comfort thresholds of 23°C and 25°C were exceeded is also presented in order to evaluate the amount of time internal temperatures are exceeding the comfort limits.

The analysis of zone temperatures during occupied hours requires that several assumptions are made. Specific occupancy schedules for the zones were considered, i.e. different zones were occupied at specific times per day and that these times were the same every day. Obviously this is not the case in reality; the residents while expected to follow a routine program on their everyday life (which is attempted to be represented by the occupancy schedules), they are also expected to move randomly in the different zones of the house according to their daily schedule in a manner that cannot be accurately represented by the analysis. In addition, periods where the residents were away also cannot be accounted for in such analysis. Furthermore, the risk that the choice of 'occupied hours' may result in different frequencies of elevated temperatures and that this could change the findings of an overheating assessment has been highlighted by Nicol and Spires (2013). For these reasons the frequency of temperatures above the respective thresholds occurring both over occupied time and the whole year are included in Table 5-8 and Table 5-9.

Table 5-8: Frequency of temperatures above the comfort levels and the overheating threshold occuring in the main zones of Unit 8 (timber frame) for the period October 2014 - October 2015

	Main bedroom		**Living Room**		**Kitchen**	
	Comfort Level	**Overheating Threshold**	**Comfort Level**	**Overheating Threshold**	**Comfort Level**	**Overheating Threshold**
	23°C	**26°C**	**25°C**	**28°C**	**25°C**	**28°C**
Occupied hours	23.80%	0.89%	4.66%	0.28%	1.59%	0.00%
Whole Year	24.02%	1.14%	3.31%	0.42%	1.24%	0.00%

It can be seen that zones in Unit 8 (timber frame) did not suffer from overheating during the period examined considering both the temperatures experienced during occupied hours and during the whole year. The only zone where the temperature threshold for overheating was exceeded is the main bedroom when considering the dataset for the whole year; this is done for only 1.14% of the time, just above the 1% frequency limit. It can be concluded that during the period examined practically no overheating was experienced in the main zones of Unit 8. The frequency of temperatures exceeding the comfort temperatures in the zones examined suggests that in the living room and in the kitchen the comfort temperature is not exceeded for significant amount of time. The 23°C limit of thermal comfort is exceeded for approximately 24% of the time in the main bedroom considering both occupied hours and the data for the whole year. This suggests that this zone may be found uncomfortable at times, especially considering that sleep may impaired at temperatures higher than 24°C (CIBSE, 2007). Temperatures higher than 24°C occured for 9.42% of occupied hours and 10.24% of the whole year. It can also be seen that similar findings on the performance of the dwelling were extracted considering both occupied hours and the whole year data.

Table 5-9: Frequency of temperatures above the comfort levels and the overheating threshold occurring in the main zones of Unit 31 (masonry) for the period October 2014 - October 2015

	Main bedroom		**Living Room**		**Kitchen**	
	Comfort Level	**Overheating Threshold**	**Comfort Level**	**Overheating Threshold**	**Comfort Level**	**Overheating Threshold**
	23°C	**26°C**	**25°C**	**28°C**	**25°C**	**28°C**
Occupied hours	7.81%	0.27%	0.44%	0.00%	1.92%	0.07%
Whole Year	7.69%	0.27%	0.38%	0.00%	1.13%	0.08%

Similarly to the zones of Unit 8, the zones in Unit 31 do not appear to suffer from overheating. The overheating thresholds were not exceeded in any of the zones considering both the occupied hours for each zone and the whole year data set. Both datasets provide very similar results in this case. When considering the temperature limits of indoor comfort, these are not exceeded significantly in the kitchen and the living room. In the main bedroom the 23^{o}C comfort threshold was exceeded for 7.81% during occupied hours and for 7.69% over the whole year. The 24^{o}C limit was exceeded for only 1.51% or 1.67% considering occupied hours or whole year respectively. These results suggest that discomfort is not likely to be experienced in the zones of the masonry dwelling.

The whole house average temperatures were used to compare the indoor conditions in the two houses which are independent from the building orientation. These are presented in Table 5-10 for the whole year (October 2014 – October 2015) and for the period June – August 2015 (cooling period). As there is no specific temperature threshold for assessing overheating in whole dwellings, the analysis is presented as frequencies of temperatures occurring within specific temperature bands. For this reason results do not suggest overheating occurring in the house; they merely indicate the occurrence frequency of elevated temperatures in the dwellings. Since whole house average temperatures were considered, temperature frequencies refer to the whole dataset rather than occupied time.

Table 5-10: Whole house temperature frequencies in Unit 8 and Unit 31 for the periods October 2014 – October 2015 and June - August 2015

	October 2014 – October 2015		**June - August 2015**	
	Unit 8 (timber)	**Unit 31 (masonry)**	**Unit 8 (timber)**	**Unit 31 (masonry)**
<18	6.62%	0.33%	0.00%	0.00%
18 – 25	91.88%	98.95%	94.07%	97.15%
25 – 28	1.38%	0.61%	5.48%	2.40%
<28	0.11%	0.11%	0.45%	0.45%

Temperatures in both houses remained in comfortable levels (18-25) for the vast majority of time. Temperatures in Unit 8 (timber) remained below 18^{o}C for 6.62% of the time compared with a minor 0.33% in Unit 31 (masonry). This could be attributed to the faster response of the timber dwelling to external temperature drops as a result of the lack of buffering effect. In addition, this could also be the case due to the residents being away from the house and having turned off the heating system for longer period during the winter. With regards to elevated temperatures it can be seen that temperatures higher than 25^{o}C did not occur often in either dwelling. In Unit 8 temperatures between 25°C and 28°C were recorded for only 1.38% of the time; however, this was more than double of the frequency of temperatures recorded in Unit 31 (0.61%).

Zone Comparison

Apart from the whole house average temperatures, the relative performance of two zones, the living room and the master bedroom, in Unit 8 (timber) and Unit 31 (masonry) was also assessed in terms of the occurrence of elevated temperatures. Similarly to the analysis presented in the previous paragraphs, the assessment of the zones temperatures considered the temperature profiles, the maximum temperatures and daily temperature fluctuation as well as the CIBSE static criteria for assessing overheating (Table 5-5). The analysis considered the period June- August 2015.

Living room

The temperature profiles for the living room of the two dwellings are presented in Figure 5-12.

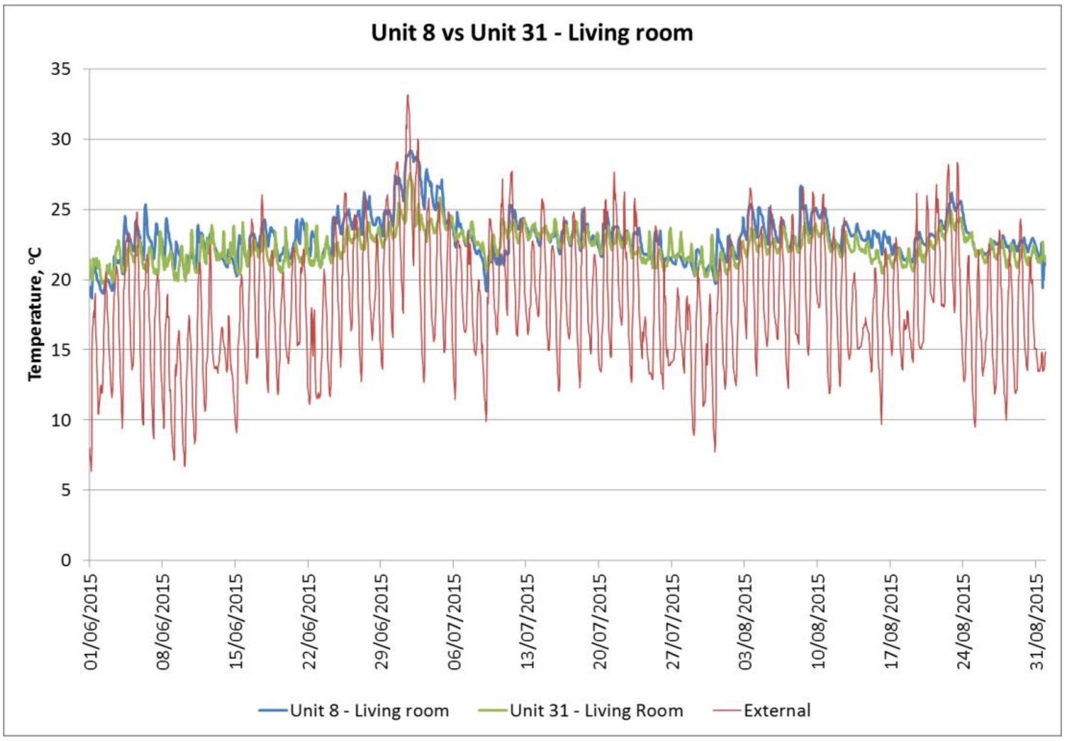


Figure 5-12: Temperature profiles for the living room zones of Unit 8 and Unit 31

It can be seen that temperatures in the living room of Unit 8 (timber) were similar or higher to the ones of Unit 31 (masonry) during the summer of 2015. There were periods of time the temperatures in the two living rooms were comparable; however, for large periods temperatures in the Unit 8 (timber) living room were higher than the respective zone in Unit 31 (masonry) presenting higher peaks and lows. This was observed mainly when the external temperature increased rapidly suggesting that the timber frame construction was more responsive to sudden changes than masonry construction.

The maximum temperature during the summer period of 2015 in the Unit 8 (timber frame) living room was 30.58°C, more than three degrees higher than the respective peak temperature in the Unit 31 (masonry) living room where a maximum of 27.54°C was reached. In general, the average daily temperature fluctuation in the two zones was comparable, 1.90 °C in the Unit 8 against 1.83°C in the Unit 31 living room. However, the maximum temperature fluctuation was by approximately one degree higher in Unit 8 (timber); 4.70°C compared to 3.67°C in Unit 31 (masonry).

Finally, considering the CIBSE static criteria (Table 5-8 and Table 5-9), the 28°C overheating threshold was not exceeded for more than 1% of the time in either zone of the two houses. In Unit 8 (timber) the overheating threshold was exceeded for just 0.42% of the time while in the Unit 31 (masonry) it was not exceeded at all. It should be noted that in the masonry house the comfort threshold (25°C) was exceeded for just 0.38% of time while in the timber dwelling it was exceeded for 3.31% of the time. The analysis considered the 24-hour schedule since the zones of the two houses had different occupancy patterns.

Master bedroom

The temperature profiles for the master bedroom of the two dwellings are presented in Figure 5-13.

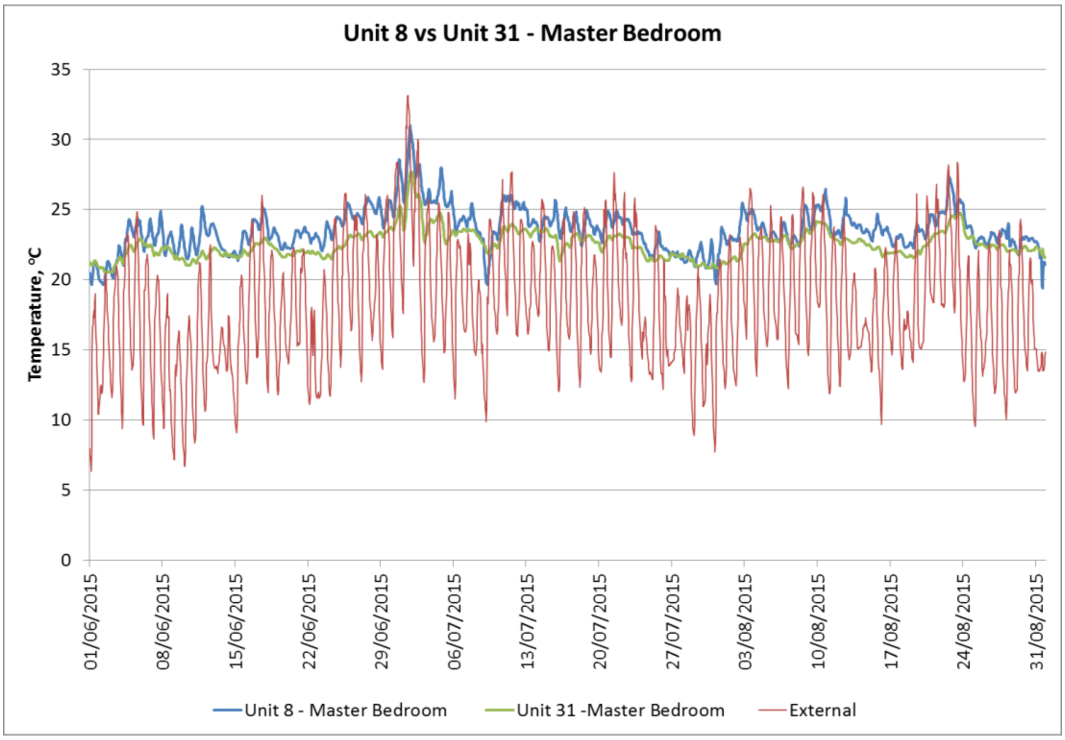


Figure 5-13: Temperature profiles for the master bedroom zones of Unit 8 and Unit 31

The temperature profiles of the two master bedroom zones were significantly different. The temperature in the bedroom of Unit 8 (timber) was consistently higher than in Unit 31 (masonry) with higher peaks and troughs; the minimum daily temperatures in Unit 8 (timber) were higher than the peak temperatures of the Unit 31 (masonry) almost on a daily basis. Only in very few occasions was the temperature higher in the masonry house zone and that occurred when the external temperature dropped suddenly, suggesting that the timber frame construction was responding faster to the external temperature changes.

The peak temperature was significantly higher, more than three degrees, in the living room of Unit 8 (timber); 30.96 ^{o}C compared to 27.69^{o}C in Unit 31 (masonry). On average, the maximum daily temperature in the Unit 8 master bedroom was 24.53^{o}C against 22.93^{o}C in Unit 31. The average daily temperature fluctuation was also higher in Unit 8 (timber); 1.72^{o}C against 0.71^{o}C in Unit 31 (masonry). The maximum temperature fluctuation during the period June – August 2015 was 5.49^{o}C for the timber frame dwelling and 4.18^{o}C for the masonry one.

Unsurprisingly, in terms of overheating occurrence, the master bedroom of unit 8 (timber) was found to suffer from elevated temperatures since the 26^{o}C threshold was exceeded for 1.14% and the 23^{o}C comfort threshold was exceeded for 24.08% of the time. The master bedroom in Unit 31 (masonry) did not suffer from overheating as temperatures in the zone were higher than 26^{o}C for only 0.27% of the time. In addition, the 23^{o}C comfort limit in that zone was exceeded for 7.69% of the time.

The higher temperatures occurring in Unit 8 (timber) could be attributed to the construction method, the fact that the living room is situated in the second floor (where the temperature is higher due to the temperature stratification - while the respective zone in Unit 31 (masonry) is on the first floor), the different orientation as well as the different occupancy pattern and window opening patterns.

5.2.4 Discussion and conclusions

Analysis of recorded temperatures led to the derivation of several useful conclusions regarding the thermal performance of the two dwellings and it can be argued that the aims of the monitoring study as stated in Section 5.2.1 were achieved to a great extent. The main findings from the long-term monitoring study can be summed up to the following statements:

- Peak temperatures were always higher in Unit 8 (timber). The difference ranged from 0.39^{o}C to 0.84^{o}C in the different periods examined.
- Average and maximum diurnal temperature variation was consistently smaller in Unit 31 (masonry) over the three summer periods.
- Timber frame construction was found to be more responsive to external temperature drops than masonry construction. The latter appeared to have a buffer effect on the sudden temperature changes.
- Overheating as defined by the CIBSE static criteria was not found to be a major issue in either building. However, this finding should be treated with care. The summer of 2015 was not particularly warm and was not suitable for assessing overheating. Had the weather conditions been warmer, the analysis may have concluded somewhat different findings in terms of overheating occurrence in different zones.

Limitations

The above useful findings were extracted exclusively from the analysis of recorded temperatures. The three year period of study allowed for comparing data and findings from different periods. This was found to be extremely beneficial for the verification of the conclusions. Nevertheless, there were several limitations in the study which should be identified in order to assist the successful conduction of similar studies in the future:

- Due to restrictions in the project budget only room temperatures were recorded and assumptions were made on the occupancy pattern of the dwellings and use of the building systems based on interviews with the occupants. The internal temperatures are the result of the synergetic action of the thermal response of the envelope, the design features and the building use pattern. Recording the occupancy of the houses, energy use and window opening schedules would be most valuable to verify the findings and determine the effect of only the construction method on the internal temperatures.
- The use of heat flux sensors was not possible as this would cause damage to the walls. Monitoring the rate of heat flux through the walls would help to quantify the heat flows in and out of the walls and determine the effect of the construction method on the ambient temperatures. This method was adopted in Chapters 6 and Chapter 7 which deal specifically with the heat flows on certain building elements.
- During the summer of 2015 weather conditions were not favourable for assessing overheating. Data analysis of summer temperatures from previous years contributed in

the identifying the risk for elevated temperatures but these could not be assessed against the CIBSE static criteria that require the analysis of recorded temperatures at an annual basis.

Due to these limitations, the analysis of monitoring data may lead to incomplete conclusions. Room temperatures in the houses were result of the synergetic effect of the wall construction method with the building design and use. While the first two limitations of the study were technical and could potentially be addressed with the use of additional equipment (provided of course that financial resources allowed for the purchase of the required equipment), the weather is a variable that cannot be controlled by the researcher and it is not an option for the monitoring to continue indefinitely until the right conditions would occur. To overcome these issues a parametric study was conducted with the use of dynamic simulations. The aims of the parametric study, the methodology and the results are presented in the following sections.

5.3 Simulations

A parametric study was conducted to determine the effect of the external wall construction method and isolate it from the complex interactions in heat flows occurring due to the different design and building use. For this reason, a model of Unit 8 was developed in EDSL Tas and its performance was assessed considering masonry and timber frame constructions presented in Table 5-2 and Table 5-3 respectively. The thermal properties of the wall constructions used in the simulations are presented in Appendix B. Reasonable assumptions were made regarding the building use and the predicted thermal performance was examined in terms of resulting indoor temperatures in the different zones. The study considered that all model inputs were kept the same with only the external wall construction changing. Detailed description and the results of the simulations are presented below.

5.3.1 Scope and Aim

The scope of the parametric study was to investigate the overheating risk of Unit 8 considering the two construction methods for the external walls, timber frame and masonry, examined at the monitoring study (Table 5-2 and Table 5-3). The performance of the house using the two wall types was evaluated in terms of occurrence of elevated temperatures and considering the CIBSE static criteria. The analysis was performed for the current and future climate.

The aims of the parametric study were:

- To determine the overheating risk of the dwelling considering the two variations in the external wall in the current and future climate
- Evaluate the performance of timber frame construction in relation to the commonly used modern masonry construction and determine the effect of the construction method on the thermal performance of the building.

5.3.2 Methodology

The basic steps of the typical approach to recommended by Tudor (2013) were followed to ensure credibility of the simulation are shown in Figure 5-14.

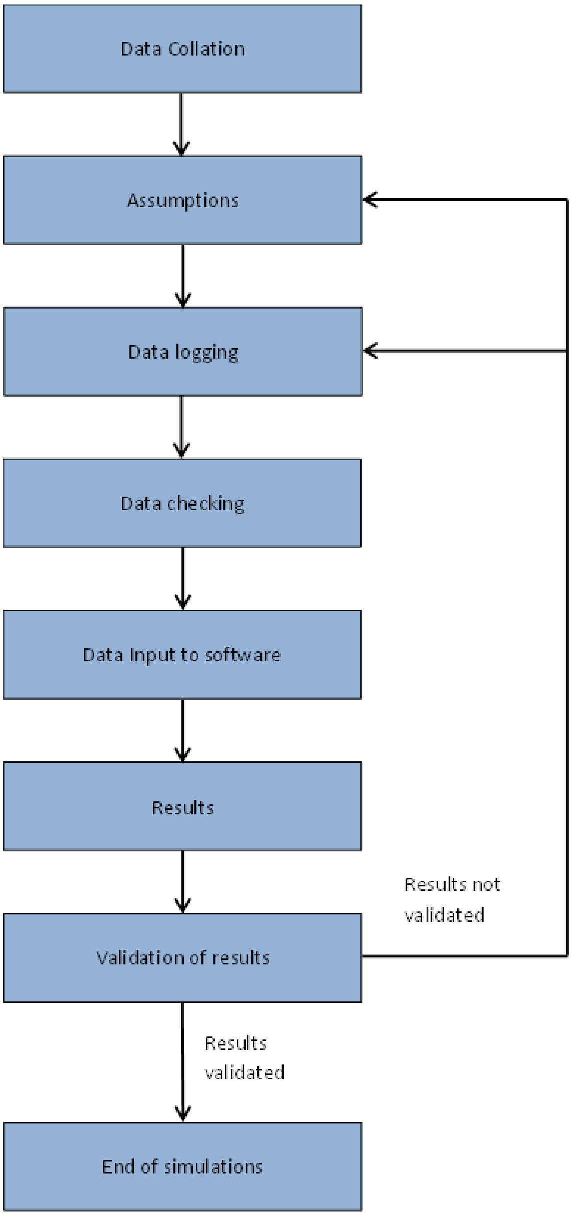


Figure 5-14: Simulation procedure based on recommendations by Tudor (2013)

At first all the information required as input in the software were collected and collated. Such information included drawings of the building, fabric specifications (U-value, constructions, material specifications etc.), occupancy pattern etc. Assumptions were then done regarding the use of the building and any missing information. Care was taken so that assumptions would be considered reasonable and these were determined after consulting with the occupants. These are presented in the next section.

Once all information was gathered and assumptions were decided they were logged for validity check and future reference. Data were then input to software and the simulation was performed. The simulation was first performed considering the timber frame construction and the results of the modelling were compared to the monitored indoor data. A climate file was developed based on the recorded external temperatures and this was used as software input in order to increase the accuracy of the simulations as it is acknowledged that the use of standardised climate files (TRY, DSY etc.) is one of the main sources of discrepancy between actual and simulated data (Hensen and Radosevic, 2004). The model was calibrated accordingly in order to meet the validation criteria presented in the following section. Once validated the model was then used to predict the future performance of the building with timber frame construction as well the current and future performance considering masonry walls.

<u>Assumptions</u>

Assumptions on the building use were based after consulting with the residents of Unit 8 in order to replicate as close as possible the actual operating conditions of the dwelling. Where information that could not be provided by the occupants was required, assumptions deemed reasonable by the author were used. These were the following:

Weather: For the current climate analysis, a climate file was developed based on the temperature readings collected on-site and from a weather station at close proximity during the period October 2014 – October 2015 in order to avoid discrepancies between actual and simulation results due to the use of different weather data. The use of the actual weather data recorded on-site enabled not only to assess the overheating risk of the two constructions under the current climatic conditions, but also to calibrate the simulation file and gain confidence on the simulation results. With regards to the future climate analysis, the PROMETHEUS weather files, created using the UKCP09 Weather Generator, were used. Validity of the method and consistency of simulation results with the CIBSE DSY and TRY files and the UKCIP02 climate data has been demonstrated by Eames et al. (2011). Free access to TRY and DSY climate files for over 40 UK locations is provided considering Medium and

High emissions scenarios for the timeslices 2030, 2050 and 2080. The weather files were produced for five percentiles (10%, 33%, 50%, 66% and 90%) for each time slice and emissions scenario, representing the likely severity of climate change and allowing for better use of the probabilistic nature of the climate projections and for dealing with the inherent uncertainty (Coley et al., 2011, Mylona, 2012).

Calendar: The analysis was performed considering two distinctive day types: winter and summer

Occupant Gains: The analysis considered the actual residents of Unit 8, namely two young adults. Occupants were assumed to contribute 65W sensible and 35W latent heat per person.

Lighting: Use of energy saving lighting was considered in all rooms

Equipment and appliance gains: The kitchen-dining area contains the following appliances: microwave, fridge, oven, and an electrical kettle. These resulted in a total daily load of 2.8kW. The living room heat gains were 0.58kW.

Infiltration rate: considered to be 0.2 ACH in all zones at atmospheric pressure.

Apertures: Windows in the ground floor were set to open only during occupancy hours in daytime for reasons of security. The windows of the first and second floor were considered to be open on a 24-hour basis when required. Windows in the living spaces were set to start open when the resultant temperature in those rooms reached 25^{o}C and reach maximum aperture when temperature exceeded 26^{o}C. Bedroom windows were set to start opening when the resultant temperature reached 23^{o}C and were fully open when it exceeded 25^{o}C.

Active conditioning system: a MVHR system was set to operate on a 24-hour basis supplying fresh air with a ventilation rate of 1ACH.

<u>Model Calibration</u>

Description of the main features of EDSL Tas and the ability of the software to produce accurate results based on the validation track record and documentation was presented in paragraph 3.2.1. However, the choice of software to perform the analysis is only one of the parameters which affect the reliability of the simulation results. Hensen and Radosevic (2004) reported the following sources of error in simulation that may lead to results that do not reflect actual conditions:

- Difference between the real weather conditions and the weather conditions assumed in the analysis
- Difference between the assumed and actual effect of the occupant behaviour on the building performance
- Divergence between the actual thermophysical properties of the building envelope and plant and the properties that are input by the user in the software
- Difference between the numerical representation of the heat and mass transfer processes occurring in practice in individual elements
- Difference between the interactions of heat and mass transfer mechanisms met in practice and calculated numerically
- Errors in the code

To ensure that reasonable assumptions were made in the modelling process the results for the Unit 8 simulated as-built (considering timber frame walls) were compared against the monitored temperatures for that house. This increased the confidence on the simulation results and contributed to the validation of the parametric study. It should be noted that currently there are no specific criteria for validating a model based on hourly temperature values. The following methodologies were used to demonstrate agreement between the actual and simulated performance of the house:

- The Pearson product-moment coefficient, $r_{Pearson}$, which demonstrates the strength of linear relationship between two variables. The coefficient values range from -1 to 1, with -1 demonstrating perfect negative linear relationship, 1 perfect positive linear relationship and 0 demonstrating no linear relationship between the two variables (Rodgers and Nicewander, 1988).

$$r_{Pearson}=\frac{\sum_{i=1}^{p}(x_i-\bar{x})(y_i-\bar{y})}{\left[\sum_{i=1}^{p}(x_i-\bar{x})^2\sum_{i=1}^{p}(y_i-\bar{y})^2\right]^{1/2}} \qquad \text{Equation 5-1}$$

- The ASHRAE Guide 14 Normalised Mean Bias Error (NMBE) and Cumulative Variation of Root Mean Squared Error (CVRMSE) indices (ASHRAE, 2002)

$$NMBE=\frac{\sum_{i=1}^{p}(y_i^{sim}-y_i^{meas})}{(p-1)\bar{y}^{meas}} \qquad \text{Equation 5-2}$$

$$\text{CVRMSE}=\frac{1}{\overline{y}^{meas}}\left(\frac{\sum_{i=1}^{p}\left(y_i^{sim}-y_i^{meas}\right)^2}{p-1}\right)^{1/2}$$ Equation 5-3

ASHRAE suggests that when hourly values are considered NMBE should exceed ±10% and CVRMSE should not be larger than 30% (ASHRAE, 2002). It should be noted that the use of these indices is intended for calibrating simulation results based on energy consumption data rather than temperature. However, they have been used by several researchers to calibrate models based on temperature data as well (Lyrian et al., 2013, Royapoor and Roskilly, 2015). Therefore and due to the lack of other standardised methodologies designed for calibrations based on temperature values the use of these indices was considered suitable for this study.

5.3.3 Results

As described earlier, the simulations were first performed considering the model of Unit 8 as-built (timber frame construction); this was calibrated against the monitored data in terms of whole building average temperatures. Calibrating the model was an iterative process where specific parameters were changed consecutively and the simulation results were then compared against the three criteria discussed in the previous paragraph. Since the focus of the work is the overheating risk of dwellings the data from the period June – August 2015 were used for the calibration. The results of the simulations of the calibrated file are presented in Table 5-11 and the temperature profile of the simulated temperatures against the monitored temperatures is shown in Figure 5-15.

Table 5-11: Calibration results based on the three criteria

Index	**Criterion**	**Value**
Pearson coefficient, r	0 no correlation 1 perfect positive linear correlation -1 perfect negative linear correlation	0.738
NMBE	> -10% and < 10%	-0.53%
CVRMSE	< 30%	24.74%

It can be seen that the simulation results of the calibrated model is in reasonable agreement with the monitored data. Although the model is not able to represent periods of sudden temperature changes which possibly occur due to periods of absence of the occupants from the house, it is able to replicate the general temperature trends. This is particularly the case during the summer months where the dwelling is free-running and the two temperature profiles appear to follow the same routes.

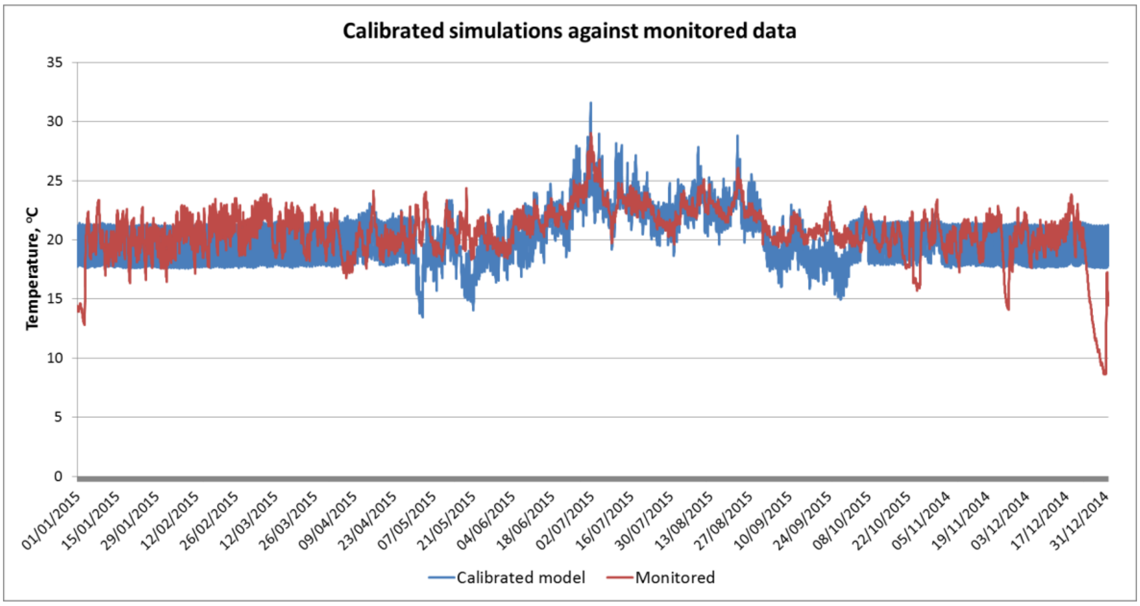


Figure 5-15: Simulated temperatures of the calibrated file plotted against measured temperatures

<u>Current Climate</u>

The calibrated model was also used to predict the temperatures considering the use of masonry construction. The performance of the two construction methods was assessed in terms of overheating occurrence in the three main zones of the dwelling (main bedroom, living room and kitchen) for 24-hour schedule and occupied hours schedule.

Table 5-12: Occurrence of temperatures above the comfort and threshold temperatures on a 24-hour basis considering timber frame and masonry construction

	Living Room		**Kitchen**		**Main bedroom**	
	Timber	**Masonry**	**Timber**	**Masonry**	**Timber**	**Masonry**
Above comfort	11.97%	6.93%	13.38%	7.71%	15.39%	14.91%
Above threshold	0.59%	0.46%	0.87%	0.79%	1.84%	1.77%

Similarly to the monitored data, it can be seen that the overheating thresholds (26°C for bedrooms and 28°C for living spaces) are barely exceeded in only zone examined which again highlights the consistency of the results to the ones of the monitoring analysis. When the 24-hour schedule is considered the 26°C (Table 5-12) overheating threshold is exceeded in the main bedroom for 1.84% of the time in the case of timber frame construction. This was reduced to 1.77% when masonry construction was considered (3.8% improvement compared to the timber construction). In the living room and kitchen the 28°C limit was not exceeded for more than 1% of the time for both constructions. Therefore, these zones were considered not to suffer from overheating.

In all cases, masonry wall construction appeared to have small benefit in reducing the amount of time the temperatures exceed the overheating temperature limit compared to timber frame construction, approximately 0.1%. However, this should be taken in the context that the reduction was over a very small figure in all cases.

The percentage of time that the 25°C comfort temperature limit in the kitchen and living room was exceeded, was significantly lower when masonry construction was used; approximately 42% in both zones. In the main bedroom, only a small reduction in the occurrence of elevated temperatures above the comfort threshold also occurred when masonry construction was considered in place of timber frame; 14.91% for masonry against 15.39% for timber frame.

Table 5-13: Occurrence of temperatures above the comfort and threshold temperatures during occupied hours considering timber frame and masonry construction

	Living Room		**Kitchen**		**Main bedroom**	
	Comfort limit: 25°C Overheating limit: 28°C		Comfort limit: 25°C Overheating limit: 28°C		Comfort limit: 23°C Overheating limit: 26°C	
	Timber	**Masonry**	**Timber**	**Masonry**	**Timber**	**Masonry**
Above comfort	4.66%	3.97%	9.86%	9.86%	5.24%	4.46%
Above threshold	0.55%	0.55%	1.46%	1.37%	0.20%	0.16%

When the occupancy schedules were considered (Table 5-13), overheating was observed only in the kitchen; this is for only 1.46% of the time for the timber frame and 1.37% of occupied hours in the masonry construction; a reduction of approximately 6%. Overheating did not appear to be an issue in the living room and main bedroom since the 28°C and 26°C thresholds respectively were not exceeded for more than 1% of the time these zones were occupied. The percentage of time above the overheating limit in all zones was very slightly reduced in the kitchen and the main bedroom, while it remained unchanged in the living room when masonry construction was considered. In addition, the percentage of time that the comfort limits were exceeded in the three zones was somewhat reduced in the living room and bathroom (approximately 15%) and remained unchanged in the kitchen when masonry construction was considered.

<u>Future Climate</u>

The future performance of Unit 8 considering timber frame and masonry construction was also assessed. The PROMETHEUS weather files that were created with UKCP09 weather generator were used in the future climate analysis. Information on the PROMETHEUS weather files were presented in Chapter 3 (Section 3.6.1). The Design Summer Year (DSY) climatic file for 2050 considering high emissions and for the 50th and 90th percentile was used. The percentiles represent the probability of the projected change not to be exceeded, i.e. the 50th percentile has a 50% probability not to be exceeded (and equal probability to be exceeded) while the 90th percentile has 90% probability not to be exceeded (and 10% likelihood that it is exceeded). The choice of the climatic files was done on the basis of examining the house performance under significant changes in climate for a medium to long term horizon. Considering additional percentiles or additional timeslices would add complexity and would not add value to the analysis as the scope of the work was to investigate the response of the construction methods. In other words, it was found that the use of these files was adequate to assess the construction performance and further simulations were not required.

Again, the performance of the construction was assessed through the frequency of occurrence of elevated temperatures above the comfort temperature and the overheating threshold in the living room, kitchen and master bedroom. This was done for the 24-hour schedule and the occupied hours and the results are presented below. The percentage of time the zone temperatures exceeded the comfort level (25^{o}C in the living room and kitchen and 23^{o}C in the bedroom) and the overheating threshold (28^{o}C in the living room and kitchen and 26^{o}C in the bedroom) in the different zones for 2050 50th and the 90th percentile is presented in Table 5-14 and Table 5-16 respectively considering 24-hour schedule in each zone.

It can be seen that overheating was an issue in all three zones considering both timber frame construction and masonry construction. In fact it was found that the difference between the two constructions was minimal in all zones; masonry construction resulted in reduced levels of overheating from 0.07% in the living room to 0.15% in the master bedroom in absolute terms (between 2% to 2.2% relative decrease in overheating).

With regards to the comfort threshold, it was found that both constructions had very similar performance. Masonry wall resulted in slightly reduced exceedance of the 25^{o}C comfort limit in the living room (0.1% less) and the timber frame resulted in slightly less exceedance of the 23^{o}C comfort limit in the master bedroom (0.15%), while both constructions had identical performance in terms of temperatures higher than the 25^{o}C comfort limit in the kitchen.

Table 5-14: Occurrence of elevated temperatures above the comfort and threshold temperatures for the living room, the kitchen and the master bedroom for 2050 50th percentile considering 24-hour schedule

	Living Room			**Kitchen**			**Master Bedroom**		
	Comfort limit: 25^{o}C Overheating limit: 28^{o}C			Comfort limit: 25^{o}C Overheating limit: 28^{o}C			Comfort limit: 23^{o}C Overheating limit: 26^{o}C		
	Timber	**Masonry**	**Masonry extra**	**Timber**	**Masonry**	**Masonry extra**	**Timber**	**Masonry**	**Masonry extra**
Above comfort	12.09%	11.99%	14.52%	14.06%	14.06%	19.14%	27.26%	27.41%	28.20%
Above threshold	3.40%	3.33%	1.88%	4.13%	4.04%	2.87%	7.39%	7.24%	5.75%

For reasons of comparison an additional masonry cavity wall construction referred to as ‘masonry extra’. The wall construction was block cavity wall finished internally with plaster. The ‘masonry extra’ wall was similar to the masonry wall, but it received a plaster finish (instead of an insulation and plasterboard finish). The build-up of the wall is shown in Table 5-15 and the thermal properties of the materials in Appendix B. The wall had the same U-value as the other constructions examined and high levels of exposed thermal mass.The ‘masonry extra’ wall resulted in reduced levels of overheating in all three zones, approximately up to 1.5% in the living room, 1.3% in the kitchen and 1.6% in the master bedroom in absolute terms. This was a relative improvement from 22% to 45% compared to the timber frame walls and from 21% to 43.5% compared to the masonry.

Table 5-15: Build up of the ‘masonry extra’ construction

Block and block cavity wall (first floor)
OUT • 90 mm block with approx.. 15 mm render • 150 mm cavity with full fill insulation • 100 block • 13 mm plaster IN

With regards to the comfort limits, these were exceeded more frequently than with the timber frame and masonry wall construction. It can be concluded that the temperatures with the 'masonry extra' construction remained between the comfort limit and the overheating limit for longer periods (from approximately 3% up to 36% compared to the timber frame and masonry) but they did not exceed the overheating threshold as frequent as with the timber and masonry construction.

Table 5-16: Occurrence of elevated temperatures above the comfort and threshold temperatures for the living room, the kitchen and the master bedroom for 2050 90th percentile considering 24-hour schedule

	Living Room			**Kitchen**			**Master Bedroom**		
	Comfort limit: 25°C Overheating limit: 28°C			Comfort limit: 25°C Overheating limit: 28°C			Comfort limit: 23°C Overheating limit: 26°C		
	Timber	**Masonry**	**Masonry extra**	**Timber**	**Masonry**	**Masonry extra**	**Timber**	**Masonry**	**Masonry extra**
Above comfort	22.64%	22.90%	22.19%	26.19%	26.55%	28.22%	35.67%	36.00%	37.48%
Above threshold	7.56%	7.40%	5.13%	8.71%	8.54%	6.93%	13.41%	13.48%	12.07%

The situation was more prominent when the analysis considered the 2050 90th percentile climatic file. All zones were found to suffer from high levels of overheating and the comfort limits were exceeded for large periods of time. Timber frame and masonry construction presented very similar levels of temperatures exceeding the overheating thresholds in all three zones, with masonry construction resulting in slightly less overheating in the living room and kitchen (0.16% and 0.17% respectively) and slightly higher levels in the master bedroom (0.07% higher).

With regards to the comfortable limits, again the two constructions had similar performance with timber frame construction presenting slightly lower levels of exceedance (between 0.26% and 0.36% in the three zones examined). 'Masonry extra' construction again had a more prominent effect at reducing the levels of overheating (between 1.34% and 2.43%). The relative improvement was found between 10% and 32% compared to timber frame and from 10% up to 30% compared to masonry. However this was kept still at high levels. It also resulted in higher levels of temperatures exceeding the comfort limits in the kitchen and the master bedroom and slightly lower in the living room.

Table 5-17: Occurrence of elevated temperatures above the comfort and threshold temperatures for the living room, the kitchen and the master bedroom for 2050 50th percentile considering occupied hours

	Living Room			Kitchen			Master Bedroom		
	Comfort limit: 25°C Overheating limit: 28°C			Comfort limit: 25°C Overheating limit: 28°C			Comfort limit: 23°C Overheating limit: 26°C		
	Timber	**Masonry**	**Masonry extra**	**Timber**	**Masonry**	**Masonry extra**	**Timber**	**Masonry**	**Masonry extra**
Above comfort	17.12%	16.71%	15.75%	22.56%	22.47%	22.56%	16.59%	16.67%	23.09%
Above threshold	2.33%	2.05%	1.23%	5.30%	5.30%	3.11%	0.51%	0.51%	0.55%

Table 5-18: Occurrence of elevated temperatures above the comfort and threshold temperatures for the living room, the kitchen and the master bedroom for 2050 90th percentile considering occupied hours

	Living Room			Kitchen			Master Bedroom		
	Comfort limit: 25°C Overheating limit: 28°C			Comfort limit: 25°C Overheating limit: 28°C			Comfort limit: 23°C Overheating limit: 26°C		
	Timber	**Masonry**	**Masonry extra**	**Timber**	**Masonry**	**Masonry extra**	**Timber**	**Masonry**	**Masonry extra**
Above comfort	27.12%	26.99%	26.16%	29.50%	29.59%	31.14%	25.79%	26.89%	33.31%
Above threshold	5.89%	5.48%	3.29%	10.05%	10.05%	8.13%	3.44%	3.17%	3.91%

When the occupied hours were considered, the same general patterns in the constructions' performance were found. Timber frame and masonry construction had similar levels of overheating in all cases, with masonry construction presenting lower levels of overheating in the living room and master bedroom for the 90th percentile and the living room for the 50th percentile (the relative performance improvement for masonry was between 7% and 12% in these cases) while in the kitchen both construction performed the same. Overheating was not observed only in the master bedroom at the 2050 50th percentile weather file analysis.

'Masonry extra' again presented more favourable performance in the living room (almost eliminated overheating in 2050 50th percentile) and the kitchen with a relative improvement of up to 47% compared to timber frame and 41% compared to masonry in the various zones. It underperformed compared to the other two constructions only in the master bedroom at the 2050

90^{th} percentile where it resulted in higher levels of overheating (approximately 8% higher than both timber frame and masonry). It also resulted in significantly higher levels of temperatures exceeding the comfort limit (approximately 38% higher) in the master bedroom in both the 50^{th} and 90^{th} percentile analysis.

5.3.4 Discussion

The analysis of the current and future performance of Unit 8 considering the timber frame and masonry constructions that were used in Stages 1 to 3 of the Green Street development resulted to some useful conclusions regarding the performance of these two construction methods.

It was found that in the current climate masonry construction was able to reduce the amount of time the temperatures exceeded the comfort limits in most zones, considerably in some zones (such as the kitchen and living room under the 24-hour schedule where masonry resulted in approximately 42% reduced amount of time of temperatures exceeding the 25^{o}C comfort limit) and moderately in others (approximately 15% less occurrence of temperatures exceeding the comfort limit during occupied hours in the living room and the main bedroom) while it had similar levels of performance to timber frame construction in other zones.

In terms of reducing overheating, it was found that masonry construction had a small impact, almost negligible, since the percentage of time that temperatures exceeded the overheating thresholds was comparable to that of the timber frame construction. This was the case considering both the 24-hour schedule and the occupied hours in the analysis. However, overheating was an issue only in one zone, the main bedroom in the case of 24-hour occupancy and the kitchen in the case of occupied hours. Masonry construction presented less than 0.1% reduced occurrence of overheating in absolute terms in both cases; this was equivalent to 4% and 6% relative reduction of overheating compared to timber frame construction respectively.

With regards to the future performance of the house, it was found that the two constructions had similar performance in most cases. Overheating was an issue in almost all zones for both the 24-hour occupancy and the occupied hours schedule considering both the central estimate and the 90^{th} percentile. When the 2050 90^{th} percentile file was used in the analysis, excessive levels of overheating were found in all zones. The frequency of temperatures exceeding the comfort and overheating limits was comparable in most cases for the two constructions, with the maximum relative difference between them being approximately 2%. However, masonry construction presented some potential for reduced levels of overheating, as was the case in the living room in the 2050 climate 90th percentile where the overheating occurrence was by 7% lower compared to the timber frame construction (5.89% for timber frame construction compared to 5.48% for masonry in the living rooms).

The fact that the overheating potential of the two constructions was almost identical can be attributed to:

- The use of the insulated plasterboard as a finish in the masonry wall which isolated the thermal mass of the wall from the interior environment. Therefore, the thermal mass of the internal block leaf was to a great extent inactive.
- The external wall area in each zone is limited. The construction of the floor, roof, internal walls and intermediate floors was the same in all cases examined. Therefore the available area of the external walls where the two constructions were assessed was limited.
- The future warming temperatures restricted even further the ability of thermal mass to cool down in order to be able to absorb heat from the internal space.

For reasons of comparison, the performance of 'masonry extra', a very heavyweight construction, was assessed in future climatic conditions. In most cases overheating was reduced considering both the 24-hour and occupied hours schedule for both the 50th and 90th percentile. On average, overheating reduction compared to the masonry construction exceeded 20% while in some cases it exceeded 40%.

However, the amount of time that the thermal comfort limit was exceeded increased compared to the timber frame and masonry construction. This could be the result of the warming external temperatures not allowing the mass of the construction to cool down, thereby limiting the effectiveness of thermal mass as a strategy to provide comfortable indoor temperatures. In most cases, the 'masonry extra' construction resulted in a slight increase of the occurrence of temperatures exceeding the comfort threshold, between 1 and 6%, compared to the masonry construction. However, in a few occasions the temperatures considering the 'masonry extra' construction exceeded the comfort limit by up to 23% and even 39% more than the masonry construction. Both these cases were in the master bedroom (2050 50th and 90th percentile during occupied hours) where the comfort limit is 23^{o}C. This is supporting the argument that the thermal mass of the heavyweight construction is not able to discharge the excessive heat easily.

5.4 Conclusions and suggestions for further work

In this chapter the performance of two commonly used construction methods, timber frame and masonry cavity construction, was evaluated in terms of their ability to reduce the occurrence of elevated temperatures in highly insulated housing. The analysis was performed through a case study and involved in-situ monitoring of the internal temperatures in two dwellings and parametric simulation analysis.

The results of the monitoring study suggested that overheating was not an issue in either house. However, this was the result of one year's data; the study might have led to different conclusions if the summer for that year was warmer. The house built with masonry construction presented reduced frequency of elevated temperatures, lower peak internal temperatures and smaller diurnal temperature variations over the summer than the timber frame house. However, design differences and different building use patterns did not allow for concluding that masonry construction was the favourable method for reducing overheating. Therefore the parametric analysis presented in Section 5.3 was deemed necessary.

The simulation study allowed for investigating the effect of the construction method by keeping all the other parameters (building design and orientation, building use and occupancy pattern) the same. It was found that for both the current and future climate, the performance of the house considering the two constructions was very similar. This was attributed to the fact that the masonry construction was finished with insulated plasterboard isolating the thermal mass of the construction from the internal environment. In addition, the available area of external walls in each zone examined was limited and therefore the construction had limited potential of affecting the indoor conditions.

Therefore, the suggestion by Kendrick et al. (2012) that modern masonry construction does not benefit from the additional levels of thermal mass appears to be valid. The masonry wall examined even though significantly more heavyweight than the timber frame wall, did not benefit from the additional levels of thermal mass. In this respect, timber frame construction is not expected to have significantly increased overheating risk compared to commonly used masonry constructions. Especially, if the use of the non-traditional lightweight materials examined in Chapter 4 is considered, then MMC will be expected to perform equally to other construction methods. This could be true for other MMC constructions with similar levels of thermal mass, although this would need to be verified through simulations.

Every care was taken in order for the simulation parameters to reflect the actual building use and increase confidence on the results. However, the results reflect the performance of the type of building examined in this case study. Although these could be extrapolated to other building types further research is required to verify if this is the case. In addition simulation results are sensitive to a certain degree to input parameters. Conducting additional monitoring and simulation studies to include other building types is recommended for future research in the field. As it was not possible to have the same occupancy and building use in different houses, conducting large scale monitoring studies will help eliminate these differences. In addition, monitoring the occupancy schedule, window openings and energy use with the relevant equipment will be of great value for analysing the data.

Finally, in-situ monitoring of the heat flows occurring on building elements and not only the zone temperatures is suggested in order to isolate the effect of the construction on the resulting temperatures. This is done in the following chapters where the heat flows on the surface of several construction elements were investigated. Different construction elements built with different MMC and masonry construction methods were monitored in order or evaluate their thermal response and their contribution to the indoor temperature conditions. The study was conducted on the houses of the Creative Energy Homes project. A description of the houses and the constructions examined is given in Chapter 6 while the results of the analysis are presented in Chapter 7.

CHAPTER 6. THE CREATIVE ENERGY HOMES CHARACTERISATION

It was seen in the previous chapters that the use of thermal mass presents some potential to regulate internal temperatures but this is not straightforward. It was demonstrated in Chapter 4 that the use of additional levels of thermal mass reduced the occurrence of elevated temperatures in the Nottingham H.O.U.S.E. Non-traditional lightweight materials that could be easily fitted in a panellised MMC construction as a possible solution to increase the building's thermal inertia were proposed. However, the parametric study considered the use of multiple layers of material, which is uncommon in practice.

In contrast, the study presented in Chapter 5 considered commonly used constructions and it was found that, at least for the building type examined, modern masonry construction did not appear to benefit greatly from the additional levels of thermal mass compared to timber frame construction. The monitoring study of the two houses considered only the zone temperatures and it was suggested that in order to be able to determine the effect of the construction method on a building's thermal performance, heat flows on building elements should be monitored.

For these reasons, the next step in the analysis was in-situ monitoring of heat flows occurring on the surface of building elements built using different construction methods. The houses of the Creative Energy Homes project, at the University Park Campus, University of Nottingham were used as live research facilities and various building systems in these houses were investigated. In each house, one zone or, in some cases, two zones with representative construction components were monitored. The components examined comprised external and internal walls, internal ceilings and roof panels.

The study reports on the performance of nineteen building elements in total, each being monitored for a period of more than twelve months. Due to the large volume of reported data the work is presented in two chapters. In Chapter 6, the description of the houses is given along with details of the construction of the building elements and the apparatus set in each monitored zone. The methodology for analysing the data, the results and the findings of the study are presented in Chapter 7.

The value of this study was that it allowed monitoring the performance of all the main MMC and modern masonry construction methods under actual operating conditions. This work is unique since reporting on the results from such a diverse set of construction methods has never been presented before. The work provided valuable information on the thermal response of these methods and this was only made possible by the availability of the unique research facility that is the Creative Energy Homes project.

6.1 Scope and Aim

The scope of the work presented in this chapter was to monitor the heat flows occurring in a range of different building systems constructed with MMC and modern masonry constructions in order to assess their thermal performance under real operative conditions. These systems were monitored for a minimum of 12 months so that the year round performance was assessed. Particular attention was given to the summer performance as the main focus of the work is the overheating potential of buildings. The aims of the work were:

- to gather monitoring data on the actual as-built performance of MMC systems. As highlighted in the literature review very little research evidence on the thermal response of MMC is available and, to the best knowledge of the author, no similar studies reporting on the heat flows and the year-round interaction of these systems with the internal environment exist. This is expected to add valuable knowledge on the thermal performance of MMC at a period when their use on house building is expected to increase significantly;
- to assess the thermal behaviour of these systems and quantify the heat flows occurring in order to identify their potential for regulating indoor temperatures; and
- to determine the relative performance of MMC compared to modern masonry construction methods and assess whether these would present higher risk of overheating.

It has been suggested that the concerns of users and industry stakeholders on MMC is based mostly on their perceptions rather than actual data regarding their use (Rodrigues, 2009). This study aimed to address this particular issue and report on the in-situ performance of MMC systems.

6.2 Creative Energy Homes Project

The Creative Energy Homes (CEH) project is a unique live research facility at the Department of Architecture and Built Environment at the University of Nottingham, University Park campus. It was developed by members of the Architecture, Energy and Environment research group in collaboration with leading industry partners, namely E.ON, David Wilson Homes, BASF, Tarmac, The Mark Group and Saint-Gobain (The University of Nottingham, 2016b). The project comprises seven houses, built with different MMC and modern masonry methods and allowed for investigating different approaches to sustainability and low carbon housing by examining issues such as innovative construction, energy storage and integration of renewable energy and energy efficient systems.

The seven CEH houses are:

- The David Wilson Millenium Ecohouse, a four bedroom detached house built with brick and block full fill cavity wall construction. This was the first house of the CEH project completed at the end of the 1990s. It incorporates a range of renewable energy and energy efficient technologies and is being used as an office building by the members of the Department of Architecture and Built Environment.
- The E.on 2016 Research House is a residential building designed to replicate a typical 1930s semi-detached house. The three bedroom house was constructed according to the 1930s construction standards, i.e. masonry cavity wall with no insulation in the cavity. The building was retrofitted at different stages to achieve zero carbon emissions and test different insulation strategies. It is currently used as research facility by staff of the sponsor company, E.on.
- The Tarmac Homes: the two three-bedroom semi-detached houses were designed to achieve level 4 and level 6 of the Code for Sustainable Homes. These were built with modern masonry construction to very high levels of insulation (Tarmac Code 4 was built with brick and block cavity wall and Tarmac Code 6 was built with solid walls) and were used as dwellings at the time they were monitored.
- The BASF house, a three bedroom detached dwelling designed to achieve level 4 of the Code of Sustainable Homes was built with two different MMC for the external walls: Insulating Concrete Formwork (ICF) on the ground floor and Structural Insulated Panels (SIPs) on the first floor and roof. During the period that was monitored the BASF house was used as residential building.
- The Nottingham H.O.U.S.E. is a two bedroom detached house built to the design specifications of the Passivhaus Standard. The house was built with modular timber frame construction and during the monitoring period it was used as an office building by members of the Department of Architecture and Built Environment staff.
- The Mark Group house, a four bedroom detached house designed to achieve level 6 of the Code for Sustainable Homes was constructed with ICF walls on the basement and steel frame construction on the ground and first floor. The house was used as offices by research

students and members of staff of the Department of Architecture and Built Environment during the course of the monitoring period.

Not all of the CEH houses were investigated as part of this work. The analysis focused on highly insulated fabric and therefore zones from the Tarmac Homes, the BASF house, the Nottingham H.O.U.S.E. and the Mark Group house were monitored. The location of these houses is shown in Figure 6-1. Detailed description of the design of these houses, the systems used and applied construction methods is given in the following paragraphs.

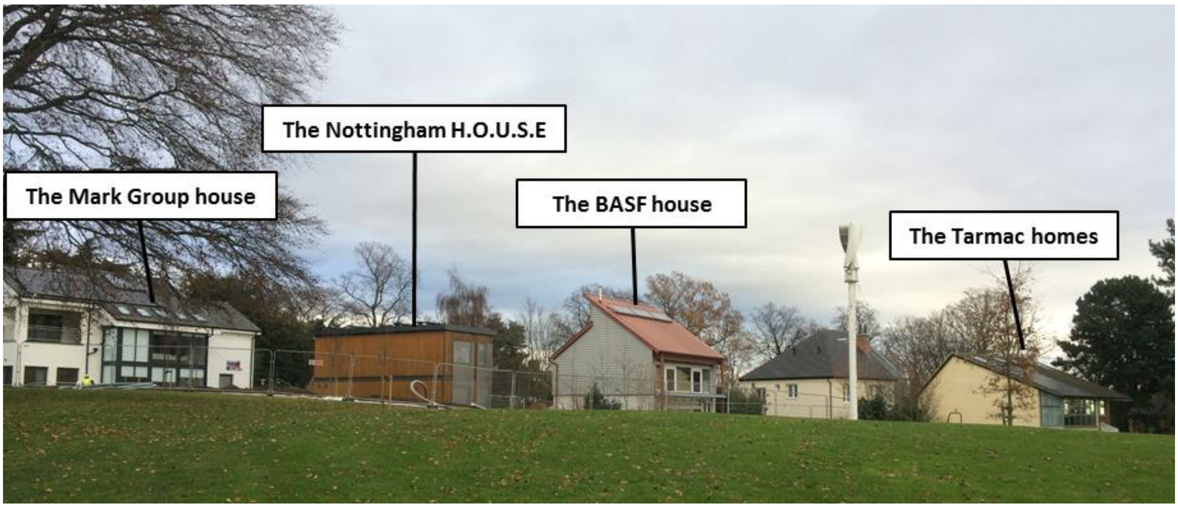


Figure 6-1: The CEH houses investigated

6.2.1 Tarmac Homes

The Tarmac Homes are two semi-detached three-bedroom houses. They were named after Tarmac UK Ltd, the main sponsor of the project, and built to achieve Level 4 and Level 6 of the Code for Sustainable Homes. Designed by the architectural firm Zedfactory Ltd they were developed as a prototype for delivering affordable housing which could be deployed at a large scale and be easily replicated. The concept of thermal mass was at the core of the design strategy and therefore masonry construction was used for the superstructure. The development of the Tarmac homes also aimed at providing the evidence that masonry construction is able to deliver housing built to such high standards of energy efficiency and environmental performance.

The design strategy to achieve the low-carbon targets relied primarily on the highly insulated fabric. Both houses were built with suspended ground floor constructed with the use of EPS insulation, laid between precast concrete beams with a U-value of 0.14W/m^{2}K. The timber trussed roof, finished with timber battens and concrete tiles, has a U-value of 0.11 W/m^{2}K.

The external walls of the Tarmac Code 6 home were built with thin-joint solid wall construction using the Tarmac aircrete Durox block insulated externally and rendered; 150mm thick EPS insulation was used and render finish to a U-value of 0.15W/m^{2}K. The external walls of the Code 4 house were built with cavity masonry construction; Hemelite blocks followed by a partially insulated cavity and finished externally with brickwork to a U-value of 0.18 W/m^{2}K. Detailed information on the built-up of the walls is given in Table 6-1 and Table 6-2 below.

High levels of solar gain utilisation were also considered to minimise the energy consumption of the houses. Large south facing glazing areas were used in the Code 4 house, while a two storey sunspace in the south façade of the Code 6 house contributed to increased levels of passive solar gains. In addition, the sunspace would act as a thermal buffer in the cooling period. Excessive summer gains when the sun is high in the horizon are avoided though the use of shading provided by the roof. External view of the south façade of the houses is presented in Figure 6-2.

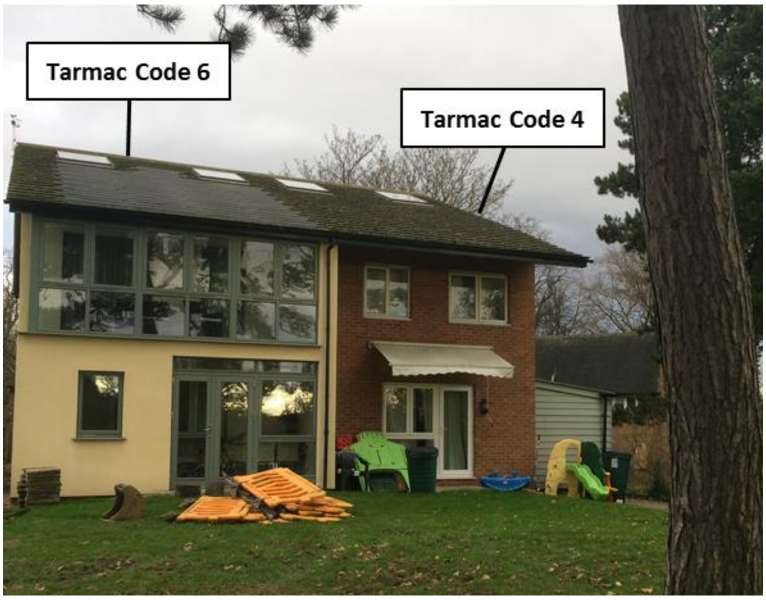


Figure 6-2: External view of the Tarmac Masonry Homes

In order to meet the strict sustainability criteria to achieve Level 4 and Level 6 of the Code for Sustainable Homes the following technologies have also been fitted in the two houses (Tarmac UK Ltd, 2008):

- Biomass boiler. A 10 kW biomass boiler developed by Ökofen has been installed covering the heating requirements of both houses. The system is equipped with a fully automated vacuum feeding system and therefore it requires little maintenance.
- Heat Recovery. A Nuaire MRXBOX90L MVHR unit has been installed to provide mechanical ventilation with heat recovery from the exhaust air in order to reduce the energy demand

of the house during the heating period. The system is equipped with a bypass in order to provide ventilation with cool outside air when heating is not required

- Solar hot water. Two flat plate solar collectors supplied by Viridian Solar with an aperture area of 3.05m2 were installed on the roofs of the two houses. The system is fitted with a 210 litre hot water cylinder and is expected to cover approximately 70% of the hot water requirements of the houses; any additional auxiliary heating required will be provided from the biomass boiler.
- Photovoltaic panels. A 3.75 kW_p PV system comprising of 72 tiles – solar collectors has been installed on the roof of the Code 6 house, enough to cover the peak expected electricity requirements of the house, estimated to approximately 3.5 kW.
- Sun pipes. One Monodraught Square SunPipe has been installed in each roof to provide natural light in the internal staircase.
- Rainwater collection. The rainwater collected from the roofs of the houses will be stored in waterbutts for use in the garden.

In order to investigate the in-situ performance of different building elements and monitor the heat flows, the living room zone of each house was examined in this study. The external wall, internal wall and ceiling in each zone were monitored. Detailed description on the apparatus and the build-up of these elements is presented in the following sections.

<u>Building systems</u>

The build-up of the main building systems examined in the Tarmac Code 6 and Code 4 house is presented in Table 6-1 (Code 6) and Table 6-2 (Code 4) below. The Tarmac Code 6 house comprises an externally insulated solid wall, timber frame internal wall partition and intermediate floor with hollow core concrete slab. The Code 4 house comprises a masonry partially filled cavity wall, timber frame internal wall partition and I-joist timber floor.

Table 6-1: Typical build up of the construction elements found in Tarmac Code 6

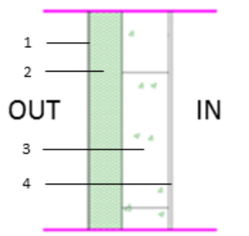
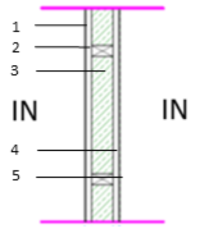
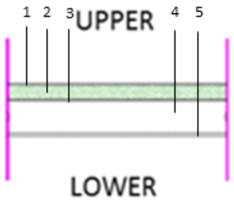
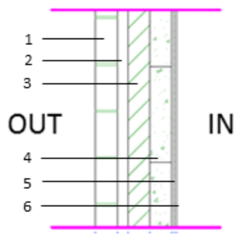
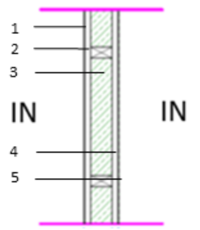
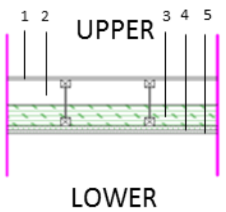
SOLID WALL		OUT 1. 5mm render 2. 150mm Expanded Polystyrene (EPS) 3. 215mm Durox Supabloc 4. 13mm plaster IN	Admittance: 1.78 W/m²K U-value: 0.15 W/m²K Decrement factor: 0.14 Time lag: 12.39 hours κ-value: 47.82 kJ/m²K
INTERNAL WALL		IN 1. Skim coat 2. 15mm Gyproc SoundBloc 3. 63x38 CLS studwork at 600mm vertically 4. 15mm Gyproc SoundBloc 5. Skim coat IN	Admittance: 1.16 W/m²K U-value: 0.28 W/m²K Decrement factor: 0.97 Time lag: 1.77 κ-value: 15.90 kJ/m²K
INTERNAL FLOOR		UPPER 1. 10mm floor finish 2. 65mm Truflow screed 3. 6mm iso rubber 4. 150 mm precast pre-stressed hollow core concrete slab 5. 10mm Lightweight plaster LOWER	Admittance: 3.05 W/m²K U-value: 1.38 W/m²K Decrement factor: 0.19 Time lag: 9.26 hours κ-value: 72.53 kJ/m²K

Table 6-2: Typical build up of the construction elements found in Tarmac Code 4

CAVITY WALL		OUT 1. 103 mm facing brick 2. 50 mm air cavity 3. 100 mm Kingspan TW50 (PIR) 4. 100 mm Hemelite blocks 5. 10 mm air gap 6. 12.5 mm plasterboard IN	Admittance: 2.38 W/m²K U-value: 0.18 W/m²K Decrement factor: 0.11 Time lag: 12.35 hours κ-value: 8.75 kJ/m²K
INTERNAL WALL		OUT 1. Skim coat 2. 15mm Gyproc SoundBloc 3. 63x38 CLS studwork at 600mm vertically 4. 15mm Gyproc SoundBloc 5. Skim coat IN	Admittance: 1.16 W/m²K U-value: 0.28 W/m²K Decrement factor: 0.97 Time lag: 1.77 hours κ-value: 15.90 kJ/m²K
TIMBER FLOOR		UPPER 1. 10 mm decking 2. 120 mm cavity 3. 100 mm mineral quilt 4. 22 mm chipboard 5. 12.5 mm plasterboard LOWER	Admittance: 1.38 W/m²K U-value: 0.31 W/m²K Decrement factor: 0.96 Time lag: 1.75 hours κ-value: 8.75 kJ/m²K

Apparatus

In order to evaluate the thermal performance of these elements, the temperature and the heat flux on their surface was monitored with the use of Hukseflux HFP-01 heat flux sensors and T-type thermocouples. The ambient temperature at the centre of each zone was also recorded with the use of a T-type thermocouple. The data acquisition system used was Datataker DT80 in the Code 4 zone and a Squirrel SQ800 in the Code 6 zone.

It is recommended that at least two sensors are installed on each element in order to avoid potential thermal bridges and ensure that at least one of the sensors is installed on a homogeneous part of that element. In this study, one heat flux sensor was installed on the surface of each element due to restrictions on the available equipment. It should also be noted that the Tarmac homes were built to a very high level of workmanship quality and with methods that did not involve repeating thermal bridges. Therefore, it is considered that the sensor readings reflect the actual performance of the respective building element. The location of the monitoring equipment in the two zones is shown in Figure 6-3.

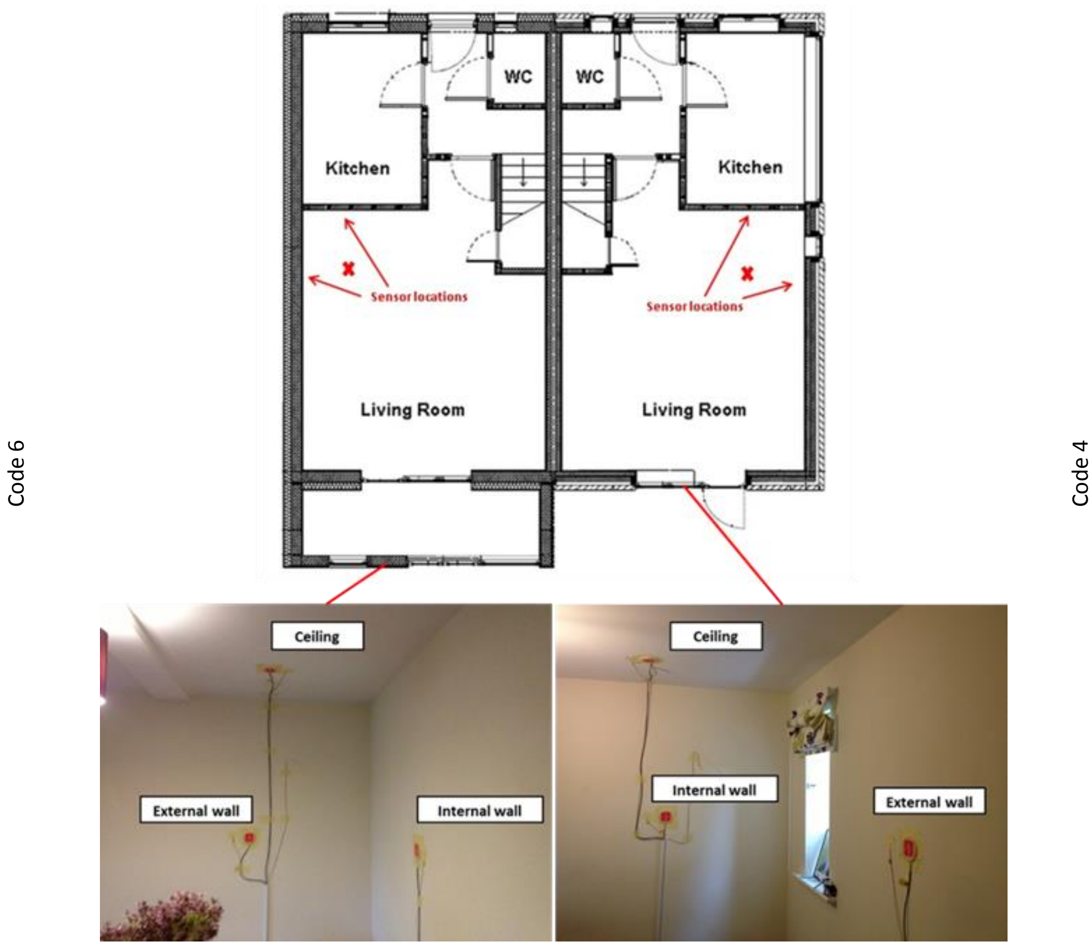


Figure 6-3: Location of the heat flux sensors and thermocouples at the ground floor of the Tarmac Code 6 (left) and Code 4 (right) houses

6.2.2 BASF house

The BASF Research house was designed by Derek Trowell Architects to provide an affordable and low carbon solution to the shortage of skilled labour and lack of available land. The BASF house achieved level 4 of the Code for Sustainable Homes introducing a range of innovative construction methods and sustainable technologies (BASF, no date-a). The house construction was completed in January 2008. Similarly to the Tarmac Homes the house design considered high levels of insulation and the use of solar gains to achieve the stringent energy efficiency requirements and low emissions targets. The south façade is a sunspace with internal and external fully glazed surfaces while the highly insulated external walls comprise the north, east and west orientations. The north wall has 23% glazed area while the east and west walls do not have any windows making it possible to be built as a semi-detached or terrace house. In the site of the Creative Energy Homes project it has been built as a detached house (BASF, no date-a).

The plans of the ground and first floor of the BASF house are presented in Figure 6-4 and external views of the south and north façade of the house are presented in Figure 6-5.

The house was designed to high insulation standard achieving low U-values for the various building elements; the walls and roof had a U-value of 0.15 W/m^{2}K, the external south facing windows of the sunspace have a 2.7 W/m^{2}K U-value, while the respective U-value for the internal windows of the sunspace is 1.7 W/m^{2}K and for the north facing windows 1.66 W/m^{2}K.

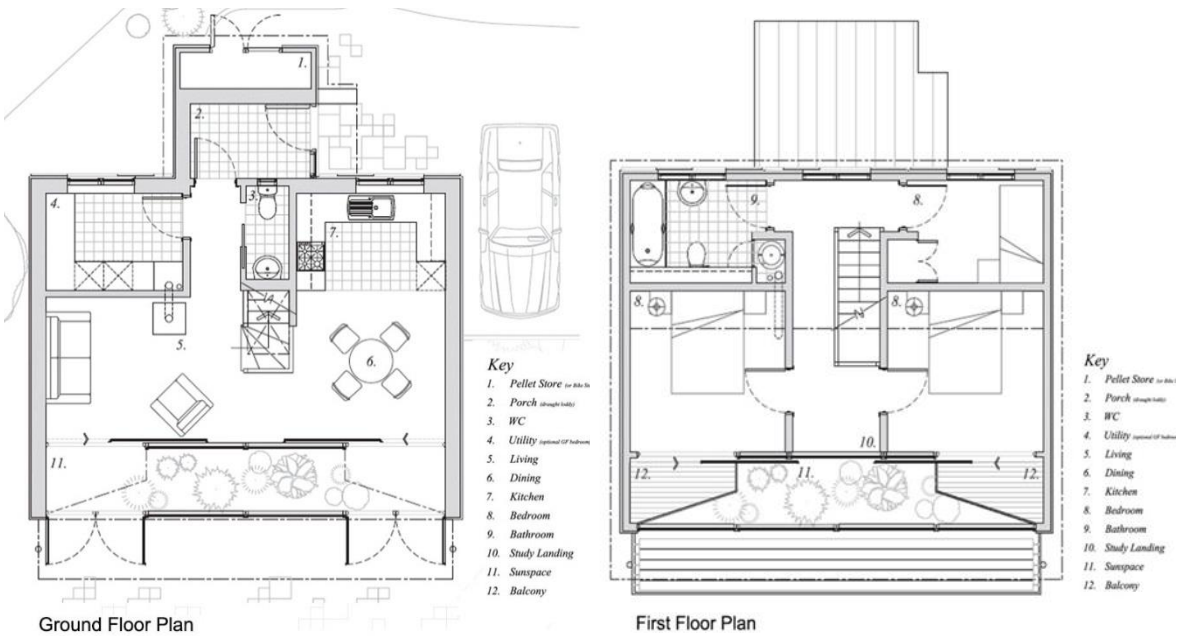


Figure 6-4: Plan of the ground and first floor of the BASF house (The University of Nottingham, 2016a)

Figure 6-5: View of the BASF house from the a) South (left image) and b) North (right image)

Both in-situ and offsite MMC were used in the construction. The ground floor walls were built with Insulating Concrete Formwork (ICF). The BASF Neopor® ICF system was used in the ground floor. The ICF blocks were installed by Logix shaping the perimeter of the ground floor, including all the openings, and were then filled with concrete. An additional internal and external layer of Springvale Platinum EPS insulation was used in order to achieve U-value of 0.15W/m^{2}K (BASF, no date-a).

The walls of the first floor and the roof were constructed with timber Structural Insulated Panels (SIPs). Prefabricated timber SIP panels with polyurethane insulation core provided by the Elastogran Group, member of the BASF group, were assembled to form the superstructure of the first floor. The panels were lightweight cut to size in the factory including all the openings. The external walls were also fitted internally with an additional layer of Springvale Platinum EPS insulation to reach the desired U-value. The SIP construction was chosen due to the lightweight construction, the ability to achieve high insulation and airtightness levels and minimize thermal bridging and the offsite construction potential; According to BASF, the house achieved 90% less infiltration than timber frame structures (BASF, no date-a, BASF, no date-b).

A range of sustainable technologies have been incorporated to achieve the low carbon emissions target. An earth-to-air heat exchanger has been used to preheat the incoming air during the cold months and pre-cools it during the hot months. The air is driven through pipes buried in the ground before entering the house achieving a 10^{o}C change (10^{o}C increase in winter and 10^{o}C decrease in summer) in its temperature according to BASF (BASF, no date-a). After being pre-conditioned, the air then enters the house through an inlet across the ground floor level.

Due to the chosen construction methods the BASF house has low levels of exposed thermal mass; the timber SIP panels are lightweight and the ICF walls despite being heavyweight, they have the concrete encapsulated in EPS insulation formwork and therefore isolated from the internal space. In order to provide additional levels of thermal mass to the building, the ceiling of the kitchen was fitted with the KNAUF Smartboard 23, which incorporates Micronal phase change material, and finished with conventional plasterboard. By storing sensible as well as latent heat the use of the PCM board aimed at reducing the diurnal temperature variation and the temperature peaks.

In order to investigate the performance of the different building elements, monitoring equipment was installed in two zones of the house, the kitchen-dining area located in the ground floor and the north bedroom in the first floor. In each zone the external wall, internal wall and ceiling were examined. Detailed description on the used apparatus and the build-up of these elements is presented below.

<u>Building systems</u>

The build-up of the systems examined in the two zones of the BASF house is presented in Table 6-3 (ground floor kitchen-dining) and Table 6-4 (first floor bedroom). Apart from the ICF wall, the kitchen-dining area comprises a concrete block internal wall finished with plasterboard and a timber joist internal ceiling in filled with insulation and lined with PCM board and plasterboard. Similarly to the external wall in the first floor, the roof was also constructed with SIP panels while the internal walls were built with timber frame construction.

Table 6-3: Typical build up of the construction elements found in the ground floor of the BASF house

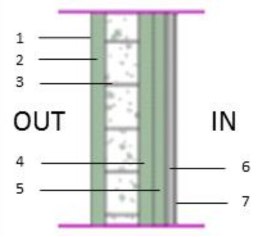
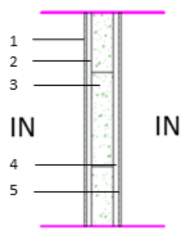
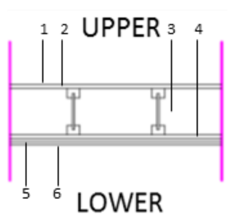
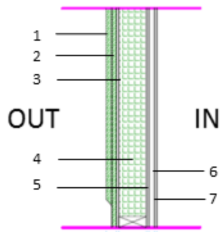
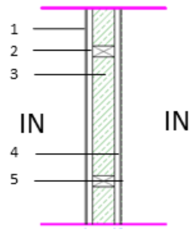
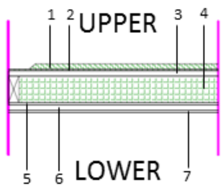
EXTERNAL WALL		OUT 1. 12 mm render 2. 70 mm Extruded Polystyrene 3. 159 mm Concrete 4. 70 mm Extruded Polystyrene 5. 55mm extruded Polystyrene 6. 25mm air cavity 7. 12.5 mm plasterboard IN	Admittance: 0.82 W/m²K U-value: 0.15 W/m²K Decrement factor: 0.02 Time lag: 9.61 hours κ-value: 10.00 kJ/m²K
INTERNAL WALL		OUT 1. 12.5 mm plasterboard 2. 25 mm cavity 3. 100 mm lightweight concrete block 4. 25 mm cavity 5. 12.5 mm plasterboard IN	Admittance: 1.77 W/m²K U-value: 0.71 W/m²K Decrement factor: 0.64 Time lag: 5.32 hours κ-value: 41.50 kJ/m²K
INTERNAL CEILING		UPPER 1. Carpet 2. 18mm Oriented Strandboard 3. 200 mm I-joists 4. 18 mm Oriented Strandboard 5. 15 mm PCM plasterboard 6. 12.5 mm plasterboard LOWER	Admittance: 2.10 W/m²K U-value: 1.14 W/m²K Decrement factor: 0.91 Time lag: 2.50 hours κ-value: 38.80 kJ/m²K

Table 6-4: Typical build up of the construction elements found in the first floor of the BASF house

EXTERNAL WALL		OUT 1. Corus Prelaq Nova PLX Sheet steel cladding 2. Breather membrane 3. 11 mm Oriented Strand Board (OSB) 4. 128 mm Polyurethane insulation (PUR) 5. 11 mm Oriented Strand Board (OSB) 6. 25mm cavity 7. 12.5 mm plasterboard IN	Admittance: 1.34 W/m²K U-value: 0.15 W/m²K Decrement factor: 0.89 Time lag: 3.71 hours κ-value: 18.80 kJ/m²K
INTERNAL WALL		OUT 1. 12.5 mm plasterboard 2. 25 mm cavity 3. 100 mm timber frame in-filled with insulation 4. 25 mm cavity 5. 12.5 mm plasterboard IN	Admittance: 0.79 W/m²K U-value: 0.17 W/m²K Decrement factor: 0.98 Time lag: 0.38 κ-value: 10.00 kJ/m²K
EXTERNAL ROOF		OUT 1. Corus Prelaq Nova PLX Sheet steel cladding 2. Breather membrane 3. 23 mm Oriented Strand Board (OSB) 4. 128 mm Polyurethane (PUR) 5. 11 mm Oriented Strand Board (OSB) 6. 25mm cavity 7. 12.5 mm plasterboard IN	Admittance: 1.36 W/m²K U-value: 0.15 W/m²K Decrement factor: 0.86 Time lag: 4.17 hours κ-value: 18.80 kJ/m²K

Apparatus

As discussed previously, the zones selected for the analysis were the kitchen-dining area and the north bedroom. The kitchen-dining room was selected in the ground floor for reasons imposed by the geometry of the house while the north bedroom on the first floor was preferred than the other two bedrooms due to the fact that the building elements would not receive direct solar radiation. In each zone three construction elements were considered, external wall, internal wall and ceiling. The heat flux and temperature at the surface of each construction were recorded, as well as the ambient temperature in the respective zone.

Regarding the kitchen – dining room, three HUKSEFLUX HFP01 heat flux sensors were installed in the external wall, the internal wall and the ceiling. With regards to the ceiling a second heat flux sensor was installed in September 2014 in order to investigate in detail the performance of the PCM. Next to each heat flux sensor, a T-type thermocouple was installed. A T-type thermocouple was also used to record the ambient temperature of the space. The data acquisition system used was a Fieldlogger 512K by Novus Automation.

The same equipment was used in the north bedroom; three HUKSEFLUX HFP01-05 heat flux sensors were installed on the surface of the external and internal wall surface and the ceiling, and three T-type thermocouples were installed to monitor the surface temperature, one thermocouple next to each heat flux sensor. A T-type thermocouple was used to monitor the ambient temperature in the room. All data were collected with a Fieldlogger 512K data acquisition system. The apparatus that was set to the ground floor of the BASF house is shown in Figure 6-6 below. The equipment installed on the first floor is shown in Figure 6-7.

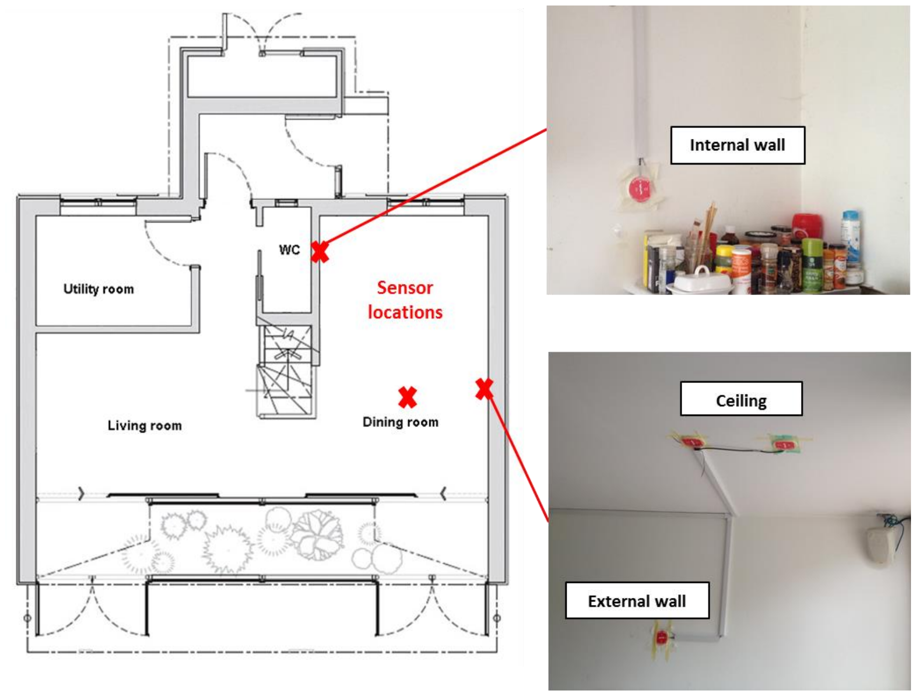


Figure 6-6: Location of sensors at the Ground Floor bedroom of the BASF house

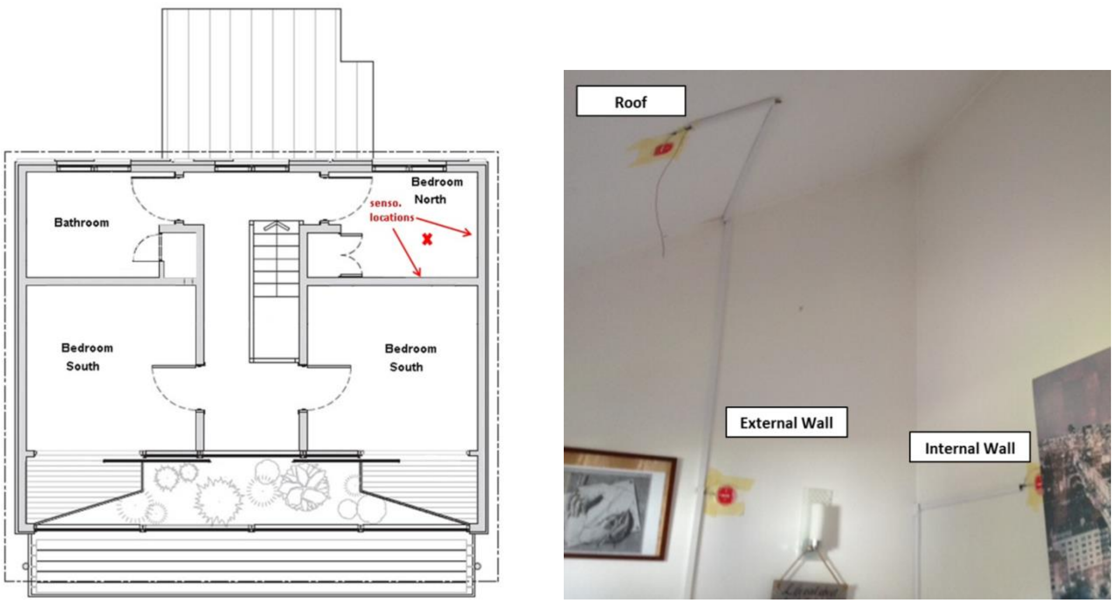


Figure 6-7: Location of sensors at the First Floor bedroom of the BASF house

6.2.3 The Mark Group House

The Mark Group House is a three-floor (including basement), four-bedroom detached house located at the Creative Energy Homes site. Originally designed as a house, it is now used as an office building for research staff and students of the Department of Architecture and Built Environment. The Mark Group house, originally called the Stoneguard C60 house out of the main sponsor, was the first house of the Creative Energy Homes to be designed and developed. However, due to financial problems of the main sponsor at the time, the project was stopped for a significant amount of time and finally completed in January 2014 with a new sponsor, Mark Group Ltd.

The house was designed by a team of the teaching and research staff at the Department of Architecture and Built Environment. The basement walls were constructed with Insulating Concrete Formwork (ICF) blocks provided by Logix and the ground floor and first floor walls were constructed with steel frame panels provided by Stoneguard Ltd. The external walls were finished with two different External Wall Insulation systems; Ibstock's Brick Shield system with brick slip finish and Wetherby's Epsiwall system with white silicone render finish. A group of undergraduate students took part in the construction of the building gaining valuable training experience and demonstrating that these construction methods can be easily applied without the need of excessive training.

The house was designed to achieve Level 6 of the Code for Sustainable Homes and to do so a number of energy saving design strategies and technologies were applied. Not surprisingly the same design philosophy of utilising increased levels of solar gains and high levels of fabric efficiency that was used in the other CEH houses was also considered at the development of the Mark Group House. The external walls have a U-value of 0.15 W/m^2K and the roof 0.12W/m^2K. Solar gains were maximised by providing south orientation through arrangement of the house on the east-west axis and the use of a sunspace in the south façade. The sunspace also facilitates the ventilation strategy of the house. With the use of openings located on the house interior preheated air may either be introduced in the house when required or, during the summer, hot air may be driven out of the sunspace through the roof windows. The sunspace also increased the levels of daylight inside the house by maximising the glazing areas.

A range of low carbon and energy efficient technologies were also employed to reach the high environmental standards required for achieving level 6 of CfSH. These include (Mark Group, 2013):

- Photovoltaic panels. 16 Sanyo HIT PV panels were installed in the roof with a nominal power of 3.84kWp

- Solar collectors. 18 Solar Lux evacuated tubes supplied by Worcester Bosch Group were installed to provide hot water fed to the heating system of the house and the domestic hot water system of the house.
- Air Source Heat Pump. The heating system is an 11kW Greensource split air to water heat pump provided by Worcester Bosch Group. The system also provides domestic hot water.
- The heating network of the house consists of an underfloor heating system, the Worcester Bosch Greenfloor system, on the basement ground floor and highly efficient radiators (Stelrad Radical) on the first floor.
- Heat Recovery System. A Duplexvent Heat Recovery unit by Airflow Developments Ltd was installed to provide mechanical ventilation with heat recovery is ensuring optimum air quality throughout the whole year.
- Sun Pipes. The house is fitted with sun pipes provided by Monodraught and supply natural daylight in rooms without windows and reduce the need for artificial lighting.
- Passivhaus Certified windows and energy efficient windows.
- Low Energy Lighting to further reduce the energy consumption of the house.
- Rainwater Harvesting. The Kingspan Water Envirau system has been installed to collect the rainwater and feed it to the toilets and the washing machine.
- Phase Change Material. The sunspace includes an internal balcony. The ground floor internal ceiling of the sunspace from that balcony is finished with the Knauf Comfortboard 23, a plasterboard which incorporates the BASF Micronal PCM.

In order to investigate the heat flows on the external wall, internal wall, internal ceiling and roof, two zones of the house were monitored. These were the sunspace and the east office on the first floor. The building elements investigated in the sunspace was the internal ceiling (where the PCM board was installed) and the internal wall. The roof and the external wall were examined in the first floor office. Detailed description on the used apparatus and the build-up of these elements is presented in the following sections

<u>Building systems</u>

The build-up of the systems examined in the sunspace and office of the Mark Goup House are presented house is presented in Table 6-5 and Table 6-6 respectively. The ground floor sunspace area monitored comprises a steel frame internal wall finished with plasterboard and a steel frame internal ceiling finished with PCM plasterboard. The external wall and the roof found at the office in the first floor were also of steel frame construction.

Table 6-5: Typical build-up of the construction elements found in the Mark Group House sunspace

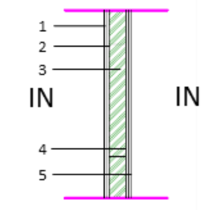
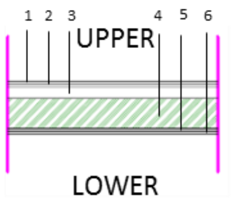
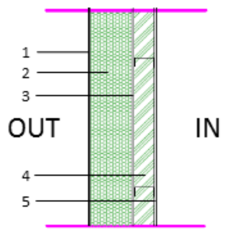
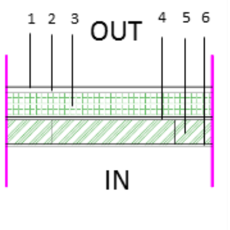
INTERNAL WALL		IN 1. 12.5mm plasterboard 2. 12.5mm cement particleboard 3. 90mm rockwool 4. 12.5mm cement particleboard 5. 12.5mm plasterboard IN	Admittance: 2.10 W/m²K U-value: 0.35 W/m²K Decrement factor: 0.85 Time lag: 3.53 hours κ-value: 32.50 kJ/m²K
INTERMEDIATE FLOOR		UPPER 1. 12mm carpet 2. 22mm plywood 3. 50mm air cavity 4. 140mm Rockwool 5. 12.5mm Cement Particle Board 6. 12.5mm PCM board LOWER	Admittance: 2.16 W/m²K U-value: 0.23 W/m²K Decrement factor: 0.88 Time lag: 3.50 hours κ-value: 32.50 kJ/m²K

Table 6-6: Typical build up of the construction elements found in the Mark Group House office

EXTERNAL WALL		OUT 1. 5mm rendering 2. 150mm Extruded Polystyrene 3. 12.5mm Cement Particleboard 4. 90mm Rockwool 5. 12.5mm Plasterboard IN	Admittance: 0.89 W/m²K U-value: 0.15 W/m²K Decrement factor: 0.29 Time lag: 7.29 hours κ-value: 10.00 kJ/m²K
EXTERNAL ROOF		OUT 1. Clay Roof tile 2. Roofing felt 3. 120mm PIR insulation 4. 12.5mm Cement Particle Board 5. 120mm Rockwool 6. 12.5mm Plasterboard IN	Admittance: 0.86 W/m²K U-value: 0.11 W/m²K Decrement factor: 0.24 Time lag: 7.10 hours κ-value: 10.00 kJ/m²K

Apparatus

As discussed earlier, monitoring equipment was set up in two zones of the Mark Group house due to the geometry of the building and the specific constructions installed in those zones.

In the ground floor sunspace area, the internal ceiling of the balcony and the internal wall were monitored. Initially a HUSKEFLUX HFP01 heat flux sensor was installed on the surface of the internal wall and the internal ceiling. A T-type thermocouple was also installed next to each heat flux sensor to monitor the surface temperature. As of September 2014, two additional HFP01 heat flux sensors were installed on each building element next to the initial heat flux sensors; one on the left and one on the right side. The additional heat flux sensors were used to achieve higher levels of accuracy through averaging the readings of all three sensors on each element and to validate the readings of the initial sensor or identify whether the initial sensor would require adjustment. A T-type thermocouple was monitoring the ambient temperature.

In the first floor office zone the external wall and the roof were monitored. Again, one HFP01 heat flux sensor was installed on the surface of the external wall and one on the roof. Next to each heat flux sensor, a T-type thermocouple was installed to monitor the surface temperature. A T-type thermocouple was also used to monitor the ambient temperature.

The location of the monitoring equipment in the two zones of the Mark Group house is presented in Figure 6-8

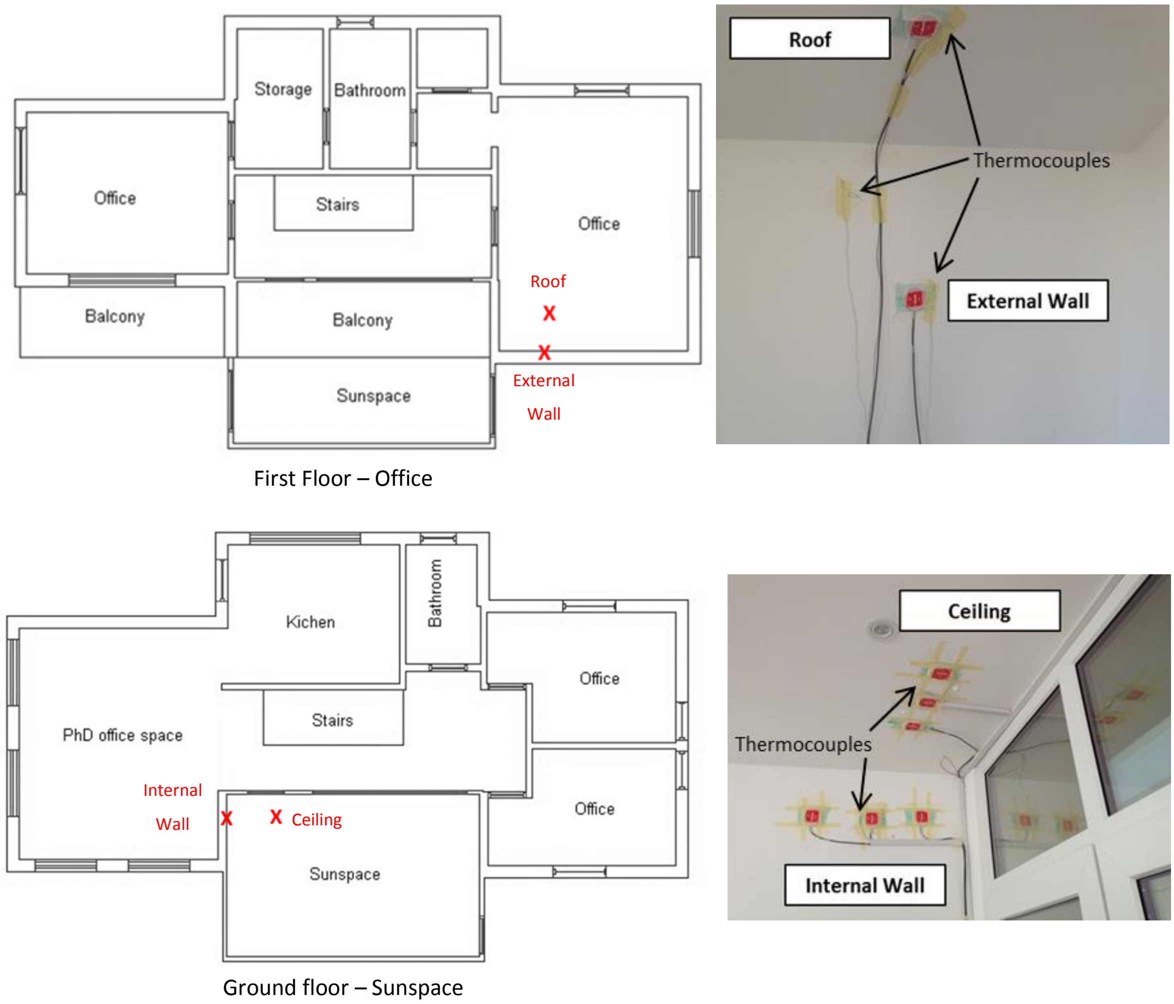


Figure 6-8: Location of sensors at the Ground Floor (sunspace) and the First Floor (office) of the Mark Group house

6.2.4 The Nottingham H.O.U.S.E.

The Nottingham H.O.U.S.E. design features and low-carbon technologies were described in detail in Chapter 4. Therefore, this information will not be repeated here. In order to assist the reader only the basic information on the house is presented in this section. If additional details are required the reader is advised to find these in Chapter 4.

The house is a two floor dwelling built with volumetric timber I-joist construction; it comprises eight modules. It was designed based on Passivhaus principles adopting a fabric first approach to achieve the stringent energy efficiency requirements. The design U-values of the main building elements were:

- External walls: 0.10W/m^{2}K
- Floor: 0.10W/m^{2}K
- Roof: approximately 0.075 W/m^{2}K

The house although originally designed as a dwelling, it is used as office building by member of staff at the Department of Architecture and Built Environment. The plans of the ground floor and first floor are presented in Figure 6-9.

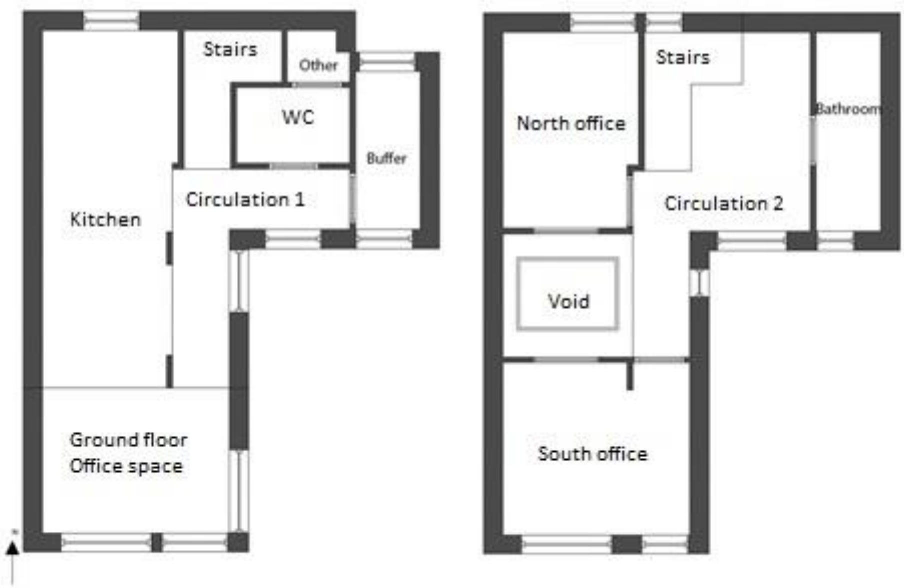


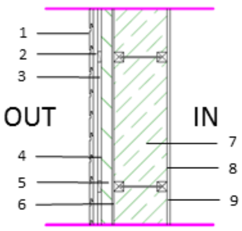
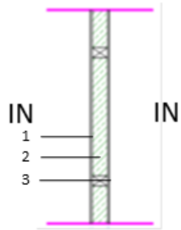
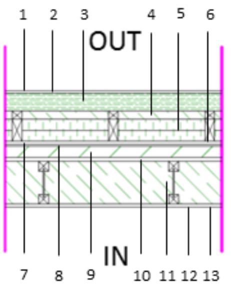
Figure 6-9: Plans of the ground floor (left) and the first floor (right) of the Nottingham H.O.U.S.E.

The south office zone on the first floor of the building was examined. The external wall, the internal wall and the ceiling of the office were monitored. Details on the construction of these elements and the apparatus are given in the following sections.

Building systems

The build-up of the systems monitored in the Nottingham H.O.U.S.E is presented in Table 6-7. The external wall and roof were built with timber I-joists and the internal partition was of timber stud construction.

Table 6-7: Typical build up of construction elements found in the office of the Nottingham H.O.U.S.E.

EXTERNAL WALL		OUT 1. 18 mm Thermowood cladding 2. 20x50 horizontal HW battens at 400 mm centres 3. 16x50 vertical SW battens at 600 mm centres 4. Breather membrane 5. 50 mm ISOVER RKL Façade insulation (glasswool) 6. 9 mm sheathing ply 7. 245 mm I joists infilled with insulation Isover Multimax 30 (fibreglass wool) 8. Vario airtight membrane 9. 12.5 mm Rigidur IN	Admittance: 0.82 W/m²K U-value: 0.10 W/m²k Decrement factor: 0.66 Time lag: 5.45 hours κ-value: 10.00 kJ/m²K
INTERNAL WALL		OUT 1. 10 mm plasterboard 2. 72 mm insulation 3. 10 mm plasterboard IN	Admittance: 0.78 W/m²K U-value: 0.25 W/m²k Decrement factor: 0.98 Time lag: 1.27 hours κ-value: 10.00 kJ/m²K
EXTERNAL ROOF		OUT 1. Sarnafill roofing membrane 2. 12 mm ply 3. 80 mm Hofatex sarking board 4. Glass fibre insulation installed (average 37.5 mm) 5. 100 mm (2x50) rigid insulation batts 6. 12mm ply 7. Roof membrane 8. 10 mm ply 9. 50 mm insulation Isover Roofine P35 (glasswool) 10. 15 mm ply 11. 195 mm I joists in filled with insulation Isover Multimax 30 (fibreglass wool) 12. Vario airtight membrane 13. 15 mm Rigidur IN	Admittance: 0.94 W/m²k U-value: 0.07 Decrement factor: 0.05 Time lag: 16.43 hours κ-value: 12.00 kJ/m²K

Apparatus

Similar to the apparatus set in the other houses, the equipment set in the Nottingham H.O.U.S.E. included the use of a HUKSEFLUX HFP01 heat flux sensor and a T-type thermocouple at the surface of each element to measure the density of heat flow and temperature at that surface. In addition, a T-type thermocouple was also used to measure the ambient temperature. In total three heat flux sensors and four thermocouples were used to monitor the external wall, internal wall and roof and the room temperature. The data acquisition system was a Squirell SQ800. The location of the monitoring sensors and the installed equipment is shown in Figure 6-10.

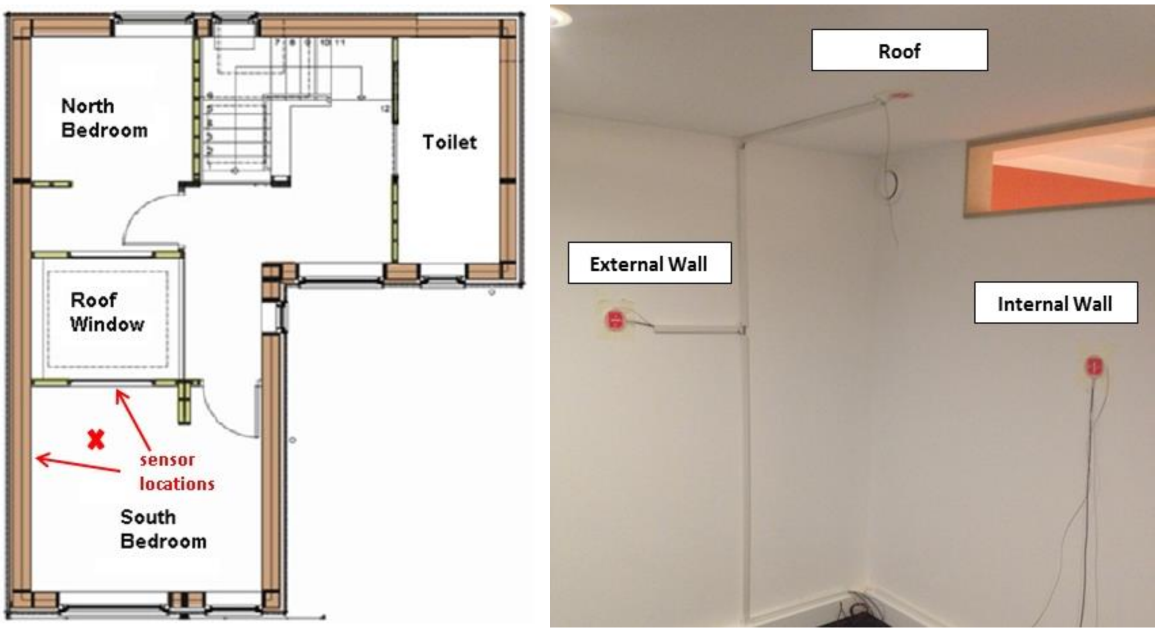


Figure 6-10: Location of sensors in the Nottingham H.O.U.S.E. (office)

6.3 Summary

The need for in-situ data reporting on the performance of MMC systems has been highlighted (Rodrigues, 2009). The present and the following chapters report on the findings of a monitoring study conducted to investigate the thermal performance of a range of MMC and modern masonry building systems. These systems were building elements found in the houses of the Creative Energy Homes Development, at the University of Nottingham. In summary the following types of external wall construction were examined:

- Modern solid wall construction
- Modern brick and block cavity wall
- Insulating Concrete Formwork (ICF)
- Structural Insulated Panels (SIPs)
- Timber frame construction
- Steel frame construction

In addition, a range of building solutions for internal partitions and ceilings were also examined. The aim of the present chapter was to provide the context to the reader; detailed description of each construction element build-up was provided along with the design features of the houses and the active and passive systems used to achieve the low emissions targets. There is a wide diversity of design features and construction methods that provide the setting of this study and therefore it was deemed necessary to present this information so that the reader would familiarise with the conditions met in each house and the available constructions. The methodology for the analysis of the monitored data, the results and the findings of the study are presented in the following chapter.

CHAPTER 7. THE CREATIVE ENERGY HOMES PERFORMANCE

In Chapter 5 it was demonstrated that monitoring the zone temperatures in a building was not adequate to lead to a conclusive result regarding the ability of the constructions to reduce the occurrence of elevated temperatures. The analysis of the recorded temperatures in the two dwellings showed that the differences in the design and occupancy and building use were also affecting the indoor conditions and did not allow for clear conclusions regarding the effect of the construction method on the indoor conditions. It was suggested that the next logical step would be to monitor the heat flows occurring in the construction components.

In addition, the need for investigating the actual performance of MMC systems under real operative conditions was also highlighted by Rodrigues (2009). Rodrigues (2009) evaluated the relative performance of walls built with different MMC with the use of dynamic simulations. The simulation analysis although provided several insights on the performance of the systems, it was suggested that investigating their performance in situ was required to verify the results.

While there have been a number of studies reporting on the in-situ heat flows on building elements, these have been focusing on determining the as-built thermal transmittance. Thus far, to the best knowledge of the author, there have been no long-term studies reporting on the dynamic thermal performance of construction components with respect to their interaction with the internal environment under real operating conditions. The value of the work presented in this chapter is demonstrated by the following characteristics of the study which make the results a unique contribution to the science of building performance:

- Long-term monitoring. Duration of the monitoring period ranged for a minimum of 12 months in some houses up to 18 months in others
- Simultaneous monitoring of a wide range of building systems. In total, 19 different building components were studied. The common period for all the systems was at least 12 months allowing the evaluation of the annual performance under the same weather conditions.

The description of the systems and the houses that were monitored in this study was given in the previous chapter. In order to assist the reader a summary of the building elements examined, the relevant construction type and the zone where each construction is found is given in Table 7-1. In the present chapter, the methodology of the study and the analysis of the monitored data are presented. The main findings are discussed along with the limitations of the analysis which in turn lead to specific suggestion for further work.

Table 7-1: Summary of building elements examined

House	Zone	Element	Construction Type
Tarmac – Code 4 House	Living Room	External Wall	Brick and block cavity
		Internal Wall	Timber frame partition
		Internal ceiling	Timber I-joist floor
Tarmac – Code 6 House	Living Room	External Wall	Solid wall
		Internal Wall	Timber frame partition
		Internal ceiling	Hollowcore concrete
BASF House	Kitchen – Dining	External Wall	Insulating Concrete Formwork
		Internal Wall	Block partition
		Internal ceiling	Timber I-joist with PCM
BASF House	Bedroom	External Wall	Structural Insulated Panels
		Internal Wall	Timber frame partition
		Roof	Structural Insulated Panels
Nottingham H.O.U.S.E.	Office	External Wall	Timber I-joist
		Internal Wall	Timber frame partition
		Roof	Timber I-joist
Mark Group House	Sunspace	Internal Wall	Steel Frame
		Internal ceiling	Steel frame with PCM
Mark Group House	Office	External Wall	Steel frame
		Roof	Steel frame

7.1 Aim and objectives

The work presented in this chapter aimed at investigating the thermal performance of building elements built with different Modern Methods of Construction in situ under normal operating conditions. The main objectives of the study were:

- to monitor and assess the zone temperatures experienced by the users;

- to monitor and evaluate the heat flows at the building elements examined and compare the relative performance of building elements in the same zones; and
- to assess the in-situ thermal performance of systems with components incorporating PCM. There is a growing body of research in the field of PCMs, however there are no studies reporting on the performance of these systems under actual operating conditions

7.2 Methodology

In each house monitoring equipment in selected zones was installed in order to record the ambient temperature as well as the heat flows and surface temperature on specific building elements. The building elements examined as well as the respective constructions are summarised in Table 7-1. The apparatus set in each zone is presented in detail in Chapter 6. A brief description of the process is presented here to assist the reader.

A HUKSEFLUX HFP01 heat flux sensor was installed at the surface of the external wall, the internal wall and the ceiling (internal or external depending on the zone). Next to each heat flux sensor, a T-type thermocouple was installed to monitor the surface temperature of the respective building element as well as the air temperature in each zone. Monitoring rate was set to 15 minutes. Acquired data were then post-processed to hourly values. The results are presented as follows:

- First the zone temperatures are presented so that the reader will gain an understanding of the temperature conditions prevalent in each zone.
- Then the heat flows on the surface of the constructions are investigated. This is performed by assessing a) the net average daily heat flow for each element per month and b) the average daily amount of energy absorbed and released by the wall per month, with a focus on the summer months.

With regards to the equipment specifications the HUKSEFLUX HFP01-05 heat flux sensors have a measurement range from -2000 W/m^2 to +2000 W/m^2 and typical accuracy for wall applications ±5%. The T-type thermocouples have reading range -200^{o}C to +350^{o}C with an accuracy of ±0.5^{o}C. The associated uncertainty was expressed with the respective error bars on the graphs .

7.3 Results

The results of the analysis are presented separately for each zone in the following paragraphs. The monitoring period of the different zones varied from 12 to 18 months, with a common period of 12 months were all zones were monitored simultaneously. In total, the performance of 19 constructions was investigated.

7.3.1 Tarmac Code 4 house

The living room zone of the Tarmac Code 4 house was monitored for a period of 18 months, from July 2013 to December 2014. The constructions monitored were a brick and block cavity external wall, timber frame internal wall and timber I-joist ceiling. The temperatures experienced during that period are presented in Figure 7-1.

The temperatures in the living room were found to be stable in general over the whole monitoring period. During the heating period the ambient temperature was fluctuating around a set point of approximately 23°C while over the cooling periods (July – August 2013 and June – August 2014) the temperatures did not exceed the 25°C comfort limit for long periods of time. Table 7-2 presents the mean daily maximum, minimum and average temperature per month as well as the mean daily temperature fluctuation of the ambient temperature. The mean daily average temperatures ranged from 18.75°C to 25.09°C and the mean maximum temperature was between 19.49°C and 26.07°C over the period July 2013 – December 2014. Over the summer months the mean daily temperature fluctuation ranged from 1.49°C to 2.19°C.

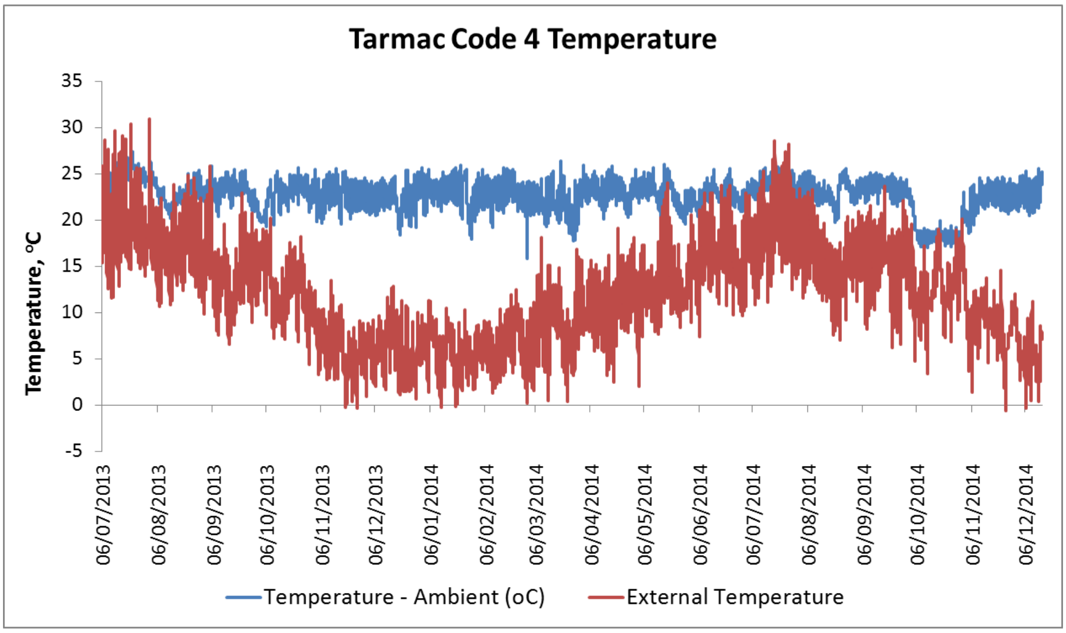


Figure 7-1: Temperature profile in the diner-living room zone in the Tarmac Code 4 house

Table 7-2: Mean maximum, minimum and average temperature and mean temperature fluctuation per month on a daily basis in Tarmac Code 4

Month	Average Ambient Temperature	Maximum Ambient	Minimum Ambient Temperature	Temperature Fluctuation
Jul-13	25.09	26.07	24.14	1.93
Aug-13	22.94	23.75	22.26	1.49
Sep-13	23.22	24.21	22.29	1.92
Oct-13	22.61	23.62	21.56	2.05
Nov-13	22.89	24.42	21.03	3.39
Dec-13	22.52	23.92	20.85	3.07
Jan-14	23.17	24.50	21.55	2.95
Feb-14	23.16	24.49	21.25	3.24
Mar-14	21.93	23.74	19.98	3.76
Apr-14	23.28	24.51	21.83	2.68
May-14	22.96	23.97	21.88	2.10
Jun-14	22.58	23.63	21.59	2.04
Jul-14	23.88	24.99	22.86	2.14
Aug-14	23.07	24.07	22.05	2.02
Sep-14	23.46	24.50	22.40	2.10
Oct-14	18.75	19.49	18.09	1.40
Nov-14	22.40	23.64	20.83	2.81
Dec-14	23.22	24.48	21.38	3.10

The heat flows and surface temperature in each building component were recorded according to the methodology described in paragraph 7.2 and were averaged to hourly and daily values. The daily average heat flow occurring in each building element per month along with the average daily ambient temperature and external temperature recorded is presented in Figure 7-2.

The heat balance (net daily heat flux) is consistently positive in almost all elements; in physical terms this has the meaning of heat entering the building element. Therefore, it can be concluded that on average all three elements absorbed heat from the zone during the period of study. It is apparent that the heat flow on the external wall is driven by the temperature difference between the ambient temperature and the external temperature; the larger the temperature difference the larger the amount of heat entering the surface of the external wall. With regards to the performance of the internal wall and the ceiling it can be seen that the internal wall is absorbing significantly more heat from internal space than the ceiling.

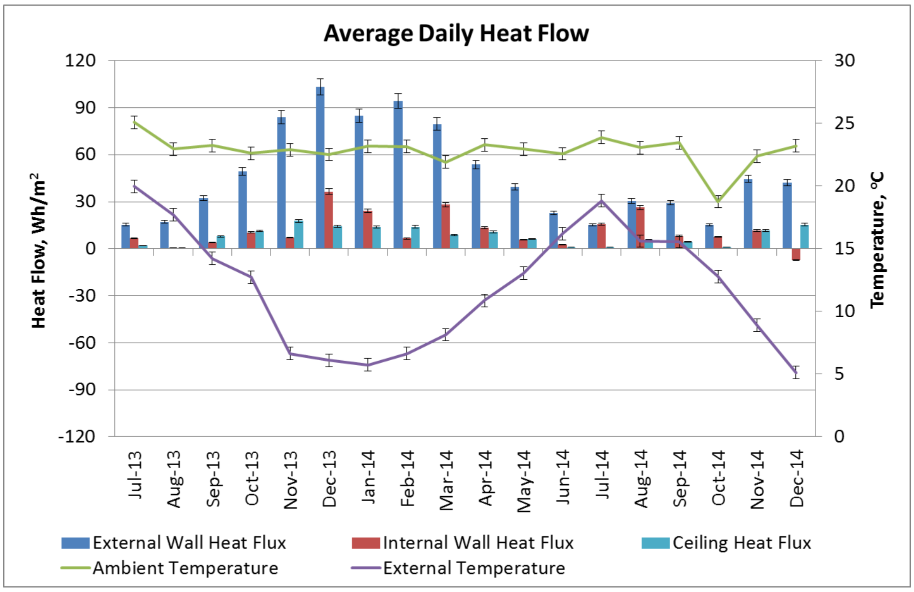
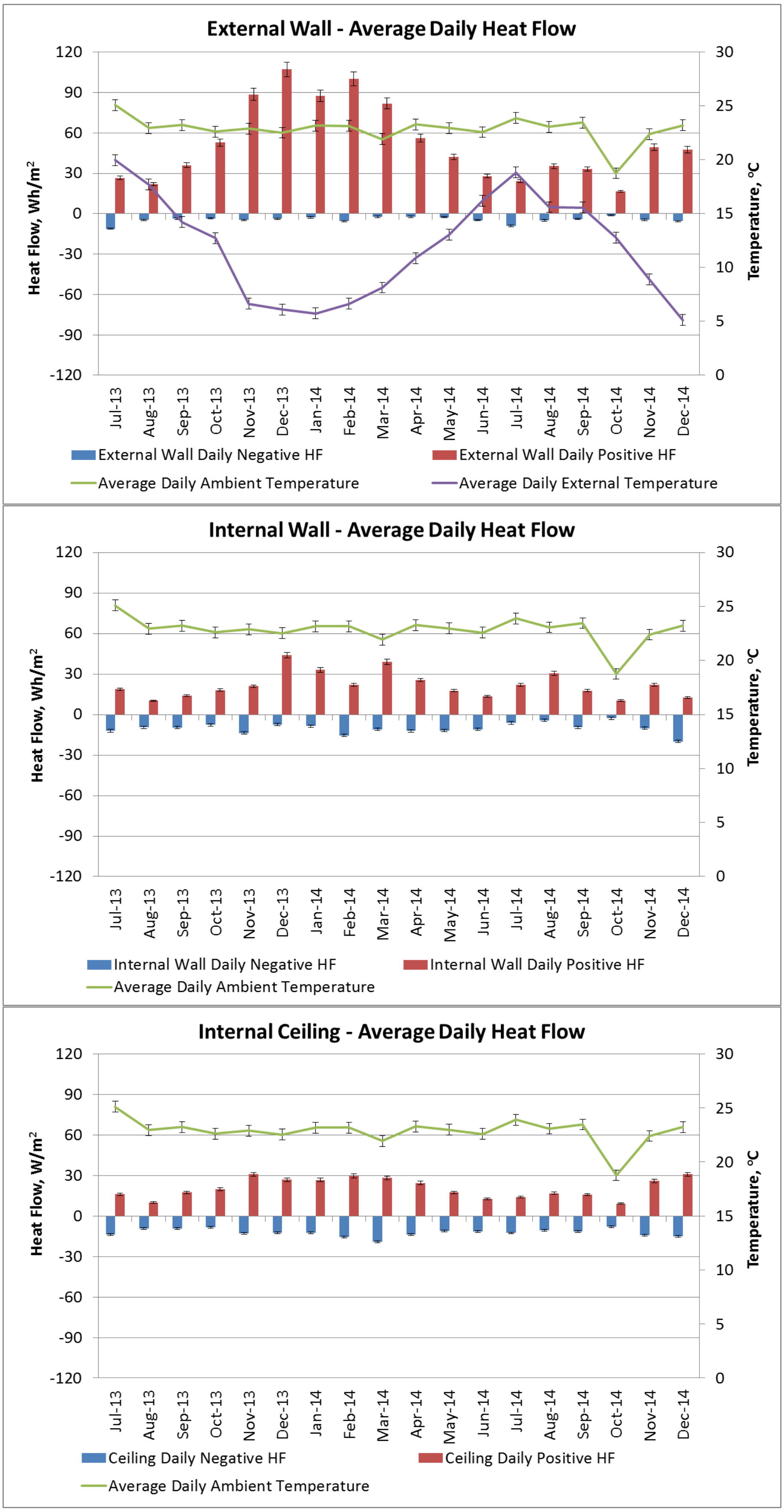


Figure 7-2: Average daily values of heat flows and ambient and external temperature for the Tarmac Code 4 house

While conclusions on whether heat is absorbed or released by in each building element on a daily basis can be derived by analysing the average heat balance, little information is provided on the response of these elements to the temperature excitation and the interaction with the surrounding environment. In order to determine the amount of heat that is being absorbed by the space (positive heat flow) and released back to the space (negative heat flow). Figure 7-3 presents the average daily heat flows in each direction of the surface of the three elements.

With regards to the external wall it can be seen that the heat flows are predominantly entering the wall surface, with only a minor proportion of heat being released back to the zone. During the summer months (July and August 2013 and June to August 2014) the amount of heat absorbed by the masonry cavity wall was 27.17 ± 1.36 Wh/m^2 on a daily basis. At the same period, the amount of heat released to space was found to be 6.94 ± 0.35 Wh/m^2 per day.

Heat flow on the surface of the internal wall and ceiling is significantly different than that of the external wall since it is not driven by the external temperature. On average during summer the timber frame internal wall (Y = 1.16W/m^{2}K, κ = 15.90kJ/m^{2}K) absorbed each day 18.99 ± 0.95 Wh/m^2 and released to space 8.63 ± 0.43 Wh/m^2. Finally, the timber joist ceiling (Y = 1.38 W/m^{2}K, κ = 8.75kJ/m^{2}K) absorbed 13.82 ± 0.69 Wh/m^2 and released back 11.72 ± 0.59 Wh/m^2 on a daily basis during the cooling periods of 2013 and 2014.



a

b

c

Figure 7-3: Average daily heat flux absorbed and released by the (a) external wall, (b) internal wall and (c) internal ceiling in the Tarmac Code 4 living room zone

7.3.2 Tarmac Code 6 house

In the Tarmac Code 6 house the living room zone was also monitored from July 2013 to December 2014. The constructions examined were the solid block external wall, timber frame internal wall and hollowcore concrete ceiling.

The temperature profile of that zone over the whole period is presented in Figure 7-4. The zone temperatures appeared to have very small diurnal variations and highlighted periods when the occupants were away from the house (December 2013 - January 2014). During the heating period, there can be seen large variations in the temperature profile, suggesting the use of portable heaters. This was confirmed by the occupants. During the summer periods again the temperatures did not exceed the 25^{o}C threshold for long periods of time.

The mean daily average, maximum and minimum temperatures and temperature fluctuation per month are presented in Table 7-3. It can be seen that the daily temperature fluctuation over the summer months did not exceed 1.38^{o}C on average. The mean average daily temperature was between 20.45^{o}C and 24.69^{o}C over the 18 month monitoring period. The respective maximum daily temperature was between 21^{o}C and 25.7^{o}C.

The average daily heat flows occurring on the surface of the external wall (solid), internal wall (timber frame) and ceiling (hollowcore concrete) are presented in Figure 7-5. It can be seen that similarly to the masonry cavity wall found in the Tarmac Code 4 house, the average daily heat balance of the solid wall was consistently positive. This was expected as the external wall heat flow is driven by the difference between the ambient temperature and the external temperature. As the temperature difference increases, the heat flow entering the surface of the solid wall is also increasing. The heat balance of the internal wall and ceiling on the other hand appeared to be variating on a monthly basis; absorbing heat during some months and releasing heat to space during others.

The average daily heat flows entering and exiting the surfaces of these elements are presented in Figure 7-6. Heat flows on the surface of the solid wall (Y= 1.78W/m^{2}K, κ = 47.82kJ/m^{2}K) are predominantly entering the wall surface with only minor amounts of heat being released to space during the months May-September 2014. The average amount of heat entering the wall surface during the summer months was 20.68 ± 1.03 Wh/m^2 per day. During the same period only 1.02 ± 0.05 Wh/m^2 were transmitted from the wall to the zone.

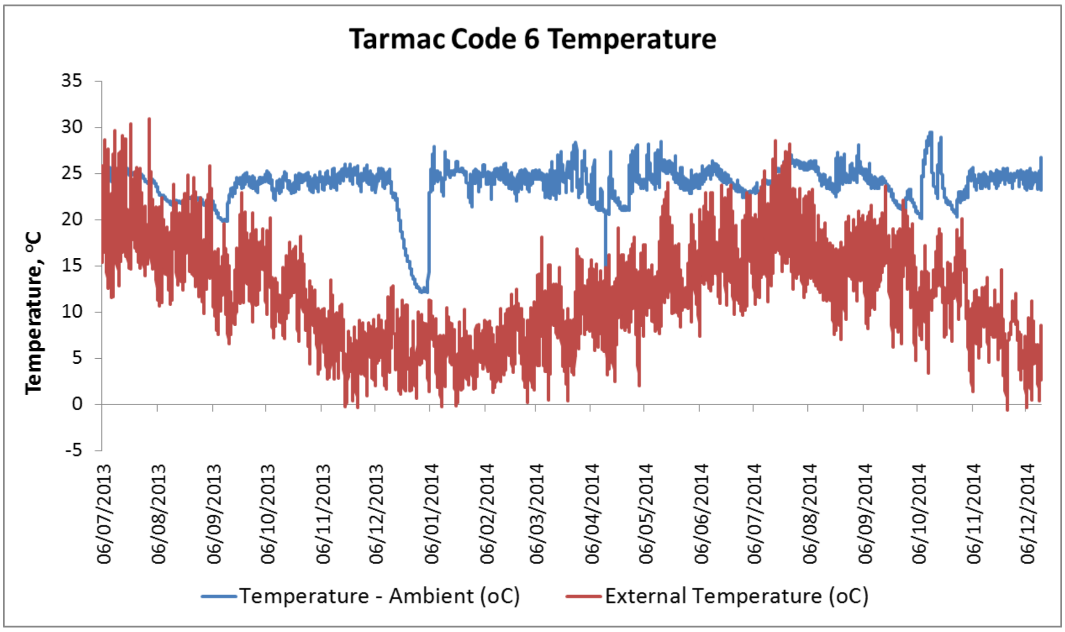


Figure 7-4: Temperature profile in the diner-living room zone in the Tarmac Code 6 house

Table 7-3: Mean maximum, minimum and average temperature and mean temperature fluctuation per month on a daily basis in Tarmac Code 6

Month	Average Ambient Temperature	Maximum Ambient	Minimum Ambient Temperature	Temperature Fluctuation
Jul-13	24.69	25.00	24.46	0.54
Aug-13	22.48	22.62	22.35	0.27
Sep-13	22.39	22.85	22.13	0.72
Oct-13	23.91	24.53	23.50	1.04
Nov-13	24.40	25.16	23.93	1.23
Dec-13	20.45	21.00	19.98	1.02
Jan-14	22.89	23.79	22.22	1.57
Feb-14	24.33	25.26	23.76	1.49
Mar-14	24.43	25.70	23.69	2.01
Apr-14	22.53	23.74	21.61	2.13
May-14	24.67	25.97	24.10	1.87
Jun-14	24.25	24.94	23.87	1.07
Jul-14	24.43	24.80	24.20	0.61
Aug-14	24.74	25.68	24.30	1.38
Sep-14	23.55	24.15	23.19	0.96
Oct-14	23.48	24.18	22.89	1.29
Nov-14	24.31	24.95	23.77	1.17
Dec-14	24.47	25.30	23.78	1.53

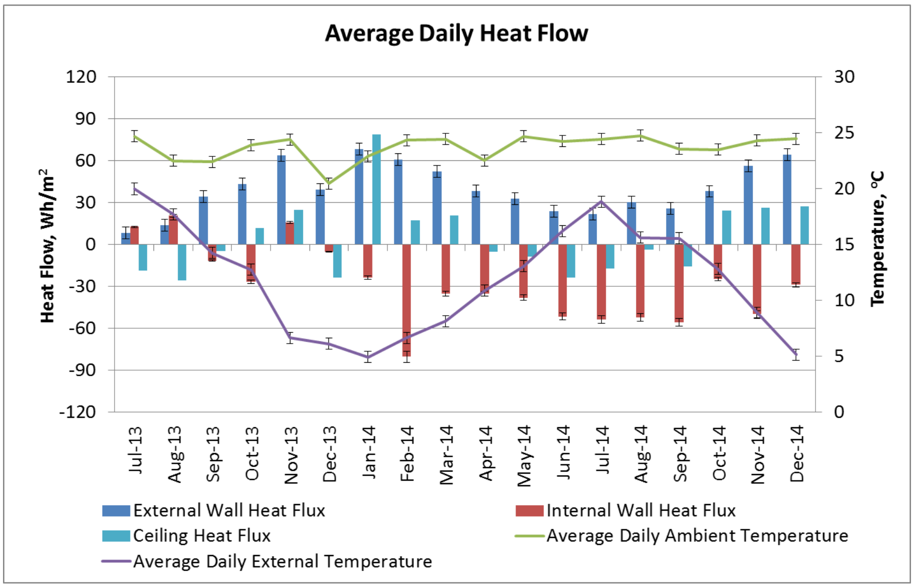
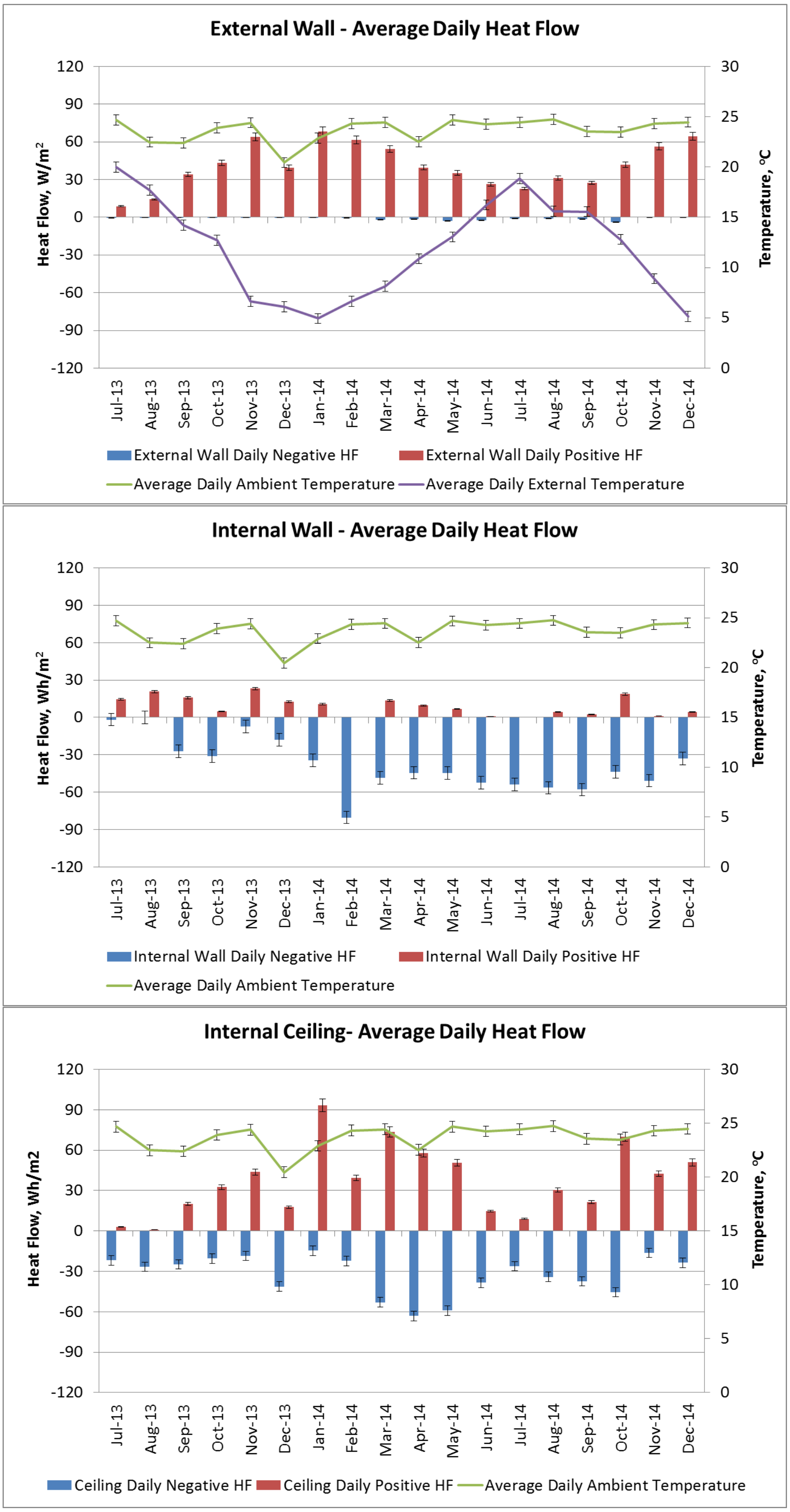


Figure 7-5: Average daily values of heat flows and ambient and external temperature for the Tarmac Code 6 house

The situation is significantly different in the case of the internal wall and the ceiling. The internal wall (Y= 1.16W/m^{2}K, κ = 15.90kJ/m^{2}K) heat flow profile suggests that for the most of the time heat is transmitted from the wall to the conditioned space. On average 8.05 ± 0.40 Wh/m^2 are being absorbed and 32.89 ± 1.64 Wh/m^2 are being released from the wall to space on a daily basis during the summer months of 2013 and 2014. However, it is of particular interest that the performance of the wall during the period July – August 2013 is the opposite of that during the period June – August 2014.

This highlighted one of the limitations of study. As the heat flows in the internal wall and the ceiling are affected by the ambient temperature of the zone examined and the adjacent zone, it would be useful to monitor the conditions in the adjacent zones as well. However, this was not possible since it would require a great degree of intervention to the buildings as the sensors would have to travel through the internal walls and intermediate floors in order to reach these zones.

The ceiling (Y= 3.05W/m^{2}K, κ = 72.53kJ/m^{2}K) heat flows appear to be balanced between the two directions of its surface. The ceiling appears to be quite responsive to the temperature excitation, absorbing heat and subsequently releasing it back to space. During the summer months, the amount of heat being released is about three times the amount of heat being absorbed; 11.58 ± 0.58 Wh/m^2 were absorbed and 29.44 ± 1.47 Wh/m^2 were released to space on a daily average. Again, the use of additional equipment in the zone above would provide useful information to the analysis.



a

b

c

Figure 7-6: Average daily heat flux absorbed and released by the (a) external wall, (b) internal wall and (c) internal ceiling in the Tarmac Code 4 living room zone

7.3.3 BASF house

Two zones were monitored in the BASF house, the kitchen-dining area in the ground floor and the north bedroom in the first floor. In the kitchen-dining area the constructions that were investigated were an ICF external wall, block partition wall and timber I-joist internal ceiling finished with PCM.

In the bedroom the constructions examined were the SIP external wall, timber frame partition wall and SIP roof. The results from the study are presented below.

<u>Kitchen – Dining Area</u>

The kitchen-dining room of the BASF house was monitored from November 2013 to January 2015. The temperatures in that zone are presented in Figure 7-7. During the heating period, the temperature fluctuated around a set temperature of approximately 20°C. During the months June – August 2014, the temperatures in the zone did not exceed the comfort threshold of 25°C for long periods of time. The mean average daily temperature was from 18.62°C to 22.87°C, while the respective mean maximum temperature ranged from 20.86°C to 25.00°C. The mean temperature fluctuation over the summer 2014 was between 2.88°C and 4.21°C (Table 7-4).

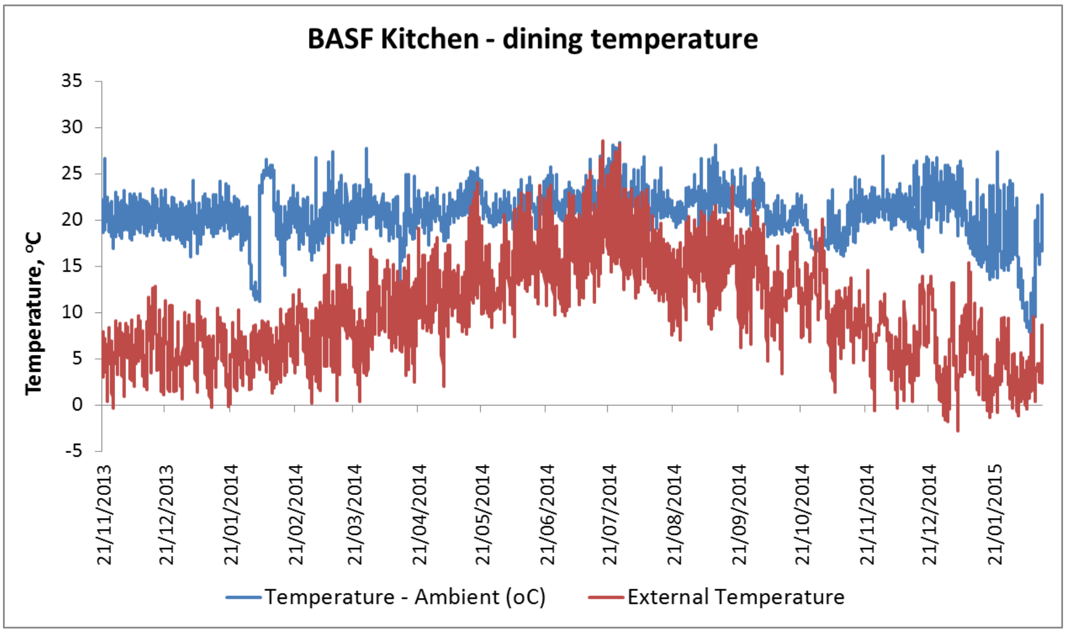


Figure 7-7: Temperature profile in the kitchen-dining room zone of the BASF house

Table 7-4: Mean maximum, minimum and average temperature and mean temperature fluctuation per month on a daily basis in the kitchen zone of the BASF house

Month	Average Ambient Temperature	Maximum Ambient	Minimum Ambient Temperature	Temperature Fluctuation
Nov-13	20.34	22.48	18.47	4.01
Dec-13	20.30	22.15	18.46	3.69
Jan-14	20.03	21.89	18.04	3.85
Feb-14	20.02	21.85	18.34	3.51
Mar-14	20.74	23.27	18.85	4.42
Apr-14	20.23	22.10	18.53	3.56
May-14	21.35	22.77	20.17	2.59
Jun-14	21.59	23.08	20.20	2.88
Jul-14	22.87	25.00	20.79	4.21
Aug-14	21.66	23.37	20.31	3.06
Sep-14	22.42	24.39	20.89	3.50
Oct-14	19.62	20.86	18.80	2.05
Nov-14	19.97	22.01	18.60	3.41
Dec-14	21.76	24.24	19.77	4.47
Jan – 15	18.62	22.57	16.51	6.06

The net heat flows on the external and internal wall and the ceiling are presented in Figure 7-8. The external wall is consistently absorbing heat due to the fact that the main driver of heat transfer is the difference between the zone ambient temperature and the external temperature. With regards to the internal wall, the heat balance is positive for most of the time suggesting that it acts as a heat sink for the zone for that period. The ceiling net heat flux is varying; the ceiling appears to absorb heat on certain months and release heat back to space at other months. The average daily heat flows in each direction for each component are presented in Figure 7-9 below.

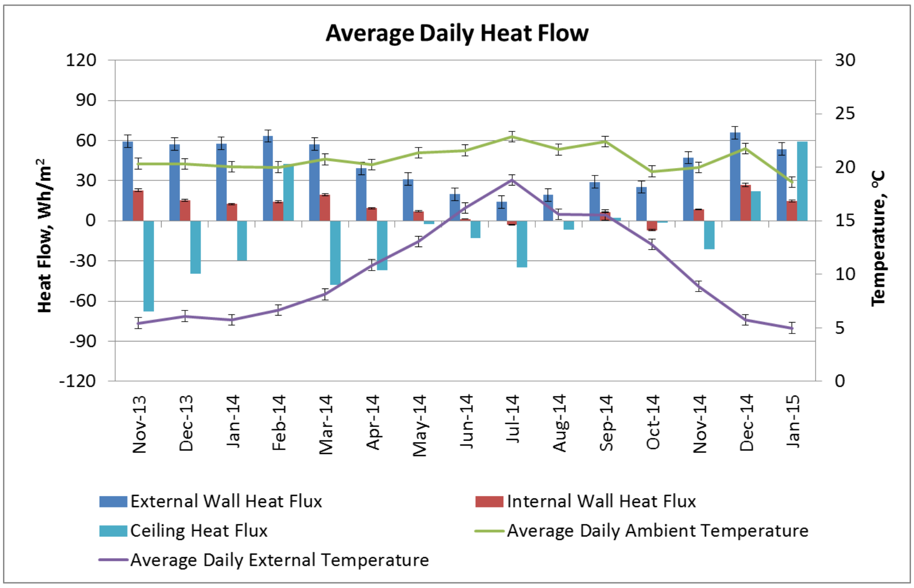
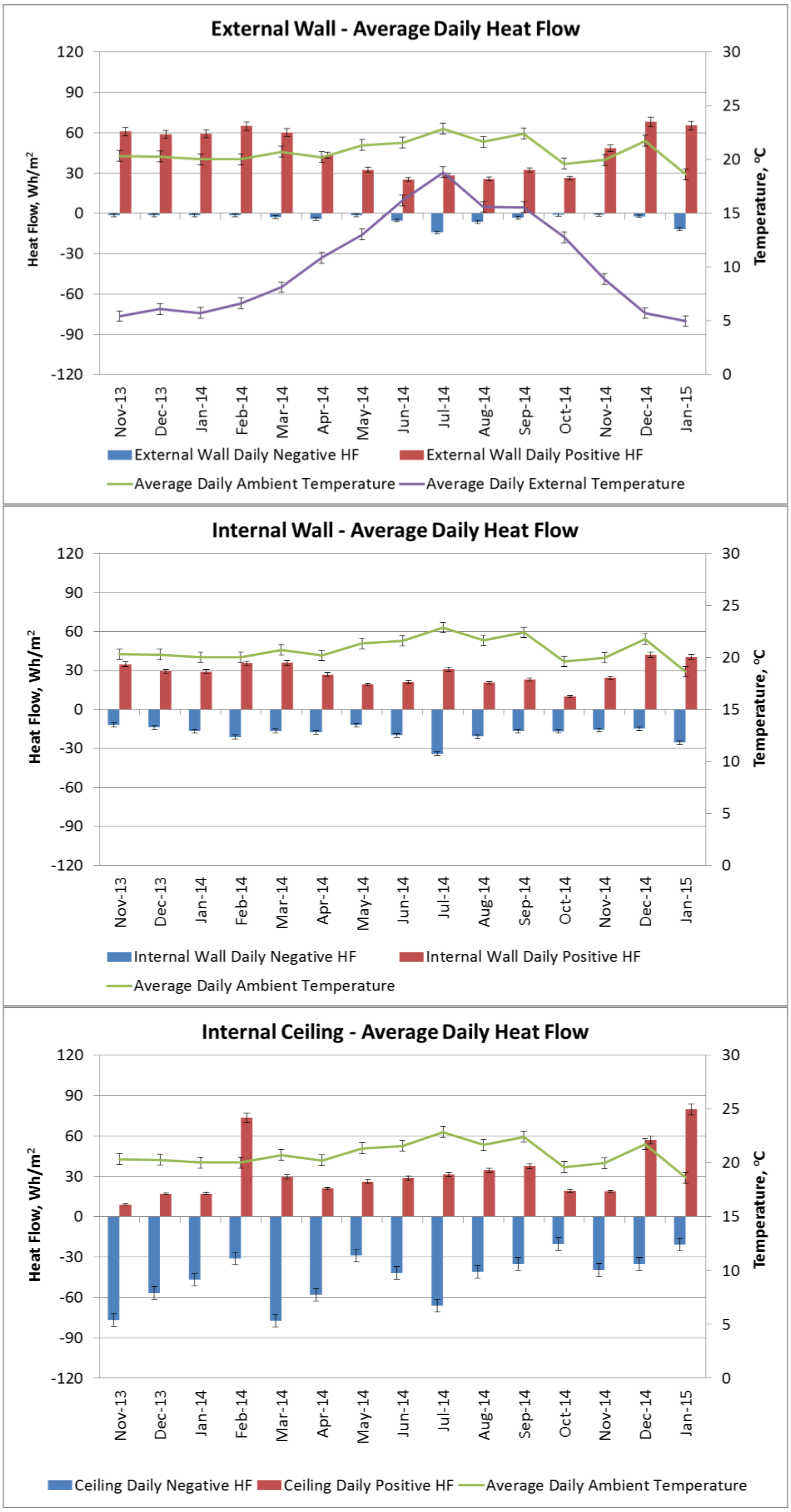


Figure 7-8: Average daily values of heat flows and ambient and external temperature for the BASF house kitchen-dining area



a

b

c

Figure 7-9: Average daily heat flux absorbed and released by the (a) external wall, (b) internal wall and (c) internal ceiling in the BASF kitchen-dining zone

Heat flows on the ICF external wall (Y= $0.81 W/m^2K$, κ = $10.00 kJ/m^2K$) are predominantly entering the wall surface. Only during the summer months, small amounts of heat are being released back to space. On average during the months June – August 2014 the external wall absorbed on a daily basis 26.40 ± 1.32 Wh/m^2 and released to space 8.62 ± 0.43 Wh/m^2.

The heat flows occurring at the surface of the internal wall (Y= $1.77 W/m^2K$, κ = $41.50 kJ/m^2K$) are significantly different. On a daily basis, heat is being transferred in both directions of the wall surface, entering and exiting the wall surface. The amount of heat absorbed by the internal wall was on average 24.26 ± 1.21 Wh/m^2 and the amount of heat released back to space was 24.90 ± 1.24 Wh/m^2 during the 2014 summer.

The ceiling was finished internally with plasterboard and behind the Smartboard with Micronal PCM was installed in order to add additional levels of thermal inertia in the zone. The ceiling appears to be the component with the largest degree of interaction to the interior space. During the summer months, the ceiling absorbed on average 31.56 ± 1.58 Wh/m^2K and released 49.66 ± 2.48 Wh/m^2 per day. Again, the need for monitoring the adjacent spaces to the internal wall and ceiling in order to identify potential is highlighted. The performance of the ceiling is examined in detail at the following section.

<u>Bedroom</u>

The bedroom zone of the BASF house was monitored from November 2013 to January 2015. The monitored temperatures during the period of study are presented in Figure 7-10. During the summer months, the temperature in the bedroom exceeded the 23°C comfort limit but it did not exceed the 26°C overheating threshold. The mean average daily temperature varied from 18.76°C to 23.31°C while the mean maximum daily temperature varied between 21.15°C and 24.37°C. The mean diurnal fluctuation during the summer months was from 1.43°C to 2.01°C (Table 7-5).

The net average daily heat flows for the external wall, the internal wall and the roof are presented in Figure 7-11 below. It is apparent that the heat flows at the roof and the external wall are consistently at the positive direction. This was in accordance with all the other external envelope components examined. It can also be seen that the net amount of heat entering the surface of the roof panel is significantly higher than the amount of heat entering the external wall surface, approximately 50% in winter months. Net heat flows on the surface of the internal wall are on either direction, suggesting that the internal wall contributes at removing heat from during some periods and adding heat during other periods. The average daily positive and negative heat flux for each building element is presented in Figure 7-12.

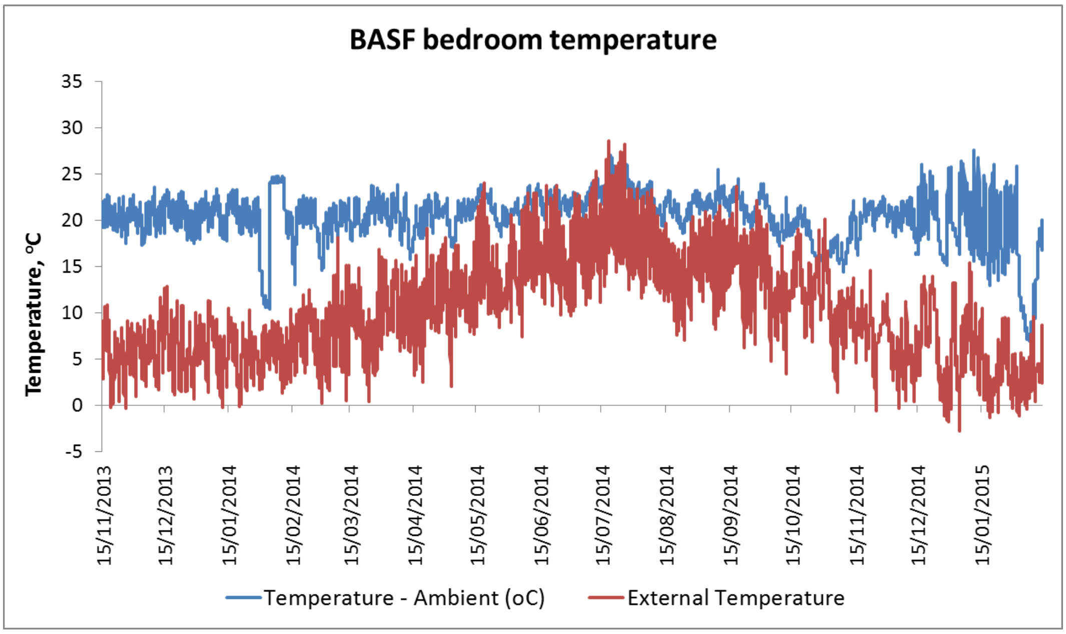


Figure 7-10: Temperature profile in the bedroom zone of the BASF house

Table 7-5: Mean maximum, minimum and average temperature and mean temperature fluctuation per month on a daily basis in the bedroom of the BASF house

Month	Average Ambient Temperature	Maximum Ambient	Minimum Ambient Temperature	Temperature Fluctuation
Nov-13	20.62	21.92	19.13	2.79
Dec-13	20.46	21.91	18.92	2.99
Jan-14	20.41	21.85	18.92	2.92
Feb-14	19.73	21.15	18.51	2.64
Mar-14	20.09	21.40	18.89	2.52
Apr-14	20.19	21.43	19.08	2.36
May-14	20.70	21.55	20.04	1.51
Jun-14	21.68	22.48	21.05	1.43
Jul-14	23.31	24.37	22.36	2.01
Aug-14	21.42	22.30	20.73	1.57
Sep-14	21.66	22.60	21.03	1.58
Oct-14	18.86	19.68	18.29	1.38
Nov-14	18.93	19.77	18.11	1.65
Dec-14	19.92	22.08	18.61	3.47
Jan – 15	18.76	23.17	16.43	6.74

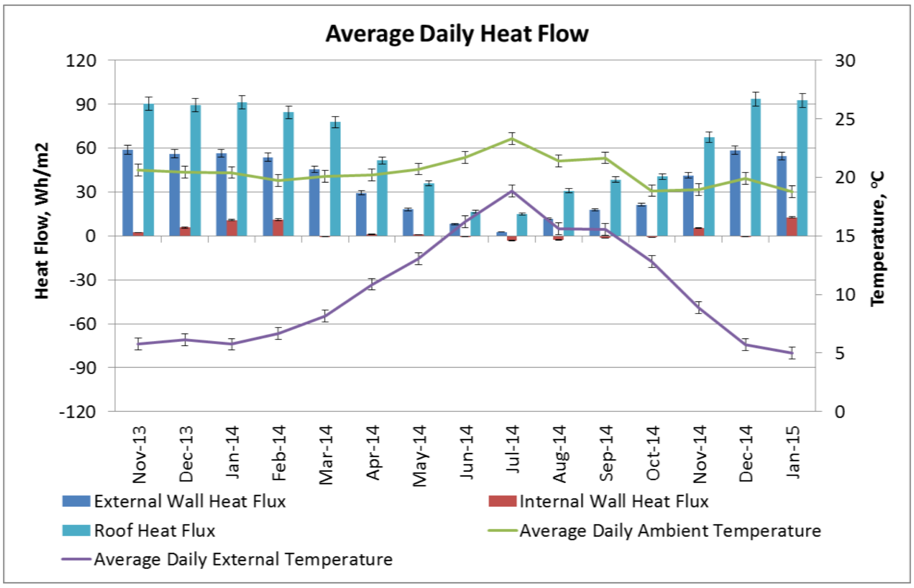
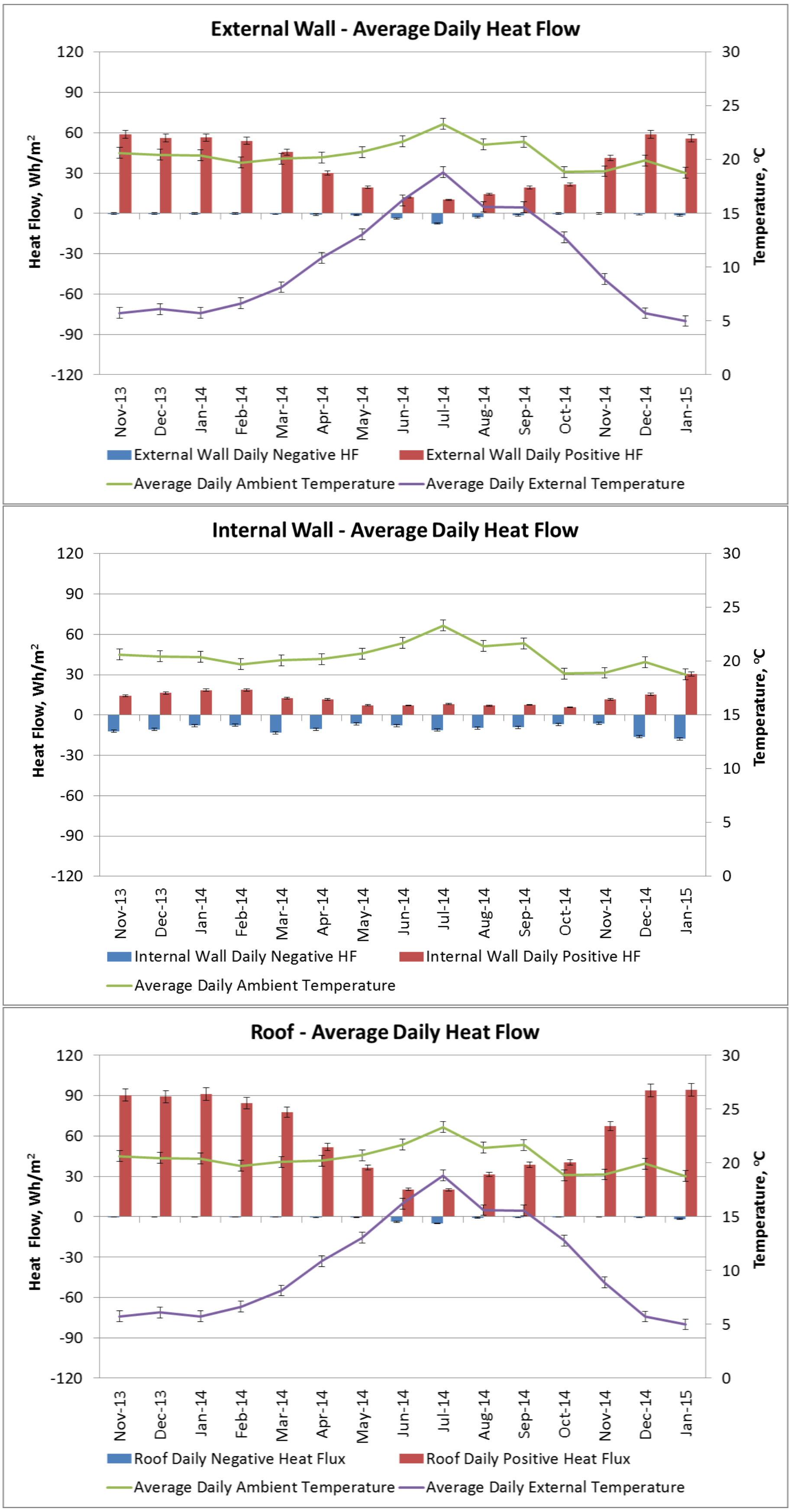


Figure 7-11: Average daily values of heat flows and ambient and external temperature for the BASF bedroom zone

Heat flows on the roof (Y= 1.36 W/m^{2}K, κ = 18.80kJ/m^{2}K)and the external wall (Y= 1.34 W/m^{2}K, κ = 18.80kJ/m^{2}K) are predominantly in the positive direction. Heat was being removed from space by these elements with practically no heat being transmitted to space during the winter months. Small amounts of heat were released to the interior on the summer months.

On average 12.14 ± 0.61 Wh/m^2 were absorbed by the surface of the external wall and 4.68 ± 0.23 Wh/m^2 were released to the zone on a daily basis during the summer months. At the same period, the roof absorbed every day on average 23.98 ± 1.20 Wh/m^2 and released 3.15 ± 0.16 Wh/m^2 to the zone. It can be seen that these two elements had very different heat flows despite the fact that they had almost identical thermal properties. This highlighted the importance of the location of the elements within the space. As the ceiling in the bedroom is quite high, the surface peak temperature in that element was consistently higher than the respective surface temperature of the external wall resulting in higher amounts of heat absorption.

Heat flows on the surface of the internal wall (Y= 0.79 W/m^{2}K, κ = 10.00kJ/m^{2}K) are more balanced. Similar amounts of heat were absorbed and released each month. During the period June – August 2014 7.39 ± 0.37 Wh/m^2 were absorbed by the internal wall on a daily basis and 9.56 ± 0.48 Wh/m^2 were transmitted from the wall to the zone space. In general, the internal wall was less responsive to the temperature excitations than the external wall and roof.



a

b

c

Figure 7-12: Average daily heat flux absorbed and released by the (a) external wall, (b) roof and (c) internal wall in the BASF bedroom zone

7.3.4 Nottingham H.O.U.S.E.

The first floor south office zone was monitored from November 2013 until December 2014. The constructions that were investigated were the timber I-joist external wall and roof and timber frame internal wall. The monitored temperatures in the zone and the external temperatures for that period are shown in Figure 7-13.

The Nottingham H.O.U.S.E. was not occupied until the end of July 2014. During the first month, there was no heating in the room and therefore the zone temperatures were similar to the external temperatures. In December 2013 the house was heated by means of two DIMPLEX DX300T 3kW electric heaters, one in the ground floor and on in the first floor. The heaters had a built in timer and were set to supply heat at a set temperature of approximately 20^{o}C from 6-9am and from 6-10pm. From mid-February until March 2014 a sudden rise in the zone temperature to 25^{o}C can be seen. This was the period of the co-heating test when the house was heated to 25^{o}C constantly.

As from April 2014, sudden rises and falls in temperature occurred. The house was in free-running mode at the time, with no heating or cooling applied. The increased solar gains over the spring and summer period in combination with the high insulation and air tightness levels and the fact that the house was closed during that time resulted in these high temperatures. In August 2014, when the house was occupied and therefore ventilated, there is a step change in the zone temperatures. This was discussed also in Chapter 4. The effect of window opening on the zone temperature was demonstrated in Figure 4-11.

The mean daily average, maximum and minimum temperatures and temperature fluctuation per month are presented in Table 7-6. It can be seen that the daily temperature fluctuation over the summer 2014 did not exceed 2.18^{o}C on average. The mean average daily temperature was between 22.10^{o}C and 25.49^{o}C during the same period. The respective maximum daily temperature was between 23.22^{o}C and 26.51^{o}C.

The average daily net heat flows on the surface of the external wall, the internal wall and the roof are shown in Figure 7-14. The external wall and roof heat flows are consistently in the positive direction, i.e. heat was entering the surface of these elements. The amount of heat entering the external wall was consistently higher than the heat entering the roof due to the lower U-value of the roof. In contrast heat was flowing in the negative direction of the internal wall, i.e. heat was transmitted from the internal wall to space. The average daily positive and negative heat flux for each building element is presented in Figure 7-15.

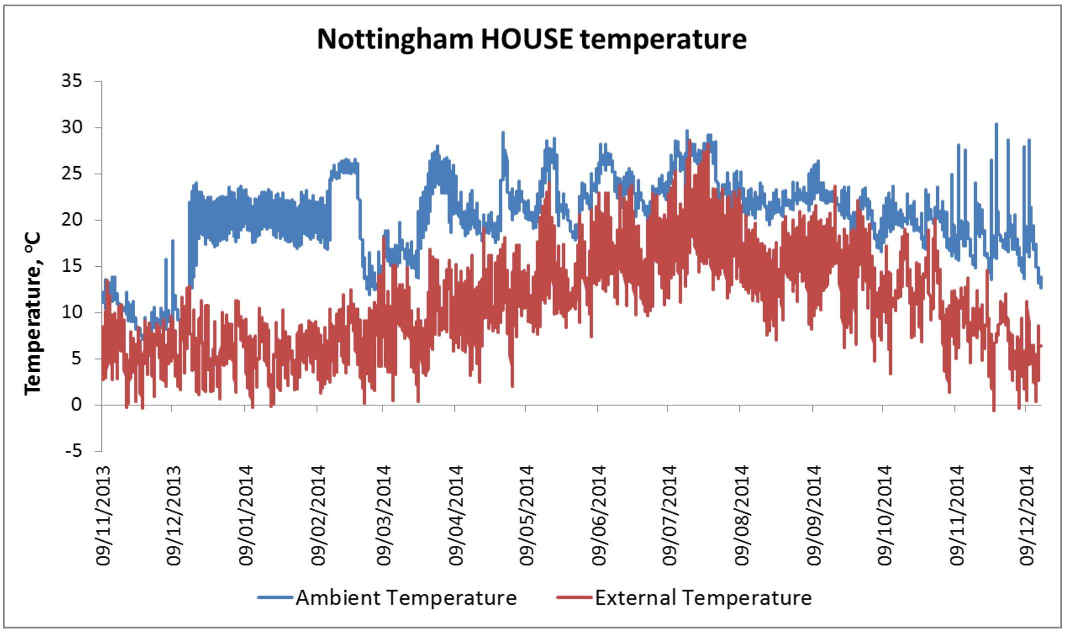


Figure 7-13: Temperature profile in the office zone of the Nottingham H.O.U.S.E.

Table 7-6: Mean maximum, minimum and average temperature and mean temperature fluctuation per month on a daily basis in the Nottingham H.O.U.S.E. office zone

Month	Average Ambient Temperature	Maximum Ambient Temperature	Minimum Ambient Temperature	Temperature Fluctuation
Nov-13	10.00	10.83	9.42	1.41
Dec-13	14.47	16.97	12.90	4.07
Jan-14	20.21	22.61	18.36	4.24
Feb-14	22.15	23.87	20.69	3.17
Mar-14	16.97	18.69	15.58	3.11
Apr-14	21.50	23.17	20.03	3.14
May-14	22.26	23.30	21.01	2.29
Jun-14	23.70	24.65	22.65	2.00
Jul-14	25.49	26.51	24.34	2.17
Aug-14	22.10	23.22	21.03	2.18
Sep-14	22.18	23.31	21.29	2.02
Oct-14	19.90	21.23	18.95	2.28
Nov-14	18.41	20.95	16.97	3.97
Dec-14	17.58	20.63	15.95	4.68

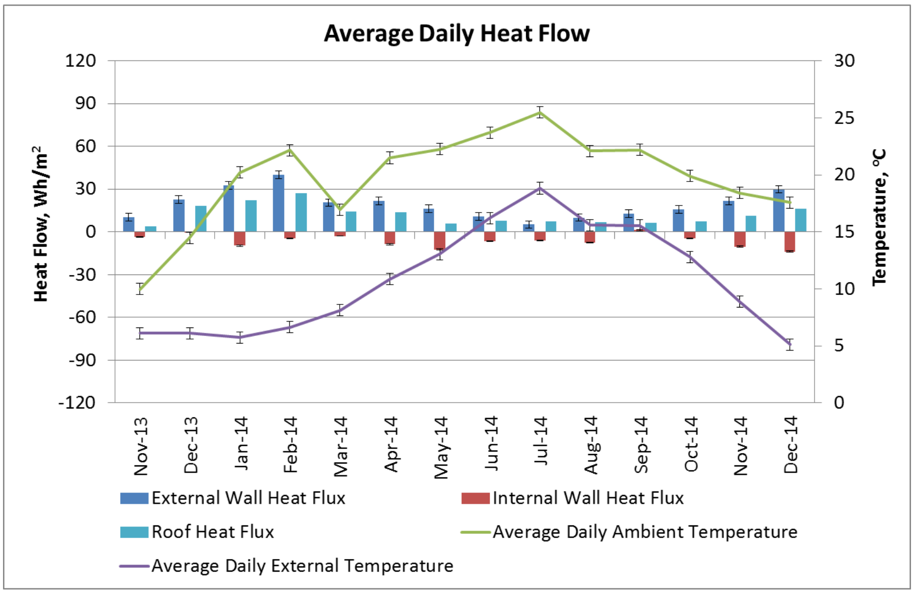
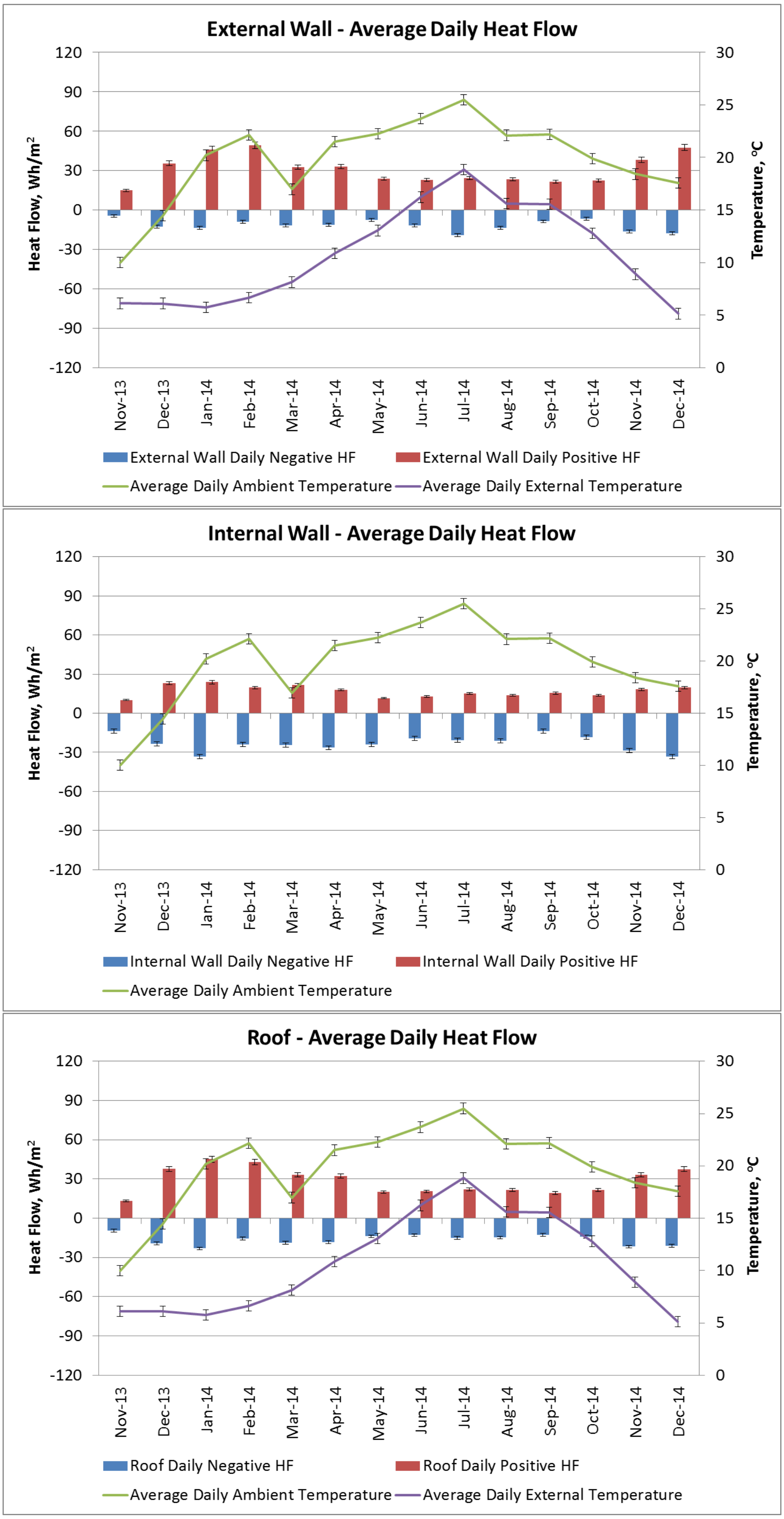


Figure 7-14: Average daily values of heat flows and ambient and external temperature for the Nottingham H.O.U.S.E. office

Heat flows on the surface of the external wall (Y = 0.82 W/m^{2}K, κ = 10.00kJ/m^{2}K) are predominantly entering the building element with the amount of heat being released back to space being significantly lower on a daily basis especially in the winter months. During the period June – August 2014 23.54 ± 1.17 Wh/m^2 were absorbed by the external wall while 14.73 ± 0.74 Wh/m^2 were released to space.

The heat flows on the roof (Y= 0.94 W/m^{2}K, κ = 12.00kJ/m^{2}K) were similar; larger amounts of heat were absorbed than were released to space. Again, the difference was more prominent on the winter months as expected since the temperature difference between the ambient and the external temperature was larger during winter. However, compared to the external wall, the amount of heat entering the roof surface was consistently lower while the amount of heat being transmitted to space was comparable. During the summer months, 21.47 ± 1.07 Wh/m^2 were absorbed by the roof while 14.21 ± 0.70 Wh/m^2 were released to the zone.

The situation on the internal wall (Y= 0.78 W/m^{2}K, κ = 10.00kJ/m^{2}K) was different. Heat flows on the surface of the internal wall were also bi-directional suggesting that heat was both entering and leaving the surface on an average daily basis. The amounts of heat being transmitted to space from the internal wall were larger than the ones absorbed suggesting that the internal wall acted as a heat source. This was due to the fact that the internal wall is adjacent to the double height space between the ground floor dining area and the roof window. The temperature in that space was possibly higher than the office temperature due to the warm air rising from the ground floor. During the period June – August 2014 13.81 ± 0.69 Wh/m^2 were absorbed by the internal wall and 20.45 ± 1.02 Wh/m^2 were released to the space.



a

b

c

Figure 7-15: Average daily heat flux absorbed and released by the (a) external wall, (b) internal wall and (c) roof in the Nottingham H.O.U.S.E. office

7.3.5 Mark Group house

Two zones were monitored in the Mark Group house, the sunspace in the ground floor and the office in the first floor. The constructions examined were the steel frame internal wall and internal ceiling (finished with PCM) in the sunspace and steel frame external wall and roof in the first floor office.

Sunspace

The sunspace area of the Mark Group house was monitored from December 2013 to November 2015 with certain short periods (in the range of several days) of missing data due to failures of the data acquisition system. The temperature profiles of the zone ambient and the external temperature are shown in Figure 7-16.

Similarly to the Nottingham H.O.U.S.E., the Mark Group house was also unoccupied until June 2014. The excessive temperatures observed in the period until June 2014 was the result of the large glazed areas of the sunspace and the fact that this space was kept closed. Temperatures were in general significantly lower from June 2014 onwards. However, increased ambient temperatures were also recorded during that period during weekends when the building was closed, since it was used as an office building.

Table 7-7 presents the mean daily average, maximum and minimum temperatures recorded in the sunspace as well as the mean diurnal temperature fluctuation per month. The maximum ambient temperature when the building was closed was very high and reached 29.37^{o}C. However, as from June 2014 when the building was occupied the average temperature experienced in the zone ranged from 16.99^{o}C to 25.62^{O}C while the respective maximum temperature from 21.28^{o}C to 27.26^{o}C. The daily temperature fluctuation was between 3.41^{o}C to 5.37^{o}C.

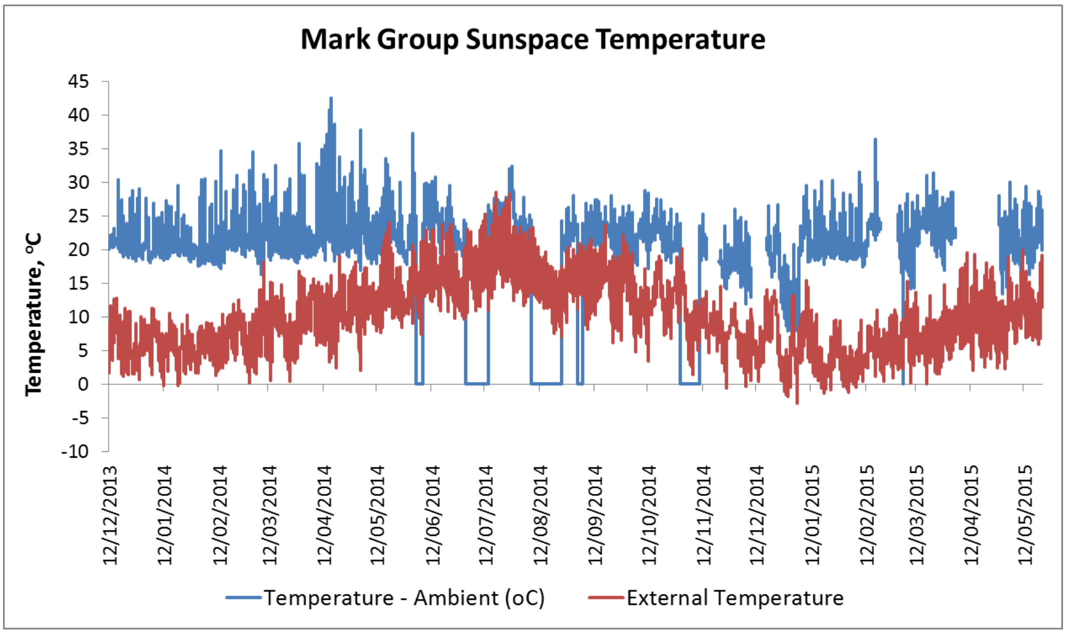


Figure 7-16: Temperature profile in the sunspace of the Mark Group house

Table 7-7: Mean maximum, minimum and average temperature and mean temperature fluctuation per month on a daily basis in the Mark Group house sunspace

Month	Average Ambient Temperature	Maximum Ambient Temperature	Minimum Ambient Temperature	Temperature Fluctuation
Dec-13	20.86	24.11	19.48	4.63
Jan-14	20.30	23.37	19.01	4.36
Feb-14	21.29	25.82	19.06	6.76
Mar-14	22.36	27.31	19.20	8.11
Apr-14	23.99	29.37	19.91	9.46
May-14	22.87	26.62	19.49	7.13
Jun-14	24.26	26.95	21.59	5.36
Jul-14	25.62	27.25	23.85	3.41
Aug-14	22.88	24.83	21.20	3.63
Sep-14	22.61	25.33	20.34	5.00
Oct-14	21.76	24.55	20.09	4.31
Nov-14	18.63	21.36	16.90	4.45
Dec-14	16.99	21.28	14.54	6.74
Jan-15	19.60	23.81	17.63	6.18
Feb-15	21.67	25.13	19.92	5.21
Mar-15	22.19	26.22	19.08	7.15
Apr-15				
May-15	22.24	25.73	19.26	6.47
Jun-15	23.53	26.35	20.98	5.37
Jul-15	24.23	26.80	21.95	4.85
Aug-15	23.84	26.17	21.69	4.48
Sep-15	22.29	25.62	19.45	6.18
Oct-15	23.04	25.68	21.04	4.64
Nov-15	24.24	26.01	22.82	3.18

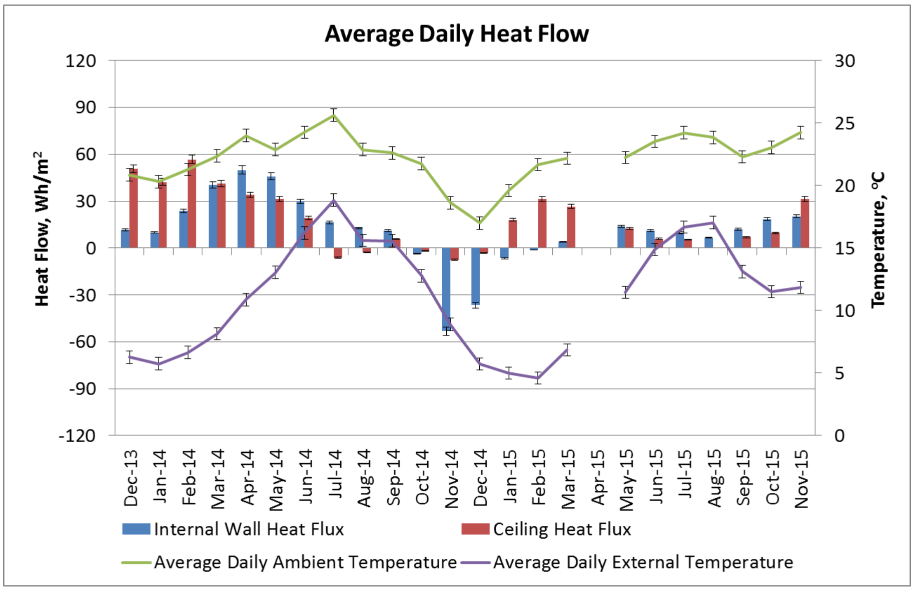


Figure 7-17: Average daily values of heat flows and ambient and external temperature for the Mark Group sunspace

The average net heat flux at the surface of the internal wall and the intermediate ceiling are presented in Figure 7-17. It can be seen that the heat balance in both elements is mostly in the positive direction suggesting that for most of the time heat is entering the surface of the internal wall and ceiling. In general, the ceiling appears to absorb larger amounts of heat than the internal wall. There are also periods when the two elements are releasing heat back to space.

In the case of the internal wall (Y= 2.10 W/m^{2}K, κ = 32.50 kJ/m^{2}K) it can be seen significant amounts of heat are being released from the wall to space in October and November 2014. This appears to be inconsistent with the heat flows observed during the rest of the period. It should be noted, that during these months there were several periods of missing data. Therefore, the averaged values may not be representative of the actual behaviour of the two elements in that period. In addition, the main driver for the heat flow in the internal wall is the temperature difference between the sunspace and the adjacent office space (PhD researchers' area) and the temperature in that zone was not monitored. The average amount of heat being absorbed and released to space from each building element is presented in Figure 7-18.

The ceiling (Y= 2.16 W/m^{2}K, κ = 32.50 kJ/m^{2}K) appears to be absorbing and releasing larger amounts of heat per day than the internal wall. During the summer months (June – August 2014 and June – August 2015) the ceiling absorbed on average 51.20 ± 2.56 Wh/m^2 and released to space 47.61 ± 2.38 Wh/m^2 of heat. The internal wall absorbed during the same period 37.78 ± 1.89 Wh/m^2 and released 23.30 ± 1.16 Wh/m². Again, the performance of the PCM board is investigated in the following section.

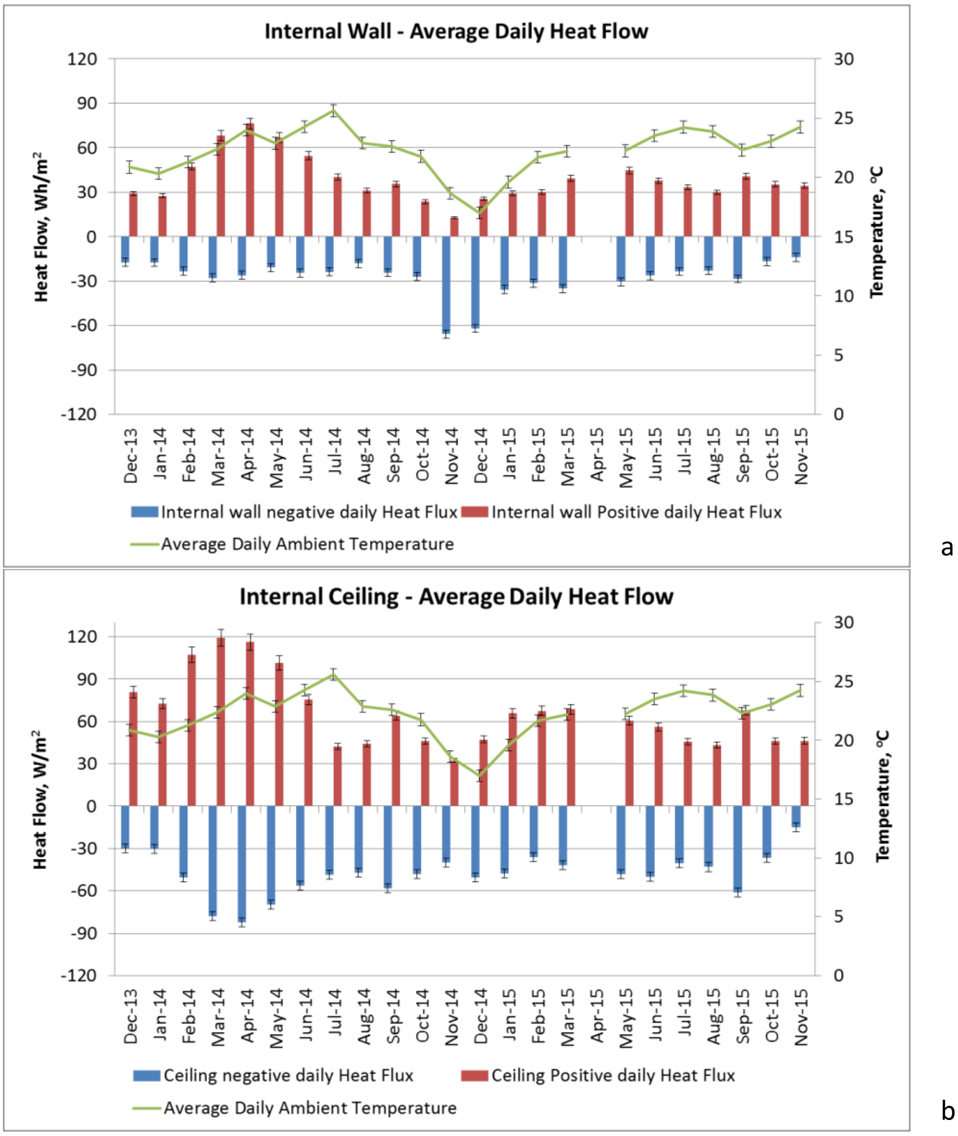


Figure 7-18: Average daily heat flow absorbed and released by the (a) internal wall and (b) ceiling in the Mark Group sunpace

Office

The Mark Group Office zone was monitored from December 2013 until December 2014. The temperature profiles of the zone ambient and the external temperature are shown in Figure 7-19. It can be seen that temperatures above the 25°C comfort limit were frequently experienced during the 2014 summer period. This was due to the fact that the zone is located in the first floor of the Mark Group house and the fact that the zone is an office with four work spaces and therefore high internal gains. Excessive temperatures that reached 30°C were monitored in one occasion in August 2014 when the external temperatures were high. The mean daily average, maximum and minimum temperatures recorded and the mean diurnal temperature fluctuation per month are shown in Table 7-8. The average temperature in the office ranged from 20.03°C to 26.63°C while the respective mean maximum temperature from 20.66°C to 27.77°C. The daily temperature fluctuation was between 1.02°C to 3.04°C.

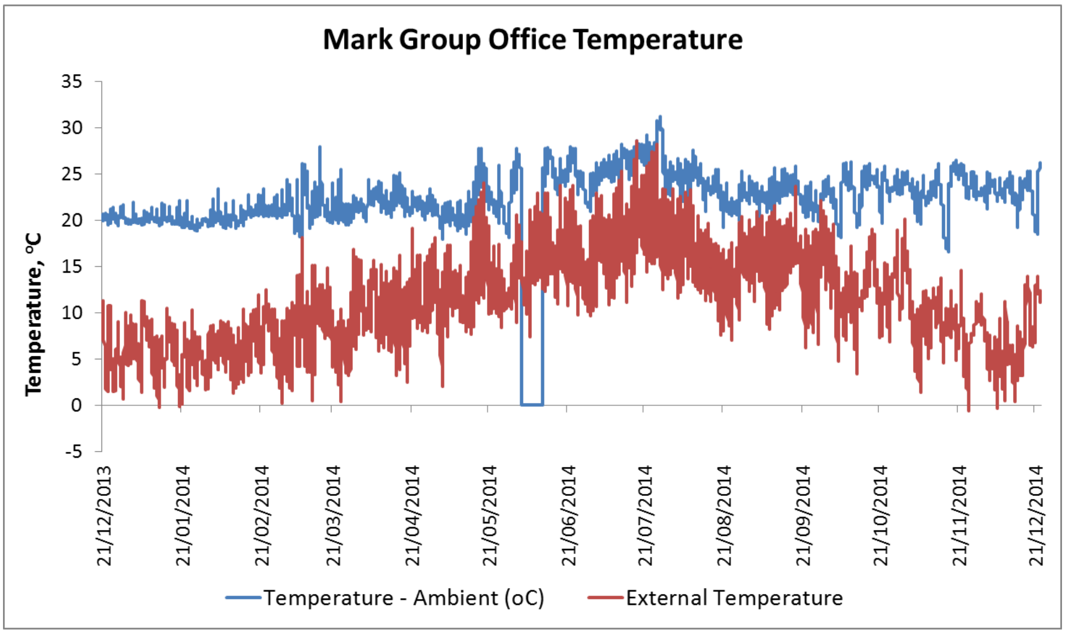


Figure 7-19: Temperature profile in the office of the Mark Group house

Table 7-8: Mean maximum, minimum and average temperature and mean temperature fluctuation per month on a daily basis in the Mark Group house office

Month	Average Ambient Temperature	Maximum Ambient Temperature	Minimum Ambient Temperature	Temperature Fluctuation
Dec-13	20.24	20.84	19.82	1.02
Jan-14	20.03	20.66	19.55	1.11
Feb-14	20.66	21.59	19.97	1.62
Mar-14	21.43	23.12	20.09	3.04
Apr-14	22.00	22.97	21.00	1.98
May-14	21.74	23.03	20.37	2.66
Jun-14	25.13	26.12	23.85	2.26
Jul-14	26.63	27.77	25.23	2.54
Aug-14	23.58	24.74	22.33	2.41
Sep-14	22.80	23.95	21.54	2.41
Oct-14	23.33	24.41	22.23	2.18
Nov-14	23.16	24.29	22.18	2.12
Dec-14	22.98	24.10	21.92	2.18

The average daily net heat flux for the external wall and the roof are presented in Figure 7-20. The heat balance of these elements suggests that on average heat was being absorbed by both the roof and the external wall. This was expected, since the main driver of heat flow through the external elements is the temperature difference between the external and the ambient temperature. The amount of heat that entered the surface of the external wall was slightly higher than the amount of heat that entered the surface of the roof; this was the result of the lower U-value of the roof. The average amount of heat being absorbed by the surface of the two elements and released back to space on a daily basis is presented in Figure 7-21 below.

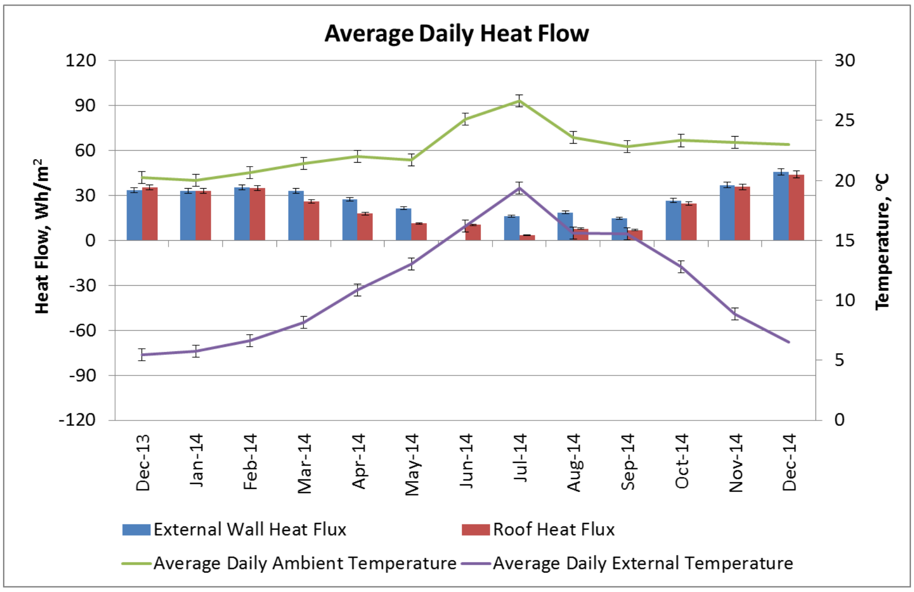
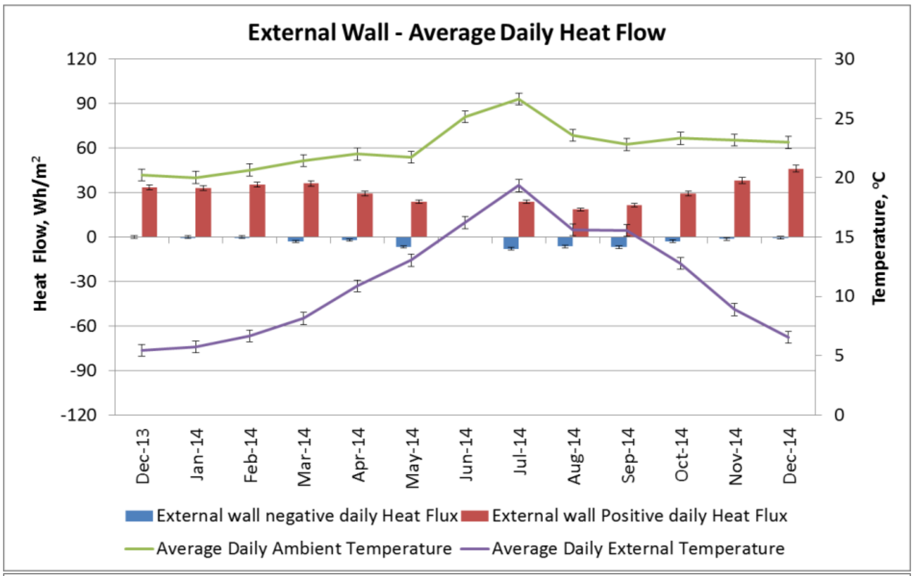


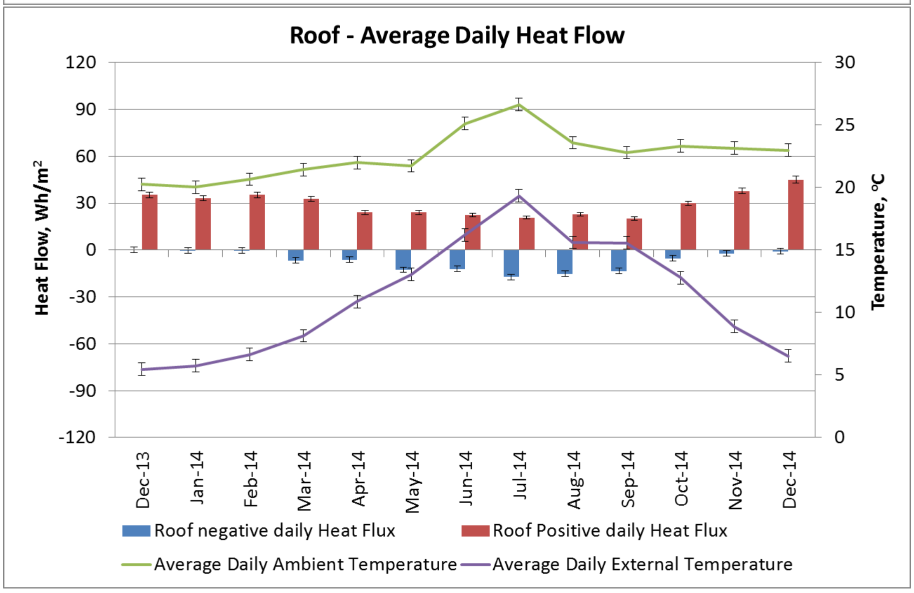
Figure 7-20: Average daily values of heat flows and ambient and external temperature for the Mark Group office

Based on the average daily positive and daily heat flows presented in Figure 7-21, it can be seen that the roof (Y= 0.86 W/m^{2}K, κ = 10.00 kJ/m^{2}K) appears to be more interactive to the internal environment than the external wall (Y= 0.89 W/m^{2}K, κ = 10.00 kJ/m^{2}K). Similar amount of heat are being absorbed by both components. However, the roof appears to release more heat to space on a daily basis. During the summer months the roof absorbed 22.06 ± 1.10 Wh/m^2 and released 14.83 ± 0.81 Wh/m^2 of heat. With regards to the external wall, recorded data for the period June – mid-July were omitted from the analysis due to a failure of the heat flux sensor which was therefore replaced by another HFP-01 heat flux sensor. During the period July – August 2014 the external wall absorbed 21.27 ± 1.06 Wh/m^2 and released 7.07 ± 0.35 Wh/m^2.

Again, the location of the building elements appear to have a significant effect on their response despite the fact that the dynamic thermal properties were practically identical.



a



b

Figure 7-21: Average daily heat flux absorbed and released by the (a) external wall and (b) roof in the Mark Group office

7.4 Assessment of the performance of PCM boards

As seen in Table 7-1, two of the building elements examined, incorporated plasterboards encapsulating Phase Change Materials (PCMs). PCMs are becoming increasingly popular among designers as non-traditional materials that offer the benefits of thermally massive constructions without adding significant weight to the structure. The benefits of PCM boards rely on the fact they can store both sensible and latent heat. Research on the performance of PCMs in the lab and through simulations as well as on the development of new products is also growing; however, there is little evidence on the actual in-situ performance of building elements incorporating PCM boards under actual operating temperatures. The Creative Energy Homes project provided a unique opportunity to investigate the long-term in-situ performance of building constructions finished with

PCM boards and compare it against that of conventional plasterboards. The results of such long-term study reported in the following paragraphs are considered to be unprecedented.

The two building elements investigated were the internal ceilings found in the Mark Group sunspace and the BASF kitchen zone. The PCM boards were installed with two different methods. In the kitchen-dining room of the BASF house, the KNAUF Smartboard 23 incorporating Micronal PCM was installed on the ceiling and then it was covered with conventional plasterboard because it did not comply with fire regulations. In contrast, the internal ceiling examined in the Mark Group sunspace was finished with the KNAUF Comfortboard 23, also incorporating the Micronal PCM. The Comfortboard complied with fire regulations and therefore it was in direct contact with the space.

The KNAUF Comfortboard 23 has a specific heat capacity of 13 kJ/m^2K, latent heat capacity of 200 KJ/m^2 and thermal conductivity of 0.23 W/mK (Knauf, 2013). The additional latent storage capacity of the PCM is considered to reduce the peak temperatures experienced in a zone keeping the ambient temperature within the comfort zone for longer (Figure 7-22). The melting point of the encapsulated PCM occurs at approximately 23^oC and according to the manufacturer 30kg of Micronal® PCM provides storage capacity of 1kWh; the PCM board used contained 3kg of Micronal® PCM per square meter (BASF, 2008).

The respective thermal properties of the KNAUF Smartboard 23 used were: specific heat capacity of 1.20 kJ/kgK, latent heat capacity of 330 KJ/m^2 and thermal conductivity of 0.18 W/mK. The phase change temperature for the Smartboard was also 23^oC (BASF, 2006)

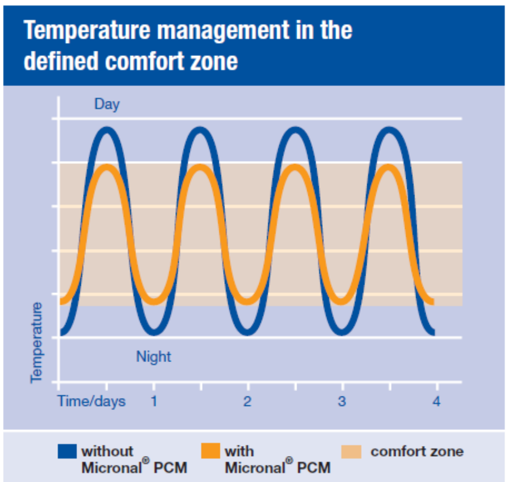


Figure 7-22: Ambient temperature profile in a zone without and with Micronal PCM (BASF (2008))

It was seen in the previous paragraphs that both these ceiling elements were absorbing and releasing back to space larger amounts of heat than the respective internal walls in the same zones that were finished with conventional plasterboard (Figure 7-9 in paragraph 7.3.3 and Figure 7-18 in paragraph 7.3.5). The analysis considered the average performance of the components during the cooling period examined. During that period it was seen that the ceilings absorbed 30-35% more heat than the internal walls and released back approximately twice as much heat as the internal walls did. Obviously, this difference was the result of several different design parameters such as the location of the elements, the conditions at the adjacent zones etc., and not just the thermophysical properties of the boards. However, they do also highlight that the addition of PCM boards did have a substantial effect at the thermal response of the ceilings.

In order to evaluate the performance of the two PCM boards in detail and compare it to that of conventional constructions, the temperature and heat flux profile of the ceiling and internal wall elements during a typical summer month were examined. The temperature and heat flux profiles for the Mark Group sunspace recorded in August 2015 is presented in Figure 7-23. The respective profiles for the kitchen of the BASF house were examined for July 2014 and are presented in Figure 7-24. The different periods for the analysis were selected such that the results would report on the response of the PCM boards to a range of different zone temperatures.

With regards to the Mark Group sunspace, the PCM board installed in the internal ceiling appeared to have a lower peak surface temperature compared to the plasterboard of the internal wall almost consistently. This was more prominent when the ambient temperature was within the comfort zone, i.e. when the zone temperature did not exceed 25^{o}C. This appeared to be consistent with the claims of the manufacturers of PCM products. However, it was not always the case; there were times when the surface temperature of the PCM board and the plasterboard were very similar, especially at high zone ambient temperatures exceeding 25^{o}C.

With regards to the heat flux at the surface of the two elements, it can be seen that the PCM board absorbed and released larger amounts of heat on a daily basis compared to the plasterboard internal wall. This was in accordance with the findings from paragraph 7.3.5 where it was seen that the ceiling exchanged larger amounts of heat with the environment. The ceiling was found to absorb and release larger amounts of heat that the internal wall consistently. It was also found that the difference in monitored heat flux between the ceiling and the internal wall (i.e. the amount of heat that the ceiling and the internal wall exchanged with the internal space) was larger when the zone temperature was between the comfort levels suggesting that the PCM board performed better at that temperature band. At higher temperatures, the ceiling was still found to exchange larger amounts of heat on a daily basis than the internal wall, albeit the difference was smaller.

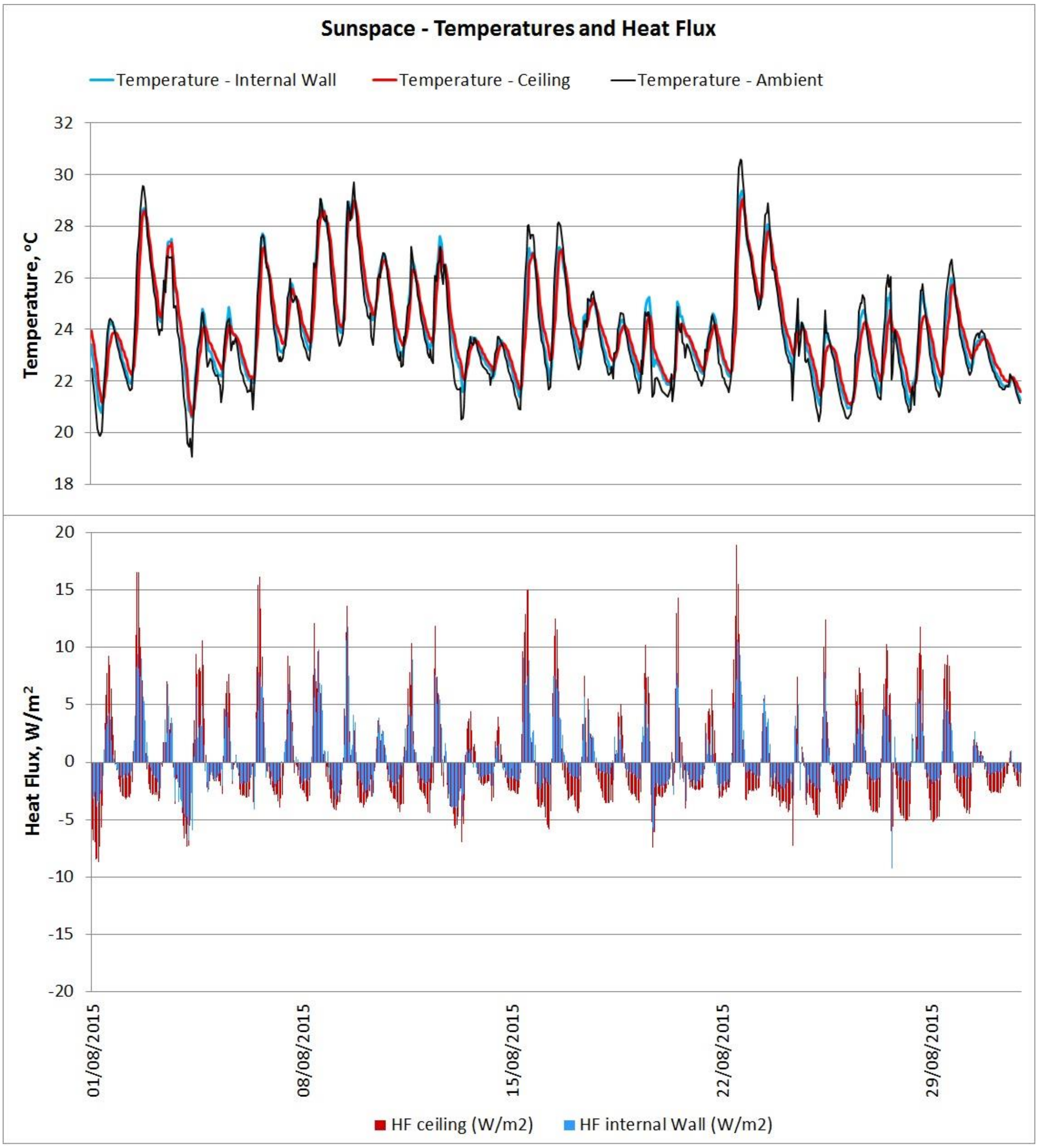


Figure 7-23: Surface temperatures and heat flux at the ceiling and internal wall of the Mark Group sunspace (August 2015)

The analysis of the temperature profiles in the BASF kitchen zone showed that the surface temperature of the ceiling was consistently higher than that of the internal wall regardless of the levels of room temperature. This seemed to be in disagreement with the theoretical performance of the PCM board; however, this can be attributed to the room geometry; the ceiling sensor was at a distance from the internal wall sensor and therefore the difference in the surface temperature is more likely to be affected by the local conditions. The internal wall, the only available to monitor due to the room geometry, is on the north side of the house in close proximity to the window, whereas the location of the ceiling sensor (where the PCM boards were found) was on the south side of the house close to the large glazed surface of the sunspace (Figure 6-6). In addition, the PCM board in that zone was not in direct contact with the air since it was covered by plasterboard. Similarly to the findings from the Mark Group sunspace analysis, the ceiling absorbed and released more heat on a daily basis than the internal wall consistently. This was expected from the findings of paragraph 7.3.3. Again, at high temperatures the difference in the heat flux between the two elements was reduced while at lower ambient temperatures the difference was higher.

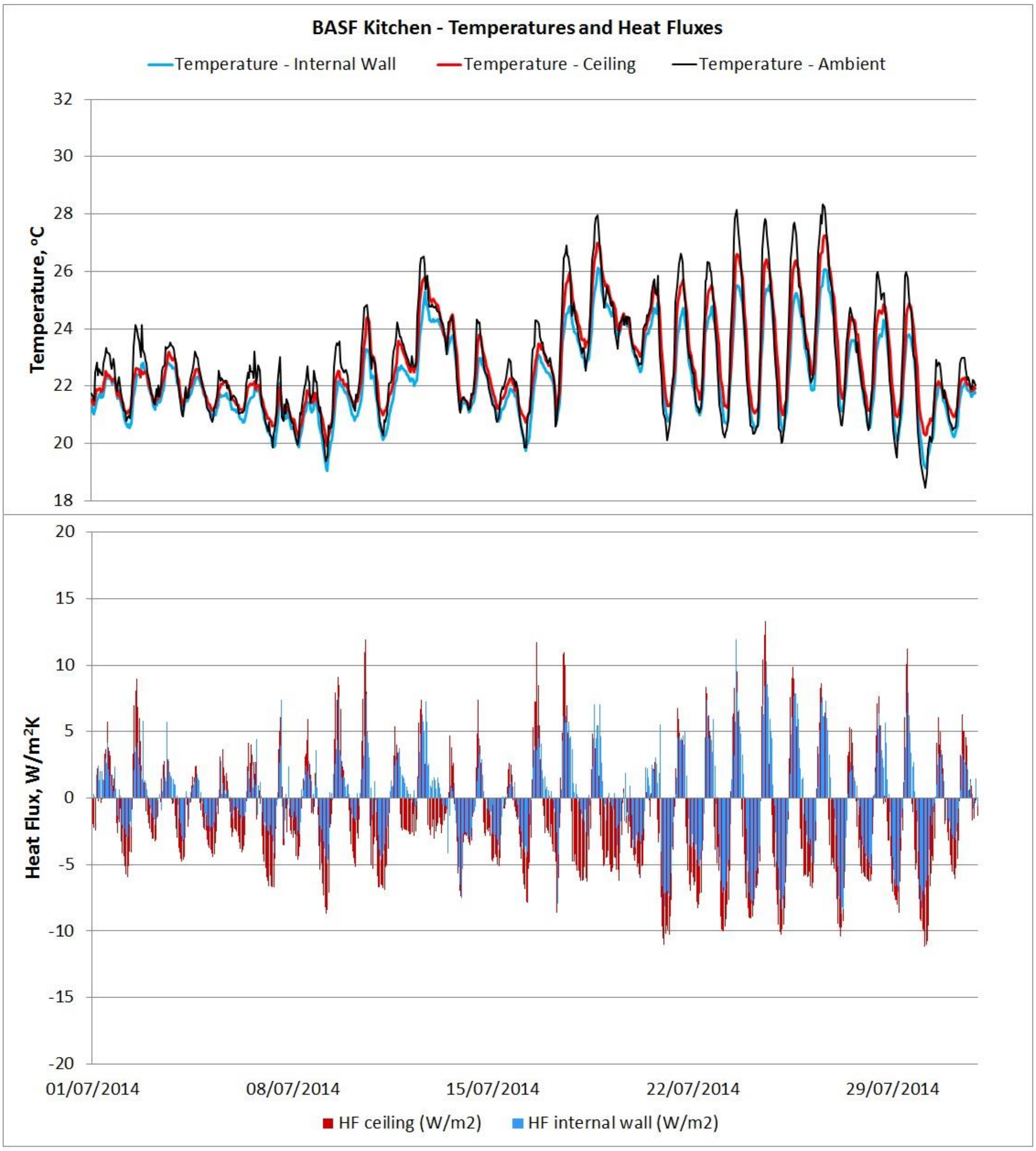


Figure 7-24: Surface temperatures and heat flux at the ceiling and internal wall of the BASF kitchen zone (July 2014)

The next of the analysis involved the heat flux profiles of the two PCM boards. These were investigated in order to identify whether the effect of latent heat storage was as prominent in-situ as under laboratory conditions. Based on the manufacturer, the KNAUF Comfortboard 23 has a specific heat capacity of 13 kJ/m^{2}K and latent heat capacity of 200 KJ/m^2 at the Phase Change

Temperature (23^{o}C) (Knauf, 2013). The Smartboard 23 has a latent heat capacity of 330 KJ/m^2 (BASF, 2006). It would be expected, therefore, to observe a large increase in the heat flux occurring at the region of 23^{o}C.

The average heat flux at the surface of each board per degree of surface temperature was determined during the processes of heat absorption (therefore melting of the PCM when in the Phase Change Temperature region) and heat release (therefore also solidification when in the region of the phase Change Temperature). The profiles of heat flux per degree of temperature for the PCM boards found in the Mark Group house and BASF house are presented in Figure 7-25 and Figure 7-26 respectively.

It can be seen that the amount of heat absorbed by the Comfortboard in the sunspace of the Mark Group house gradually increased up to a maximum and the decreased. At higher temperatures (between 31 and 33^{o}C) the panel absorbed again large amounts of heat. However, such high temperatures were not met frequently in the zone and therefore the resulting heat flux was determined with very few readings. For this reason, this should be treated with care as it would be susceptible to the effect of and outliers. It could also be the result of rapid increase in air temperature that resulted to high rates of heat transfer through the PCM board. Such rapid increases in air temperature where not uncommon when the space was closed at weekends due to the large glazed areas of the sunspace.

The maximum amount of heat, approximately 8W/m^2, was absorbed at the region of temperatures between 24 – 25^{o}C. This was slightly higher than the recommended phase change temperature of 23^{o}C but it could be due to inaccuracies by the equipment Slightly lower amounts of heat (approximately 6W/m^2) were absorbed at temperatures ranging from 23 – 24^{o}C and 25 – 26^{o}C while on a wider temperature range (between 20-23^{o}C and 26-29^{o}C) approximately 5W/m^2 were absorbed. With regards to heat release and solidification, the largest amounts of heat, approximately 4 – 4.5W/m^2 were released when the surface temperature ranged between 19^{o}C and 21^{o}C. Similar amounts of heat (between 3 and 4 W/m^2) were released when the surface temperature was between 21^{o}C and 24^{o}C.

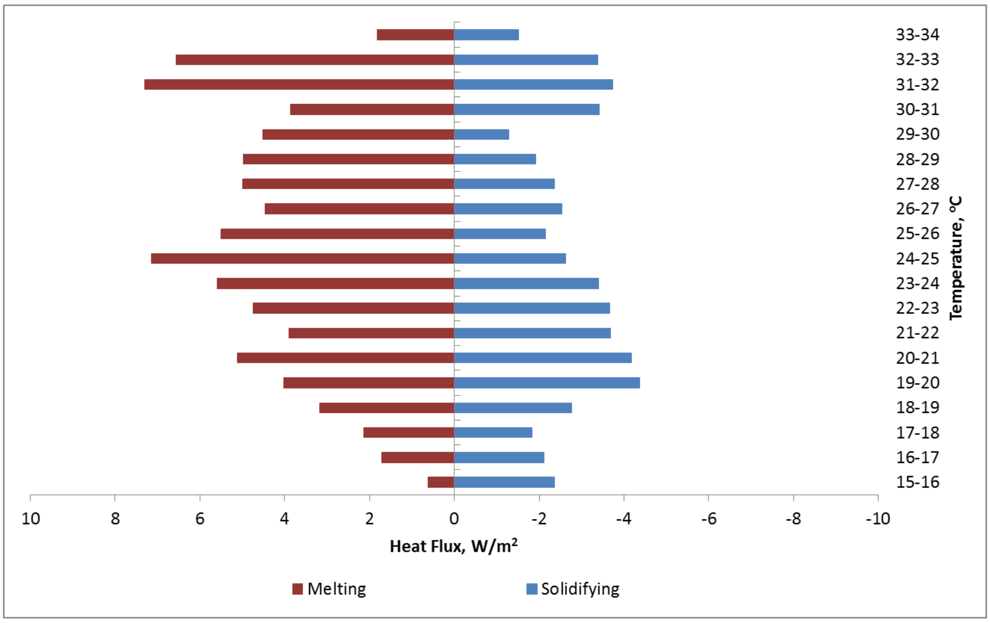


Figure 7-25: Heat flux profile of the PCM board found in the Mark Group sunspace during the process of melting and solidification

The heat flux profile at the surface of the BASF house kitchen ceiling showed that the largest amount of heat flux was absorbed at a temperature range between 22°C and 27°C (between 4 - 5W/m^2), with most of the heat flux absorption occurring marginally between 23°C and 24°C (approximately 5.5 W/m^2. In terms of heat release, it can be seen that a heat flux of 3W/m^2 occurred at a temperature range between 20°C and 26°C. The peak heat flux was released when the surface temperature was between 25°C and 26°C. This was significantly different than the peak heat flux released at the Mark Group PCM board that occurred between 19 and 21°C.

Based on the monitored data, it can be concluded that in both zones the ceilings that incorporated the PCM boards were absorbing and releasing larger amounts of heat than the internal wall elements at any level of ambient temperature. At lower ambient temperatures the relative performance was higher compared to the internal walls.

The heat flux profile of the two PCM boards suggested that there was a temperature range where heat flow was more prominent at either direction. This was more profound in the Comfortboard and less on the Smartboard where a wide temperature band of increased heat flow was observed. This is explained by the fact that the Comfortboard in the sunspace internal ceiling element was in direct contact to the zone space while the Smartboard was covered by a conventional plasterboard. In other words, it was the temperature of the plasterboard that was monitored rather than the temperature of the Smartboard. The PCM board was isolated from the space and its response to the space temperature excitation was buffered by the plasterboard.

However, a clear increase in heat flow at a certain temperature band, significantly higher than heat flow at any other temperature range was not observed in the two zones. Figure 7-27 shows the heat flux profile constructed by Rodrigues (2009) based on data provided by the manufacturer. It should be noted that the heat storage is expressed in J/g instead of W/m^2, however, a similar profile would be expected. It can be concluded that the profile of neither board presented this clear increase in heat storage. This suggests that the change of phase of the PCM material likely occurred in somewhat wider temperature range.

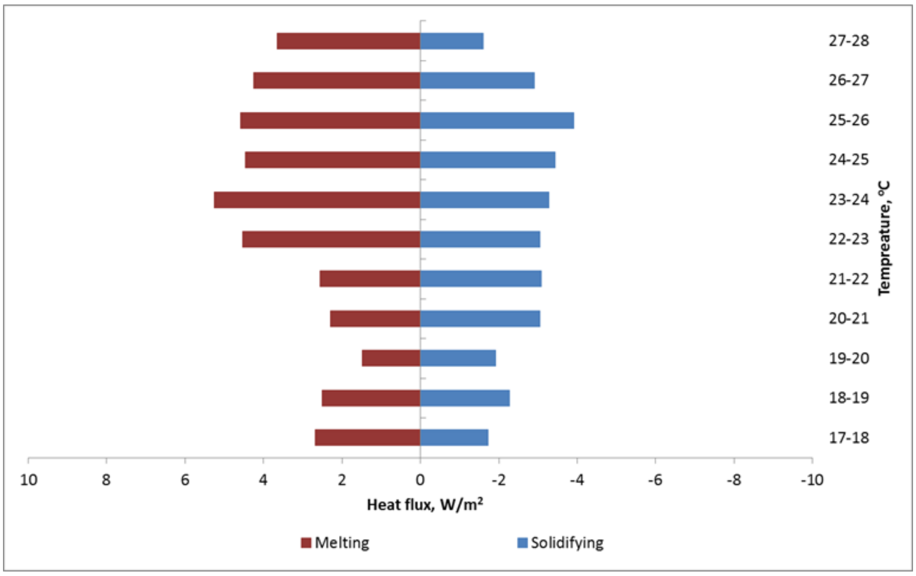


Figure 7-26: Heat flux profile of the PCM board found in the BASF house kitchen during the process of melting and solidification

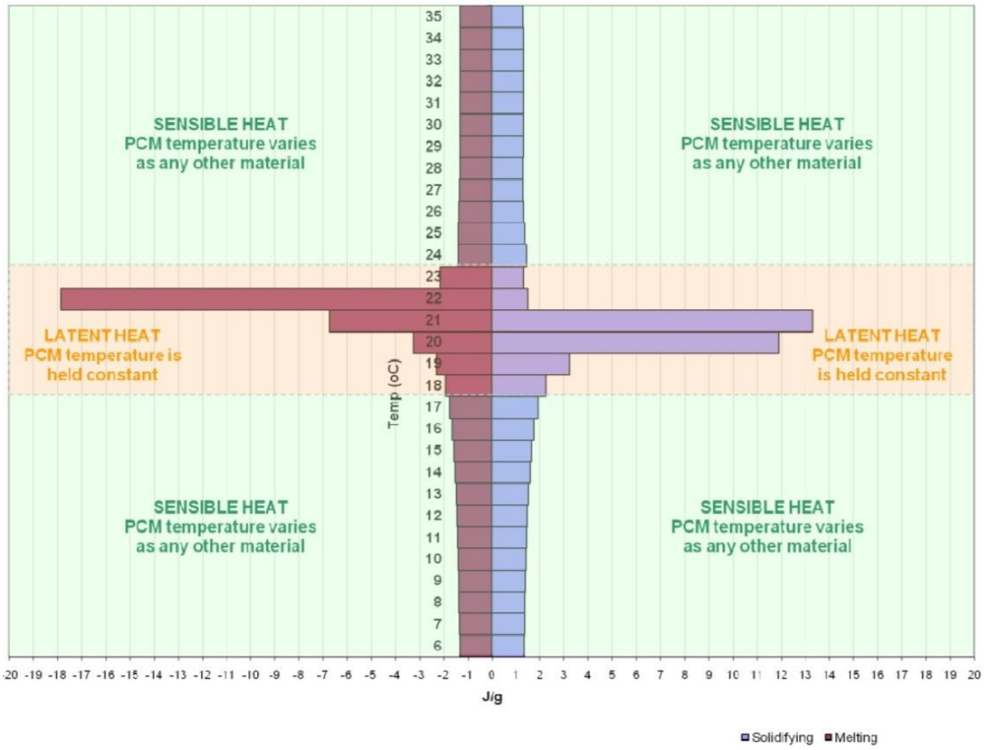


Figure 7-27: Heat flux profile according to the manufacturer’s data (Rodrigues, 2009)

7.5 Conclusions and suggestions for further work

The work presented in this chapter focused on the thermal performance of components built with Modern Methods of Construction and modern masonry methods. The components found at the houses of the Creative Energy Homes project were monitored for a period of 12 to 18 months. The analysis of the recorded temperatures and heat flows focused on the summer period, since the aim of this work is to evaluate whether MMC present higher propensity for overheating compared to traditional methods of construction.

It was found that most of the zones investigated did not suffer from overheating. Elevated temperatures above the comfort limit were experienced in some zones, the Nottingham H.O.U.S.E. office and the Mark Group sunspace and office. However, this was found to be the case due to the fact that these zones were unoccupied and therefore closed and not ventilated, rather than due to the thermal performance of the construction. In the case of the office zone in the Mark Group house, elevated temperatures were also attributed to the high internal gains experienced in that zone. Furthermore, the two office zones were located at the first floor and therefore they were more likely to experience higher temperatures.

With regards to the heat flows at the surface of the external elements, namely external walls and roofs, the heat flows were driven mainly from the temperature difference between the internal and external temperature. In terms of net heat balance the masonry cavity and the solid wall absorbed the largest amounts of heat per day on average over the summer months, approximately 20 Wh/m^2 per day, followed by the ICF wall with approximately 18 Wh/m^{2}and the steel frame wall with roughly 14 Wh/m^2. The timber frame and SIP wall were found to absorb the least amount of heat, almost 9 Wh/m^2 and 7.5 Wh/m^2 on average. The average amounts of heat absorbed on a daily basis over the summer months are presented in Table 7-9.

In addition, it can be seen that the dynamic thermal properties of the elements did not reflect the response of these elements. For example the timber frame wall with much lower admittance and κ-value than the solid wall and cavity wall was able to absorb similar amounts of heat and significantly more heat. Similarly, the steel frame wall had a more responsive behaviour to the thermal excitations than the solid wall (Table 7-9).

These values though should be considered indicative, since the ambient temperature conditions in each house were markedly different. In order to eliminate the effect of the environmental parameters in the assessment of the performance of building elements, these should be tested in laboratory conditions. This is performed in the following chapter where an assessment methodology is presented involving testing of a wall sample in a climate chamber and numerical simulation.

Table 7-9: Average rates of heat absorption and release on a daily basis during the summer months

	Admittance (W/m^2k)	κ-value (kJ/m^2K)	Heat absorbed (Wh/m^2)	Heat released (Wh/m^2)	Net heat balance (Wh/m^2)
Cavity wall	2.38	8.75	27.2	6.9	20.2
Solid wall	1.78	47.82	20.7	1.0	19.7
ICF wall	0.82	10	26.4	8.6	17.8
SF wall	0.89	10	21.3	7.1	14.2
TF wall	0.82	10	23.5	14.7	8.8
SIP wall	1.34	18.80	12.1	4.7	7.5

The analysis of the internal walls also highlighted limitations of the monitoring study and the need for testing under set laboratory conditions. Despite the fact that most of the internal walls examined were timber frame partitions, these were found to have varying levels of heat exchange to the surrounding zones. The different temperature conditions found in the zones monitored, as well as the lack of monitoring equipment at the adjacent zones were the main reasons that did not allow for further insight. The net daily heat balance for the timber frame internal walls of the CEH homes was found between approximately -15 Wh/m^2 (i.e. heat release) and 10.5 Wh/m^2. The block internal wall at the kitchen of the BASF house had an almost zero energy balance, absorbing and releasing similar amounts of heat while the steel frame internal wall released on average 1.26 Wh/m^2in the sunspace over the summer months. These values were normalised by the average temperature fluctuation in order to account for the difference in the zone temperature conditions.

Examining the performance of the internal ceilings showed that the PCM boards on the ceiling of the Mark Group sunspace and the BASF kitchen absorbed and released larger amounts of heat than the hollowcore concrete ceiling and the timber frame ceiling in the Tarmac Code 6 and Code 4 house respectively.

Detailed analysis of the temperatures and heat flows of the PCM boards suggested also that the PCM boards were more responsive than the conventional plasterboards found in the neighbouring internal wall elements; they were absorbing and releasing larger amounts of heat when subjected to the same temperature conditions. A clear increase of the heat stored at specific temperature range (as suggested by the manufacturers) was not found. An increase of the heat stored due to latent heat storage took place at a somewhat wider temperature band, suggesting that the phase change occurred at a wider temperature range. It is recommended that additional monitoring under actual operating conditions of PCM boards is carried in order to assess their performance in situ. Furthermore, in order to evaluate the difference between conventional plasterboards and PCM boards these should be installed at the same building element and in close proximity and monitored.

CHAPTER 8. CONSTRUCTION METHODS DYNAMIC ASSESSMENT

The in situ monitoring analysis presented in Chapters 6 and 7 has provided significant information on the actual performance of the different MMC components on site. However, these components were part of the larger system that is the building, and the resulting heat flows were also affected by the environmental parameters such as the building design and geometry, the occupancy and ventilation patterns and the heat gains. The analysis presented at the previous chapter highlighted the need to assess the thermal performance of building components in isolation from external parameters performed under controlled conditions.

As a consequence, the work presented in this chapter focuses on the dynamic characterization of building elements under specific temperature conditions. This was performed through experimental investigation in laboratory conditions and through the use of appropriate Finite Element Analysis software (FEA).

At first, the main theoretical methods developed to characterise the transient performance of complete building components and estimate their thermal response for cooling load applications are presented, in order to identify the most suitable methodology and specify the testing conditions. Next, the experimental methods developed by researchers to test complete wall sections under dynamic conditions in a laboratory environment were reviewed. This was useful to define a testing protocol and identify the parameters required to be controlled and monitored.

Physical testing of an insulated brick wall was performed at the climate chamber facility at the Department of Architecture and Built Environment, University of Nottingham. A description of the climate chamber facility used in the experimental analysis and the results of the testing are presented in the following sections. Due to limitations on the project budget however, it was not possible to construct a sample of all six MMC walls and test them. For this reason, the next step of the developed methodology involved the use of FEA analysis.

A model of the climate chamber and the wall sample was created and validated with the use of the results of the experimental analysis. In this manner, the analysis of a different number of wall sections under different conditions was made possible (which would not otherwise be) since the cost of performing such analysis on a physical scale was prohibitive. The results of the FEA analysis are discussed in section 8.6. Finally, the conclusions of this work are summarised in the last section and recommendations are made for future work in order to advance the research and expand the evidence on the thermal performance of MMC components.

8.1 Scope and Aim

The work presented in this chapter aims at investigating the thermal performance of walls built with Modern Methods of Construction commonly met in practice, under set transient conditions. The study focuses on the performance of the complete components, irrespective of other parameters that may affect the internal conditions in a building such as the building geometry, occupancy patterns, ventilation patterns etc. The analysis considered the six external wall constructions found at the Creative Energy Homes project presented in Chapters 6 and 7. The response of these walls to specific temperature excitations used to characterise the dynamic performance of multi-layered walls was examined. The main objectives of the study were:

- To determine the dynamic characteristics of the wall constructions to a unit sinusoidal temperature excitation and compare the results to those obtained with the analytical method provided by the International Standard BS EN ISO 13786:2007 commonly used in assessing the dynamic performance of constructions
- To assess the difference in the dynamic response of building elements which consist of thermally non-homogeneous layers when the repeating thermal bridges of the construction are accounted for
- To determine the response of the walls to a unit pulse temperature excitation, a method used commonly in cooling load calculations to compute the conduction heat flows on building elements
- To simulate the thermal performance of these wall constructions under actual operating conditions

Studies focusing on the dynamic response of building components were reviewed in section 8.3. These studies are far from extensive and focus only on one methodology or cover limited wall constructions. It is considered that the thermal performance of wall constructions built with MMC has not been thoroughly examined. In that respect, the work presented in this chapter provides valuable information on the response of MMC components that has not been presented before.

8.2 Transient heat conduction for cooling load calculations

Applications related to determining peak summer temperatures or the design cooling load of a zone or a building take into account the transient heat transfer through the building envelope. Despite the fact that heat transfer through radiation and convection may also occur in small cavities within the wall materials, transient heat transfer is predominantly governed by heat conduction. Therefore it is described by the heat conduction equation which for the case of one-dimensional heat conduction is expressed by (Clarke, 2001):

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{a} \cdot \frac{\partial T(x,t)}{\partial t} \qquad \text{Equation 8-1}$$

Where,

a = thermal diffusivity of the material, ($a = \frac{k}{\rho c_p}$) in m^2/s

T = temperature, in K

x = thickness, in m

t = time, in s

The most widely used methods for solving the partial differential heat equation are the response function methods (analytical solutions) and numerical methods (Barnard et al., 2001).

Numerical methods provide a value of the variables of the equation at discrete points of the domain. Based on the discretization method applied the three main numerical methods used in heat transfer applications are:

- Finite difference method
- Finite element method
- Finite volume method

Response function methods provide an analytical solution to Equation 8-1 with the use of the Laplace transformation that transforms the differential equation from the time-domain to a simplified subsidiary equation in the imaginary space. The subsidiary equation is then solved and through inverse transformation the solution is applied back to the time-domain. There are two main categories of transfer function methods (Clarke, 2001):

- time – domain
- frequency – domain

The most common time-domain method is the thermal Response Factor method. The benefit of the Response Factor method is that it can provide solution to both periodic and non-periodic thermal loads. For this reason this method is very popular especially in North America (Clarke, 2001).

The basis of the Response Factor method lies in determining the response of the construction to a unit temperature excitation, called the unit response function (URF). The heat flux response of a multilayer construction on the internal surface to a unit pulse air temperature excitation at the external surface is shown in Figure 8-1. In the graph, r1, r2, …, r6 are the response factors (RFs) of the construction at time t= 1, 2, …, 6 respectively. The response factors depend only on the material properties and the arrangement of the layers so for any component they only need to be calculated once (Clarke, 2001).

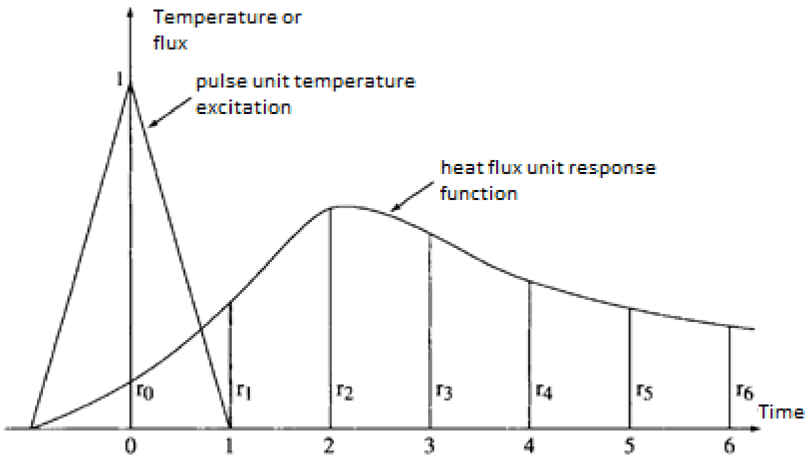


Figure 8-1: Unit response factor of a component to a unit pulse temperature excitation (Clarke, 2001)

Any temperature excitation can be broken down to a number of pulse or rectangular excitations. Among the two, the pulse representation of the temperature time series is most commonly used (Duska et al., 2006). The response of the system can then be defined by combining the response factors of each temperature pulse. For a linear and invariant system, these heat flux responses are the product of the response to the unit temperature excitation times the magnitude of the actual pulse. In this manner, the solution of a complicated thermal load is obtained through combining the results of simpler pulse loads based on the principle of superimposition (Spitler, 2014).

The thermal response due to a temperature excitation, T, is determined (Duska et al., 2006):

$$q_j = r_j \cdot T$$ Equation 8-2

where,

q_j = heat flux at time j, W/m^2

r_j = response factor at time j, W/m^{2}K

T = temperature, K

Four response factors describe the heat flow at the internal and external surface of a building element (Martin et al., 2010):

$r_{o\text{-}o}$ = response of the outside surface due to an excitation on the same surface (W/m^{2}K)

$r_{i\text{-}o}$ = response of the internal surface due to an excitation on the outside surface (W/m^{2}K)

$r_{o\text{-}i}$ = response of the external surface due to an excitation on the internal surface (W/m^{2}K)

$r_{i\text{-}i}$ = response of the inside surface due to an excitation on the same surface (W/m^{2}K)

The heat flux on the external surface and the internal one is then calculated as follows (Martín et al., 2010):

$$q_{o,n} = \sum_{j=1}^{\infty} r_{o\text{-}o}\, T_{o,n-j} - \sum_{j=1}^{\infty} r_{o\text{-}i}\, T_{i,n-j}$$ Equation 8-3

$$q_{i,n} = \sum_{j=1}^{\infty} r_{i\text{-}o}\, T_{o,n-j} - \sum_{j=1}^{\infty} r_{i\text{-}i}\, T_{i,n-j}$$ Equation 8-4

Where

$q_{i,o}$ = heat flux on the inside/outside surface (W/m^2)

$T_{i,o}$ = temperature on the inside/outside surface (K)

n = current time step

j = time step (hours)

Another commonly used time-domain method is the Conduction Transfer Function (CTF) method. This method treats much of the thermal response history of the building element by replacing many of the response factors from a past temperature excitation with heat flux history. In this manner, the analysis is simplified, as the Thermal Response Factor method requires the calculation of a great number of RFs especially when considering elements with high levels of thermal mass. The heat flux at each surface is then calculated by (Spitler, 2011):

$$q_{i,n} = -A_0 T_{i,n} - \sum_{j=1}^{m} A_j T_{i,n-j\delta} + B_0 T_{o,n} - \sum_{j=1}^{m} B_j T_{o,n-j\delta} + \sum_{j=1}^{p} C_j q_{i,n-j\delta} \qquad \text{Equation 8-5}$$

$$q_{o,n} = -B_0 T_{i,n} - \sum_{j=1}^{m} B_j T_{i,n-j\delta} + D_0 T_{o,n} - \sum_{j=1}^{m} D_j T_{o,n-j\delta} + \sum_{j=1}^{p} C_j q_{o,n-j\delta} \qquad \text{Equation 8-6}$$

Where,

$q_{i,o}$ = conduction heat flux at the internal and external surfaces respectively (W/m^2)

$T_{i,o}$ = temperature at the internal and external surfaces respectively (K)

A_j = inside CTF coefficient, j = 0,1,2,…,m

B_j = cross CTF coefficient, j = 0,1,2,…,m

C_j = flux CTF coefficient, j = 0,1,2,…,p

D_j = outside CTF coefficient, j = 0,1,2,…m

n = current time step

δ = time step duration (hours)

With regard to cooling design load calculations, a simplified approach has been developed. For a series of identical design days with periodic temperature variation (sol-air temperature) and constant internal zone temperature, the Periodic Response Factor (PRFs) may be computed and used in the Radiant Time Series Method (Spitler et al., 1997). Heat flux was then calculated with the use of the PRFs as follows:

$$Q_n = A \sum_{j=0}^{23} r_{pj} \left(T_{sa,n-j\delta} - T_{rc}\right) \qquad \text{Equation 8-7}$$

Where,

Q_n = hourly heat gain in the surface under consideration (W)

A = surface area (m^2)

r_{pj} = periodic response factor at the jth step, j=0,1,2…,23 (W/m^2K)

T_{sa} = sol-air temperature (K)

T_{rc} = constant zone temperature (K)

n = current time

δ = time step duration, (h)

In the frequency domain methods the weather variation is treated as a series of harmonic cycles. These are represented by a steady state component and a number of sinusoidal periodic variations. The periodic components of the time series have increasing frequency while they are decreasing in amplitude. The weather time series is expressed as follows (Clarke, 2001):

$$f(t) = u_0 + \sum_{m=1}^{k} u_m \sin\left(\frac{2\pi mt}{L_p}\right) + \sum_{m=1}^{k} v_m \cos\left(\frac{2\pi mt}{L_p}\right) \qquad \text{Equation 8-8}$$

Where,

$1/L_p$ = fundamental frequency (Hz)

t = time (s)

u_0 = steady state component, (°C)

u_m = amplitude of m-th sine wave (°C)

v_m = amplitude of the m-th cosine wave (°C)

The thermal response factors of the building element to each separate harmonic are then calculated and through the principle of superposition the response of the system to the weather time-series excitation is determined by summing the effects of the individual periodic components (Clarke, 2001).

The simplest form of the frequency domain method is when considering steady temperature on the one side of the building element and a series of identical sinusoidal temperature variations represented by a fundamental harmonic. This method is considered in the International Standard *BS EN ISO 13786:2007 – Thermal performance of building components – Dynamic thermal characteristics – Calculation methods* (BSI, 2007c) to provide properties that characterise the dynamic performance of complete building components.

According to the methodology of BS EN ISO 13786:2007, the transient characteristics of the building component are determined considering sinusoidal temperature excitations, $\theta_n(t)$, in the two surfaces and the resulting sinusoidal heat flows $\Phi_n(t)$. The sine wave variation is expressed as the variation of the temperature and the heat flow around their average using complex numbers as follows (BSI, 2007c):

$$\theta_n(t) = \overline{\theta}_n + |\hat{\theta}_n|\cos(\omega t + \psi)$$

Equation 8-9

$$\Phi_n(t) = \overline{\Phi}_n + |\hat{\Phi}_n|\cos(\omega t + \phi)$$

Equation 8-10

Where,

$\overline{\theta}_n$ and $\overline{\Phi}_n$ are the average values of temperature and heat flow respectively (°C and W)

$|\hat{\theta}_n|$ and $|\hat{\Phi}_n|$ are the amplitudes of the temperature and heat flow sine wave variations (°C and W)

ω is the angular frequency (rad/s)

ψ and ϕ the associated phase difference of the temperature and heat flow respectively (rad)

Based on the above temperature and heat flow variations, the main properties of a component associated with dynamic response are defined as follows (BSI, 2007c):

Thermal admittance, Y_{mm}, is the ratio of the complex amplitude of the heat flux through the surface of the component adjacent to zone m, $\hat{q}_m$ ($=\frac{\hat{\Phi}_m}{A}$), to the complex amplitude of the temperature in zone m, $\hat{\theta}_m$, when the temperature at the opposite zone is constant. The thermal admittance is considered the most significant property in describing the dynamic response of a building element and the heat exchange characteristics between that element and the environment (De Saulles, 2012).

$$Y_{mm}=\frac{\hat{q}_m}{\hat{\theta}_m} \qquad \text{Equation 8-11}$$

Periodic thermal conductance, Y_{mn}, is the ratio of the complex amplitude of the heat flux through the surface of the component adjacent to zone m, $\hat{q}_m$, to the complex amplitude of the temperature in zone n, $\hat{\theta}_n$, when the temperature in zone m is constant.

$$Y_{mn}=-\frac{\hat{q}_m}{\hat{\theta}_n} \qquad \text{Equation 8-12}$$

Decrement factor, f, is defined as the ratio of the modulus of the periodic thermal transmittance,

Y_{mn}, to the steady state thermal transmittance, U.

$$f=\frac{|Y_{mn}|}{U} \qquad \text{Equation 8-13}$$

Heat capacity, C_m, is the ratio of the net periodic thermal conductance to the angular frequency.

$$C_m=\frac{|L_{mm}-L_{mn}|}{\omega} \qquad \text{Equation 8-14}$$

Where,

L_{mm} is the thermal conductance, a property associating the periodic heat flow through the surface of a component adjacent to zone m when the temperature in zone m varies in a sinusoidal manner and the temperature in the opposite side remains constant

L_{mn} is the thermal conductance associating the periodic heat flow through the surface of a component adjacent to zone m when the temperature in zone m remains constant and the temperature in zone n varies in a sinusoidal manner

Areal Heat Capacity, k_m, is the ratio of the heat capacity C_m divided by the area, A, of the component

$$k_m = \frac{C_m}{A} = \frac{|Y_{mm} - Y_{mn}|}{\omega} \qquad \text{Equation 8-15}$$

Any component is characterised by four values of periodic thermal conductance, L_{mm}, L_{mn}, L_{nm} and L_{nn}, and two values of heat capacity, C_m and C_n.

BS EN ISO 13786:2007 provides an analytical solution for calculating these properties. This is done with the use of the heat transfer matrix for solving the heat conduction equation. The heat transfer matrix, Z, relates the heat flow and temperature on one surface of the component to the temperature and heat flow variations on the other surface. The analytical solution applies to components with thermally homogeneous layers.

$$\begin{bmatrix} \hat{q}_2 \\ \hat{\theta}_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \cdot \begin{bmatrix} \hat{q}_1 \\ \hat{\theta}_1 \end{bmatrix} \qquad \text{Equation 8-16}$$

Where,

$Z= \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$ is the heat transfer matrix. This is determined by the properties of the layers comprising the component, i.e.

$$Z = Z_{s2} \cdot Z_n \cdot Z_{n-1} \cdot \ldots \cdot Z_2 \cdot Z_1 \cdot Z_{s1} \qquad \text{Equation 8-17}$$

and

Z_1, Z_2, ..., Z_{n-1} and Z_n are the heat transfer matrices of the different layers beginning from layer 1, and

Z_{s2} and Z_{s1} are the heat transfer matrices for the resistance of the air layers on the surfaces 2 and 1 respectively. As the specific heat capacity of the air layers is neglected, the heat transfer matrix becomes

$$Z_s = \begin{bmatrix} 1 & -R_s \\ 0 & 1 \end{bmatrix} \qquad \text{Equation 8-18}$$

The dynamic thermal characteristics of the different wall elements found in the Creative Energy Homes examined in the previous chapters were calculated according to the above procedure with the use of the Dynamic Thermal Properties Calculator v.1.0 developed by and ARUP and launched by The Concrete Centre (ARUP, 2010). In the following section these properties will be determined by solving the heat equation numerically using commercial Finite Element Analysis software ANSYS workbench 16.1.

8.3 Experimental studies on the transient performance of building element

The experimental investigation of the thermal performance of building elements under steady state conditions is well defined by International Standards (BS EN ISO 8990:1996, ASTM 1363-11). Unlike steady state experimental procedures, there is currently no standardised procedure for assessing the transient thermal performance of building components, nor are there specific requirements set for defining the facilities for conducting such tests.

However, many researchers have designed and conducted experimental protocols for assessing and characterising the thermal performance of wall constructions under dynamic conditions.

Brown and Stephenson (1993) as part of the ASHRAE Research Project 515 developed a methodology to determine experimentally the dynamic heat transmission characteristics (Conduction Transfer Function coefficients) of seven wall specimens with the use of a guarded hot-box facility. The project's objectives was to determine whether the dynamic characteristics predicted by the calculation method for non-homogeneous walls were close to those measured experimentally and to demonstrate that the experimental procedure was producing accurate results. The procedure involved determining the thermal resistance under steady temperature gradient and then applying sinusoidal temperature variations and power input variations and measuring the thermal response of the walls. The method was able to provide accurate CTF coefficients.

Martín et al. (2010) presented an experimental methodology to calculate response factors in a modified guarded hot-box apparatus for wall assemblies when the properties of the materials are not known. A perforated clay block sample wall plastered at both surfaces was constructed and its thermal resistance (R) and its corresponding U-value were determined under steady state conditions using the guarded hot-box apparatus according to the standard EN ISO 8990:1996 (BSI, 1996). Next, the metering box was removed and the dynamic test was performed after validating the modified apparatus. A temperature (triangle) pulse of 10^{o}C/h was applied on the cold chamber with an hourly step increase and decrease. Simulation of the wall sample was also performed and the results of the test were compared against those obtained through finite volume software FLUENT 6.2. The response factors calculated experimentally were in agreement with those obtained by the simulation, although the errors when adding the response factors and comparing them to the U-value were larger for the experimentally defined response factors (9.5% and 7.7% against 0.5% for the simulation).

Other studies have also been conducted in climate chamber facilities. Ulgen (2002) performed an experimental and theoretical analysis for the determination of time lag and decrement factor of 10 wall configurations. The apparatus used was a climate chamber consisting of two spaces separated by the wall samples. Sinusoidal temperature variation was imposed in the one chamber and while the second was unconditioned. The effects of heat storage capacity, S, and the thermal diffusivity, α, on the decrement factor and time lag were examined. It was found that higher values for density and heat capacity result in lower decrement factors and higher time lags. However, higher conductivity results in both higher diffusivity and heat storage and should be considered with care.

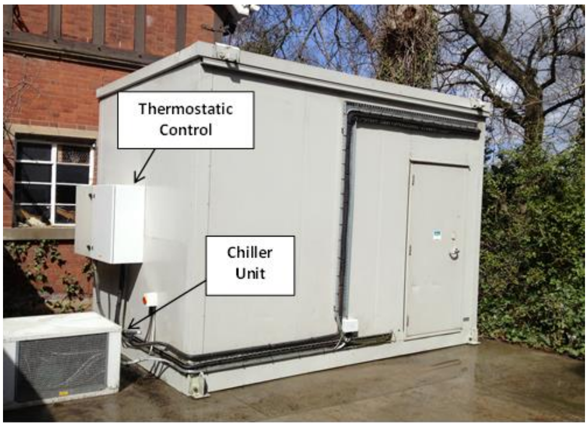
Ferrari and Zanotto (2013) compared the performance of four different wall types with same U-value (approximately 0.3 W/m^{2}K) and varying levels of thermal mass under actual service conditions in a climate chamber. The sol-air temperatures from a typical summer day and a typical winter day of Rome were applied as external conditions. These were derived from the respective Test Reference Year (TRY) climatic file. On the opposite side, the walls were subjected to free floating temperatures. The decrement factor and the time lag for each wall were first calculated according to ISO 13786:2007 and then determined experimentally based on the wall surface temperatures recorded for the 'summer' and 'winter' conditions. Since the temperatures on both sides of the walls were fluctuating an "*amplitude transmission coefficient",* AT, was applied to normalise the results (Ferrari and Zanotto, 2013)

Finally, Ng et al. (2011) investigated the transient thermal behaviour of Aerated Lightweight Concrete (ALC) wall panels in terms of time lag and decrement factor and compared the observed surface temperatures of the panels with those calculated with the use of Finite Difference Method – FDM. Four ALC wall panels with different properties were installed side by side so as to form one wall of a prototype house. The panels were subjected to the external weather conditions and the internal and external surface temperatures for each panel were recorded for a one-year period. It was found that the thermal conductivity of the panels strongly affected the external surface temperatures and the rate of the outer surface temperature increase. Thermal diffusivity, as it is linked with both time lag and decrement factor, also played an important role in the thermal behaviour of the panels under transient conditions. The results of the study suggested that low thermal diffusivity resulted in greater time lags and lower decrement factors. The inner surface temperature was found to be increasing when the thermal diffusivity increased.

As described earlier, the methodology developed to evaluate the transient thermal performance of MMC components involved both experimental testing of physical models and extensive FEA simulations. The review of the experimental methods provided in this section facilitated in defining the testing protocol and the parameters to be monitored. The description of the experimental procedure is presented in the following paragraph.

8.4 Experimental investigation

The dynamic testing of an externally insulated solid brick wall was conducted at the thermal chamber facility located at the Department of Architecture and Built Environment, University of Nottingham. The facility comprises two chambers, an inner hot chamber surrounded by an outer cold chamber. The outer chamber (cold) was conditioned by a chiller unit and thermostat with ± 0.5°C cut-off sensitivity. The temperature in the inner chamber was regulated by means of a 2kW fan heater and the use of thermostat and timer in order to achieve transient conditions. Between the two chambers a solid brick wall was constructed and tested; a section of the panel across the length of the inner chamber was removed and a solid brick wall was constructed. An external view of the climate chamber and a diagram showing the arrangement of the two chambers and the location of the solid brick wall section is presented in Figure 8-2.



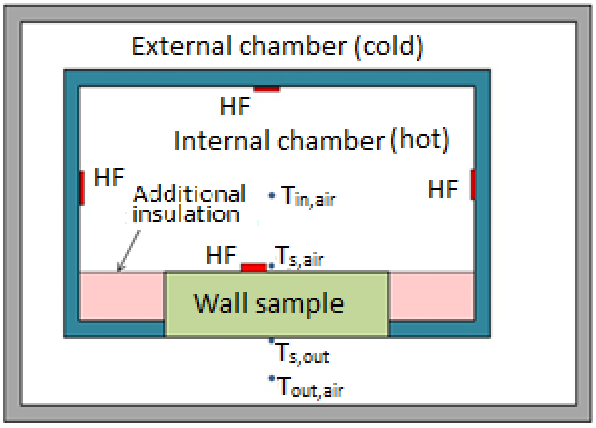


Figure 8-2: External view of the climate chamber at the Department of Architecture and Built Environment (left) and diagram of the chamber layout (right)

The inner chamber dimensions are 1.93m x 1.20m x 2.26m enclosing an area of 2.32m^2 and volume of 5.23m^3 (internal dimensions). The wall panels are rigid PIR sandwich panels with a U-value of 0.44W/m^{2}K. The outer chamber walls were also rigid sandwich insulated panels with an estimated U-value of 0.6W/m^{2}K. The internal dimensions of the outer chamber are 3.6m x 2.4m x 2.8m resulting in an enclosed internal floor area of 8.64m^2 and an internal volume of 24.19m^3 (White, 2014).

Instrumentation

A section of the internal chamber wall panel was removed and the wall sample was installed at the void (Figure 8-2 and Figure 8-3). A solid brick wall comprising a 223mm thick brick layer insulated externally with 100mm EPS insulation was constructed. The wall was finished internally with plaster and externally with render. The wall sample investigated had a width of 1.22m (out of the available 1.93m of the chamber panel) and a height of 2.15m. The size was determined so that the sample would be large enough to investigate the heat flow away from the thermal bridge occurring at the joint between the chamber panels and the wall sample without compromising the structural stability of the inner chamber.

A HUKSEFLUX HFP-01 heat flow meter was installed at the centre of the sample on both the internal and external surface, 60 cm away from the left and right joints of the wall with the chamber panels and 1.05m away from the top and bottom edges. This distance of the sensor to the wall edges was suitable to assume one dimensional heat flow according to BS EN ISO 10211: 2007 (BSI, 2007b). In addition, in order to minimize lateral heat flow, the remaining area of the chamber panel on the left and right of the wall sample was further insulated with 33 cm of rigid insulation (Figure 8-3b).

An array of six thermocouples was installed on each surface of the brick wall ($T_{s,in}$ and $T_{s,out}$ in Figure 8-2); three thermocouples were installed at the centre of the wall at heights 0.5m, 1.05m and 1.6m and another three were installed at the mid-distance between the centre of the wall and the edge (i.e. at a distance of 0.3m from the centre) at the same height intervals. The average of these six sensors was taken as the surface temperature of the wall on the external and internal surface. The set-up of the apparatus for testing the sample wall under transient conditions is presented in Figure 8-3 below. The locations of the sensors at the surface of the wall are presented Figure 8-4.

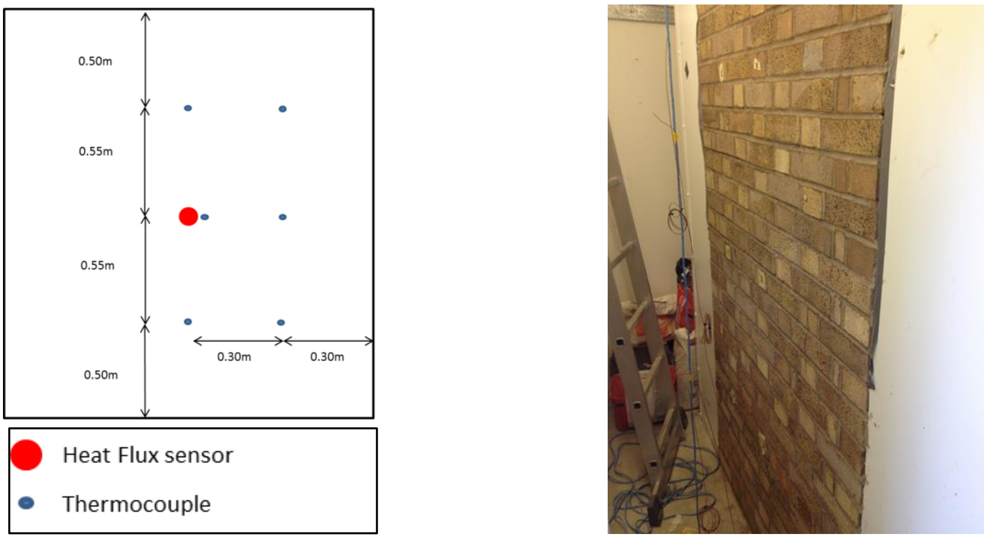
Apart from the brick wall, the rest of the chamber panels were also monitored. One HUKSEFLUX HFP01-05 heat flux sensor was installed on the internal surface of the wall panels as well as on the ceiling and floor (Figure 8-2). Similarly to the brick wall, the surface temperatures were monitored with the use of T-type thermocouples; one thermocouple was installed next to each heat flux sensor at the panel walls ceiling and floor of the chamber

a) Initial state of the inner chamber

b) Section of panel removed to install the brick wall

c) Construction of the brick wall

Figure 8-3: Internal and external views of the inner chamber and the brick wall



a) Diagram of the sensor location at the wall surface

b) Solid brick wall (w/o insulation) completed

Figure 8-4: a) Location of sensors at the surface and b) solid wall completed

The internal and external air temperatures inside the two chambers were also monitored with the use of T-type thermocouples. In order to account for the temperature stratification of the air at the internal chamber, four thermocouples were installed at the centre of the room at different height positions; 10cm, 75cm, 140cm and 215cm from the ground. Similarly, four T-type thermocouples were used to monitor the external air temperature at close proximity (approximately 30cm) to the external surface of wall.

The temperature underneath the chamber floor was also monitored with a K-type thermocouple to account for the effect of heat lost to the ground.

A series of tests were performed in the climate chamber and modifications to the data acquisition and the conditioning equipment and the chamber apparatus were performed in order to ensure accuracy of the readings and minimize the effect of external conditions on the experiment. During the course of these calibration tests, it was found that the results obtained from the climate chamber had excellent repeatability.

The next step of the methodology developed to investigate the dynamic thermal performance of MMC components involved the use of numerical simulations through appropriate Finite Element Analysis Software. A model was created and validated with the use of the tests performed in the climate chamber. The procedure followed and the results are presented in the following paragraphs.

8.5 Finite Element Analysis

Numerical simulations were performed with commercial software ANSYS, one of the most widely used and advanced programs for a range of engineering and physics applications where simulations are required. In practice, ANSYS is a suite of products offering solutions in the areas of structural, thermal, fluid, acoustics and Multiphysics. It widely used by industry and researchers and it is considered to have 'best-in-class solver technologies' (Alawadhi, 2016).

The simulation study was conducted in ANSYS Workbench 16.1 using the Transient Thermal Analysis component using the Finite Element Method for solving the heat conduction equation.

For the case of three-dimensional heat flux, the heat equation becomes:

$$q= -k\left(\frac{\partial T}{\partial x}\hat{i}+ \frac{\partial T}{\partial y}\hat{j}+ \frac{\partial T}{\partial z}\hat{k}\right) \qquad \text{Equation 8-19}$$

In order to solve the three-dimensional heat equation with FEA, the domain is discretized into differential volumes where the energy balance is solved and the heat flux is determined at either side of the volume. For a differential volume dx·dy·dz, the heat flux at the entering sides of the volume is notated as q_x, q_y and q_z while at the opposite sides is then determined by:

$$q_{x+dx}= q_x+ \frac{\partial q_x}{\partial x}dx \qquad \text{Equation 8-20}$$

$$q_{y+dy} = q_y + \frac{\partial q_y}{\partial y} dy \qquad \text{Equation 8-21}$$

$$q_{z+dz} = q_z + \frac{\partial q_z}{\partial z} dz \qquad \text{Equation 8-22}$$

These equations are then used in every differential volume and the heat flow and temperature variation throughout the domain is determined. The ANSYS Transient Thermal component has been used extensively by researchers for a range of heat conduction problems, including building applications (Ravikumar and Srinivasan, 2008, Balocco et al., 2008, Zhu et al., 2010, Haque and Hampson, 2014, Velraj and Daniel, 2014, Alawadhi, 2016) to name a few. Therefore, it was considered suitable for the purpose of the analysis.

8.5.1 Validation of the model

In order to verify the validity of the software, a model was developed to represent the heat processes occurring at the climate chamber described in the previous paragraph. The following two tests conducted in the climate chamber were used to validate the FEA model:

- Test 1: eight hours of heat input
- Test 2: four hours of heat input followed by four hours without heat and then additional four hours of heat input

Testing Protocol

The testing procedure was identical in the two tests with only the pattern of the heating changing. The general procedure was as follows:

- The first stage was the preconditioning period. The chiller unit was switched on and the temperature at the outer chamber was set at constant 10°C. The door of the internal chamber that separated the two chambers was left open for a sufficient amount of time so that uniform temperature was achieved in both chambers (and consequently at both sides of the wall). At this stage, the wall would reach steady state conditions and uniform temperature throughout the construction.
- The second stage was the heat input period. When steady state conditions were achieved, the internal chamber door was closed and sealed in order to minimize the infiltration losses.

Heat input was then applied inside the internal chamber for a set period of time, such that the average air temperature was 25°C. The heat input was provided by means of the 2kW fan heater and controlled by the timer and the thermostat.

- The third stage was the cool-off period. At this stage the heater was switched-off and the wall sample was allowed to cool down for a sufficient amount of time in order to reach near steady state temperature and the sample to be ready for the next test. In the case of test two an intermediate short cool-off period was followed by a second heat input period. After the second heat input, the cool-off period was then applied.
- Due to time limitations the cool-off period was not long enough for the wall sample to reach steady state; nearly steady state conditions were reached. In order to speed up the process the door was opened and uniform temperature was reached in both chambers. This was the preconditioning stage of the following experiment.
- The monitoring rate was 1 minute

The model of the wall was subjected to the same two internal temperature excitations. The wall internal surface temperature was used to compare the simulation results with the monitored data. The results of the validation process are presented in Figure 8-5 and Figure 8-6 respectively. It can be seen that simulated and monitored data were in good agreement and therefore additional confidence on the accuracy of the results was achieved.

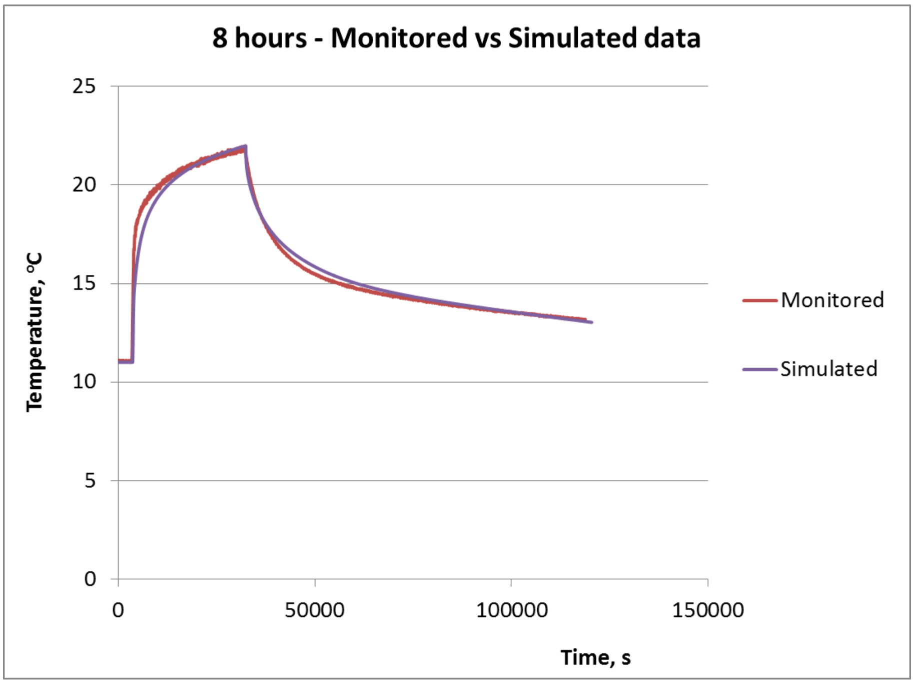


Figure 8-5: Model validation for 8 hours of heat input (wall surface temperature)

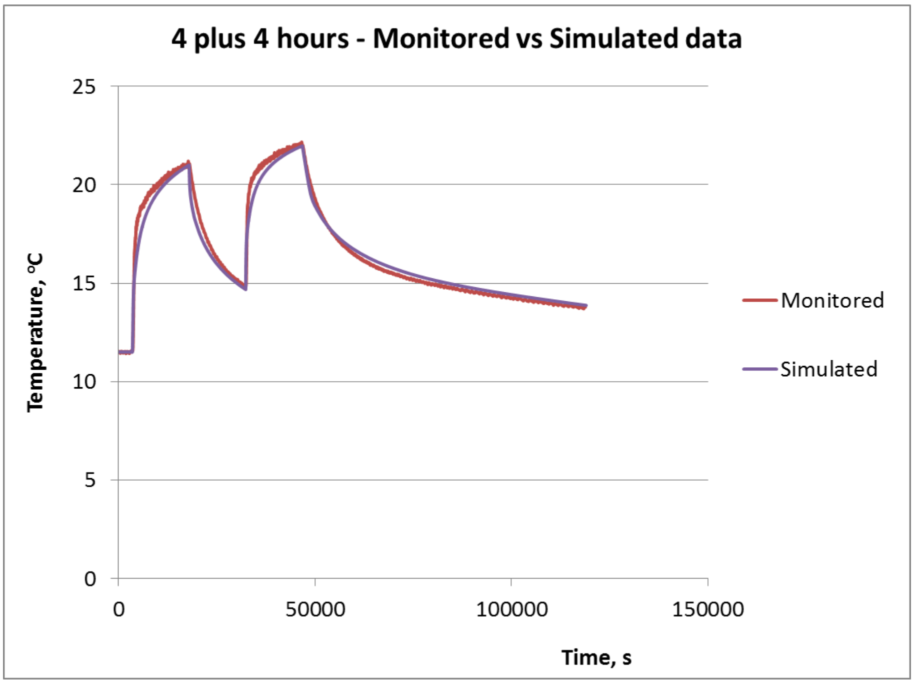


Figure 8-6: Model validation for 4 plus 4 hours of heat input (wall surface temperature)

8.5.2 Methodology

The dynamic properties of the six constructions examined in Chapter 7 are investigated in this section with the use of numerical analysis. A model of each external wall construction found in the Creative Energy Homes was built in ANSYS Workbench 16.1 and the analysis was performed using the ANSYS Transient Thermal Analysis component. The dimensions of each wall section were 1.2m wide and 2.1m high, similar to the wall section investigated experimentally in the climate chamber. The models developed and information on the geometric characteristics and meshing are presented in Figure 8-7 to Figure 8-12.

As discussed in the previous chapter, the U-values of the different external walls found in the houses ranged from 0.10 to 0.18 W/m^{2}K. For reasons of consistency, the models developed were based on a modified version of the CEH walls so that the same U-value would apply for all construction types, 0.15 W/m^{2}K. To achieve the same U-value the following procedure was followed:

- The wall models were built according to the respective drawings from each house
- The material properties were input and assigned to the specific building components
- With the use of the Steady Thermal Analysis component of ANSYS Workbench, the respective heat flow on each wall was calculated and the U-value was determined

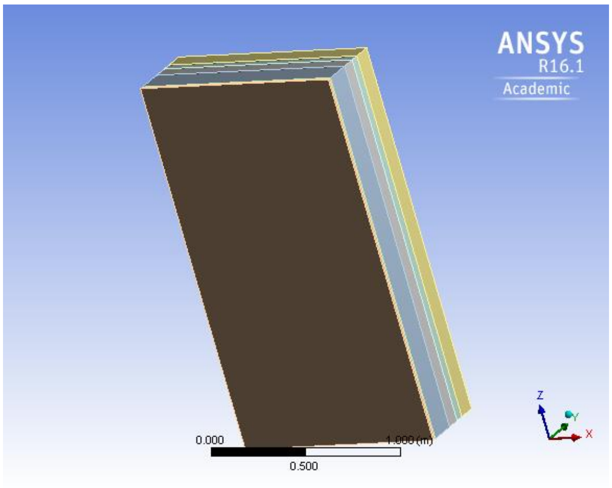
- When required, the thickness of the insulation of the outermost layers of each building element was adjusted accordingly so that the resulting heat flows would correspond to the U-value of 0.15W/m^{2}K.

Two different mesh settings were applied. An automatically generated mesh with medium size was applied to the models of the walls consisting of homogeneous layers, namely the solid masonry, the masonry cavity and the ICF wall. This was selected due to the fact that the model geometry was simple and resulted in significant computational time savings without compromising accuracy; the results for the fine mesh for one of these models were compared to those obtained by applying the medium mesh and were found consistent. The fine mesh was applied to the models of the walls with thermally non-homogeneous layers, namely the timber frame, steel frame and SIP wall since increased accuracy was required to the areas where the frame bridged the insulation layers.

Once the models were developed and calibrated to achieve the same heat flux under steady state conditions, the dynamic analysis was conducted. The following transient thermal loads were applied on the interior and exterior surface of the walls:

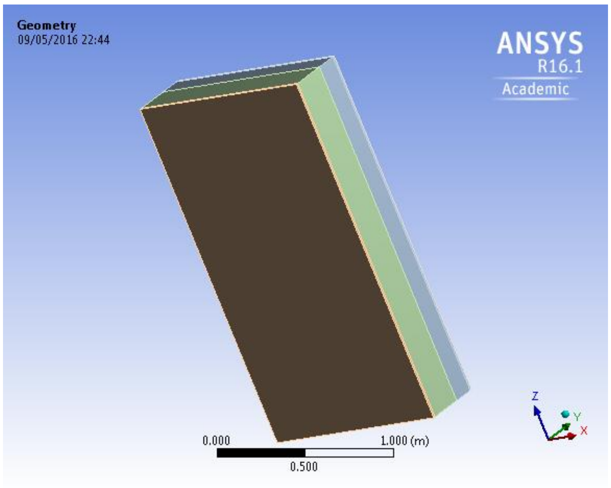
- Sinusoidal temperature with amplitude 1^{o}C and time period, T, 24 hours on the internal surface and steady temperature 0^{o}C on the external surface.
- Steady temperature 0^{o}C on the internal surface and sinusoidal temperature load with amplitude 1^{o}C and time period, T, 24 hours on the external surface.
- Pulse temperature excitation on the internal surface of the wall with magnitude of 1^{o}C and duration 1 hour.
- Actual temperature conditions recorded during the CEH monitoring study for the warmest week of the monitoring period

The first two thermal loads were applied to determine the dynamic thermal properties defined by the Standard BS EN ISO 13786:2007 (BSI, 2007c). The pulse excitation was considered so that the performance of the different constructions would be characterised according to the resulting Unit Response Functions (URFs). Finally, the actual temperature thermal loads were applied to investigate the response of the walls under actual operative conditions and assess the effectiveness of the sinusoidal and pulse excitation methods in describing the performance characteristics of building elements.



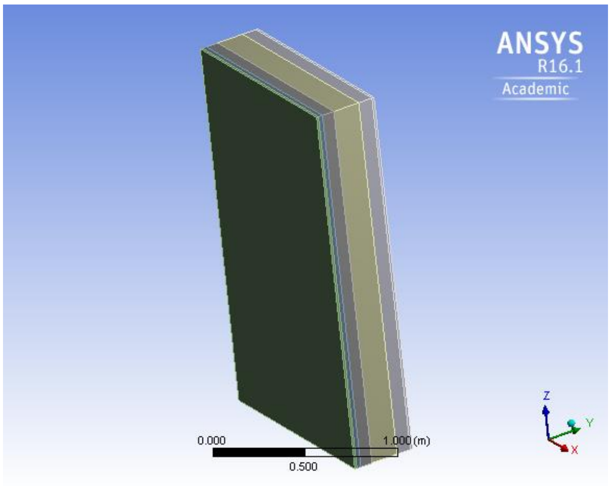
Length X: 1.2 m
Length Y: 0.4055m
Length Z: 2.1
Volume: 1.0219 m^3
Mesh: Medium
Nodes: 7350
Elements: 6120
Initial temperature: 0^oC (Uniform)

Figure 8-7: Model of the masonry cavity wall built in ANSYS Workbench 16.1



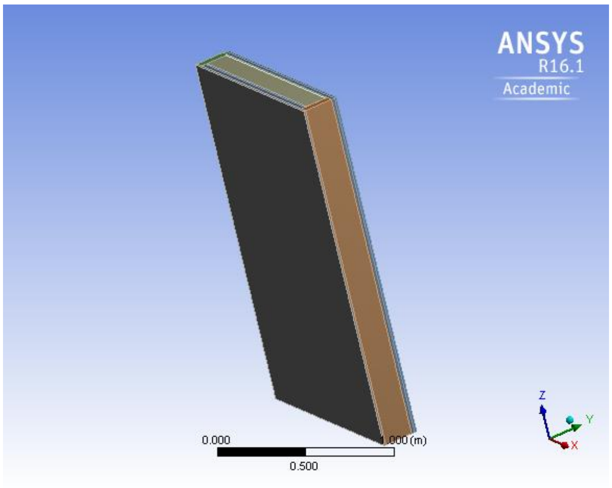
Length X: 1.2 m
Length Y: 0.374 m
Length Z: 2.1
Volume: 0.94248 m^3
Mesh: Medium
Nodes: 6615
Elements: 5440
Initial temperature: 0^oC (Uniform)

Figure 8-8: Model of the solid wall built in ANSYS Workbench 16.1



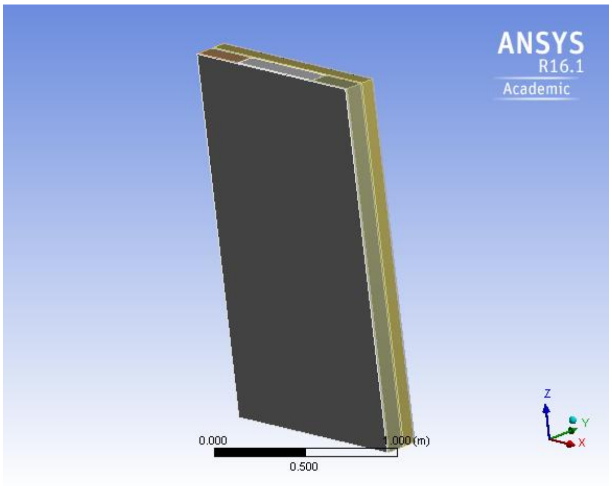
Length X: 1.2 m
Length Y: 0.366 m
Length Z: 2.1
Volume: 0.92232 m^3
Mesh: Medium
Nodes: 6615
Elements: 5440
Initial temperature: 0^oC (Uniform)

Figure 8-9: Model of the ICF wall developed in ANSYS Workbench 16.1



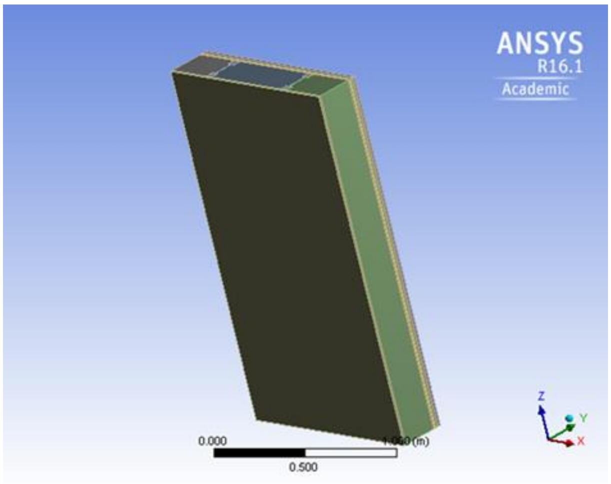
Length X: 1.2 m
Length Y: 0.2175m
Length Z: 2.1
Volume: 0.5481 m^3
Mesh: Fine
Nodes: 23100
Elements: 20060
Initial temperature: 0^{o}C (Uniform)

Figure 8-10: Model of the SIP wall developed in ANSYS Workbench 16.1



Length X: 1.2 m
Length Y: 0.2055m
Length Z: 2.1
Volume: 0.51786 m^3
Mesh: Fine
Nodes: 23100
Elements: 20060
Initial temperature: 0^{o}C (Uniform)

Figure 8-11: Model of the steel frame wall developed in ANSYS Workbench 16.1



Length X: 1.2 m
Length Y: 0.282m
Length Z: 2.1
Volume: 0.71064 m^3
Mesh: Fine
Nodes: 26820
Elements: 23718
Initial temperature: 0^{o}C (Uniform)

Figure 8-12: Model of the timber frame wall developed in ANSYS Workbench 16.1

8.6 Results and Discussion

The results of the simulation analysis for the sinusoidal temperature excitations, the pulse excitations and the actual weather thermal loads are presented below.

8.6.1 Sinusoidal excitation

First, the properties proposed by the BS EN ISO 13786:2007 Standard (BSI, 2007c) to describe the dynamic performance of building elements, namely the admittance, periodic thermal transmittance and the heat capacity were numerically computed. For this, the response of the walls under two temperature excitations was determined; a) unit sinusoidal temperature excitation at the internal side of the wall when the temperature at the opposite side was kept zero and b) unit sinusoidal temperature excitation at the external side of the wall when the temperature at the internal side was zero. The results of the numerical analysis were then compared to the results determined following the calculation method proposed by the Standard; the analytical calculation was performed with the use of the Dynamic Properties Calculator software developed by ARUP and launched by The Concrete Centre (ARUP, 2010).

In order to ensure that the response of each wall was not affected by thermal storage phenomena, the numerical simulations were performed for a 7-day period considering the same diurnal unit temperature cyclic variation. The results presented were taken from the last day of the simulation when the response of the wall had stabilised and the resulting heat flow values were identical to those from the previous day. The thermal admittance calculated numerically for each construction type was compared to that determined with the calculation method provided by the International Standard BS EN ISO 13786:2007.

<u>Masonry cavity wall</u>

The model of the masonry cavity wall is presented in Figure 8-7. The resulting heat flows on the internal surface of the wall from the sinusoidal unit temperature excitation as calculated by the by the BS EN ISO 13786:2007 Standard and numerically are presented in Figure 8-13. The thermal admittance calculated numerically was found to be 1.825 W/m^2K, slightly lower than the 1.92 W/m^2K calculated analytically with the ISO Standard.

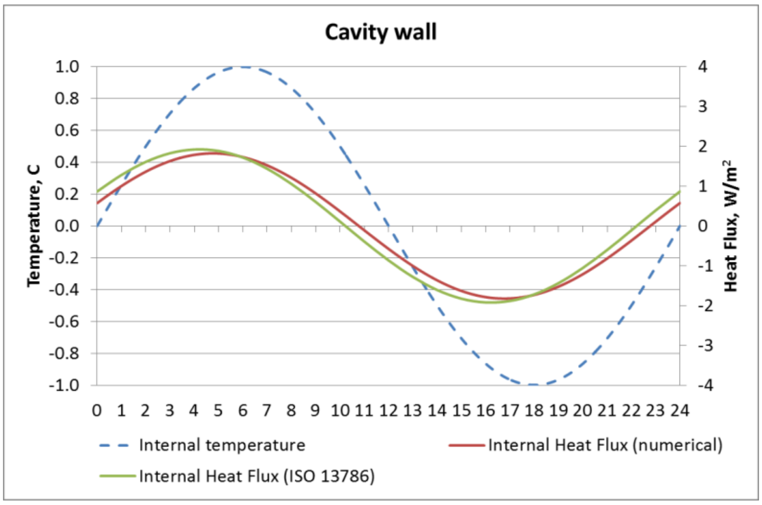


Figure 8-13: Heat flow variation on the internal surface of the cavity wall calculated numerically and with the BS EN ISO 13786:2007 method from a cyclic temperature excitation at the same surface

Solid Masonry wall

The model of solid masonry wall built in ANSYS Workbench is shown in Figure 8-8. The resulting heat flow from the sinusoidal unit temperature load as determined through the numerical and the analytical calculation are presented in Figure 8-14. It can be seen that in the case of the solid masonry wall the analytical calculation and the numerical computational method resulted in very similar values of thermal admittance, 2.13 W/m^{2}K and 1.976 W/m^{2}K respectively.

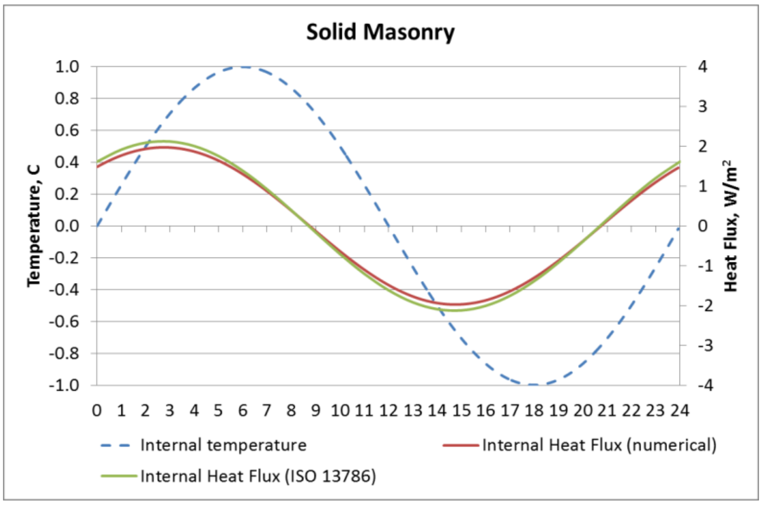


Figure 8-14: Heat flow variation on the internal surface of the solid wall calculated numerically and with the BS EN ISO 13786:2007 method from a cyclic temperature excitation at the same surface

ICF wall

The model developed of the ICF wall for the numerical analysis is shown in Figure 8-9. The sinusoidal unit temperature load and the resulting heat flow as determined from the two methodologies are presented in Figure 8-15. The thermal admittance calculated numerically was found lower than the value of the thermal admittance determined with the analytical method, 0.499 W/m^2K against 0.81 W/m^2K.

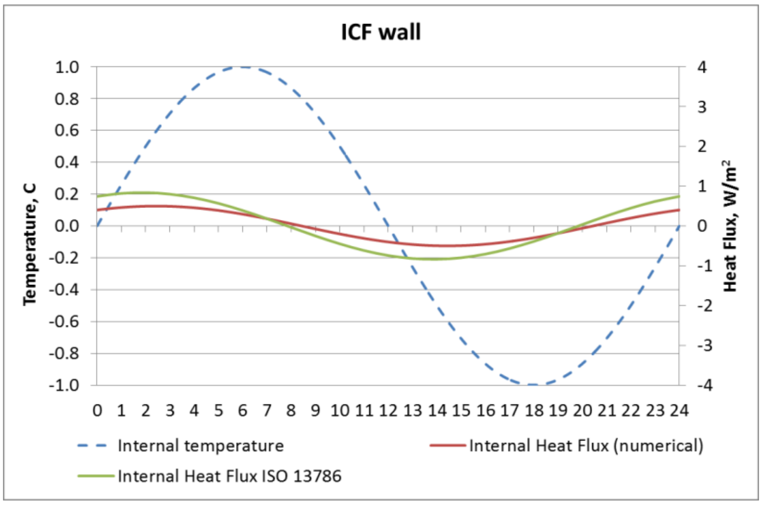


Figure 8-15: Heat flow variation on the internal surface of the ICF wall calculated numerically and with the BS EN ISO 13786:2007 method from a cyclic temperature excitation at the same surface

<u>SIP wall</u>

The SIP panel wall model developed in ANSYS Workbench 16.1 is shown in Figure 8-10. The resulting thermal admittance as calculated by the methodology of the International Standard and numerically is presented in Figure 8-16. The thermal admittance calculated numerically was found to be 0.81 W/m^2K, lower than the 1.14 W/m^2K calculated with the ISO Standard methodology. It should be noted that the admittance value reported for the numerical calculation was based on the heat flow at the centre of the wall where the heat flow is one dimensional (the 'centre of cavity' as defined by Kosny et al. (2007), ignoring the increased heat flows at the location of the frame. This was done for reasons of consistency because the analytical method of BS EN ISO 13786:2007 applies only to components comprising homogeneous layers and therefore the effect of the frame was also ignored. The actual admittance value for the whole wall section was found to be 0.81 W/m^2K when accounting for the effect of the frame on the heat flows ('clear wall' (Kosny et al., 2007))

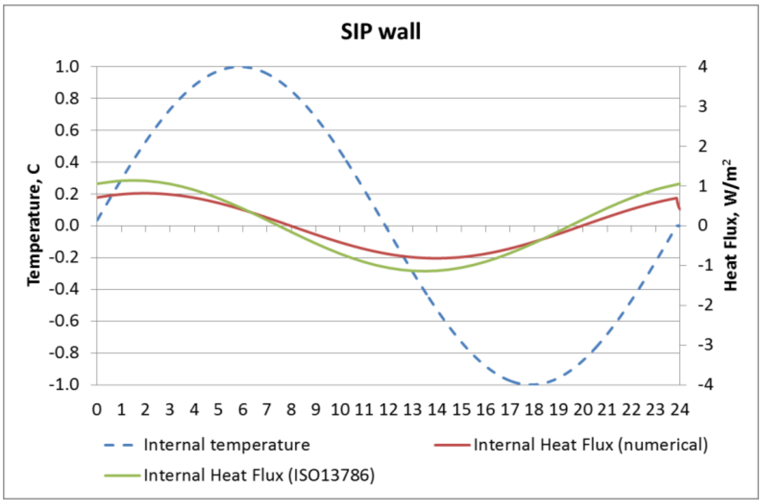


Figure 8-16: Heat flow variation on the internal surface of the SIP wall calculated numerically and with the BS EN ISO 13786:2007 method from a cyclic temperature excitation at the same surface

<u>Steel frame wall</u>

The model and the information on the numerical analysis of the steel frame wall can be seen in Figure 8-11. The resulting heat flow variation on the internal surface of the wall due to the sinusoidal unit temperature excitation is shown in Figure 8-17. The admittance value calculated analytically was 0.94 W/m^{2}K, higher than the 0.62 W/m^{2}K computed by the Finite Element Analysis software ('centre of cavity'). The 'clear wall' thermal admittance value (the value for the whole wall including the frame) was also found to be 0.94W/m^{2}K.

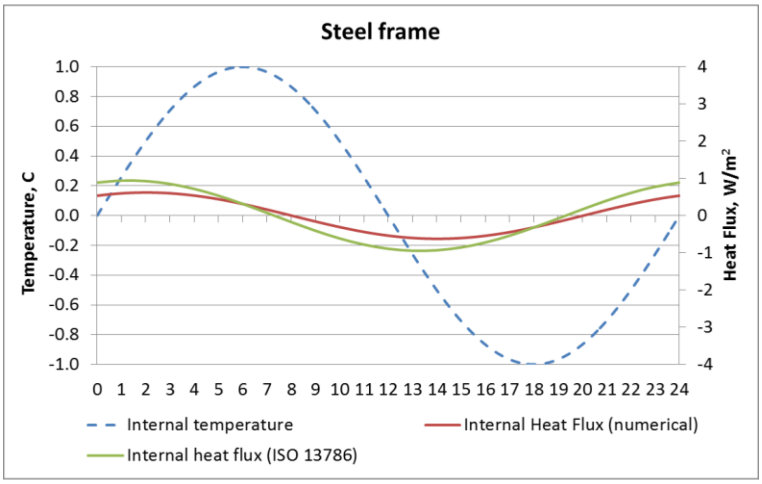


Figure 8-17: Heat flow variation on the internal surface of the steel frame wall calculated numerically and with the BS EN ISO 13786:2007 method from a cyclic temperature excitation at the same surface

<u>Timber frame wall</u>

The model for the timber I-joist wall is presented in Figure 8-12. The results of the analysis considering the two methods are presented in Figure 8-18. Similarly to the analysis of the SIP and steel frame wall, due to the fact that the analytical solution considered homogeneous layers and ignored the effect of the timber frame, the results of the numerical analysis presented in refer to the 'centre of cavity' of the wall where the framing effect is neglected. The admittance value was calculated numerically to be 0.72 W/m^{2}K while through the analytical solution it was found to be 1.30 W/m^{2}K. The 'clear wall' admittance value was found to be 0.93 W/m^{2}K.

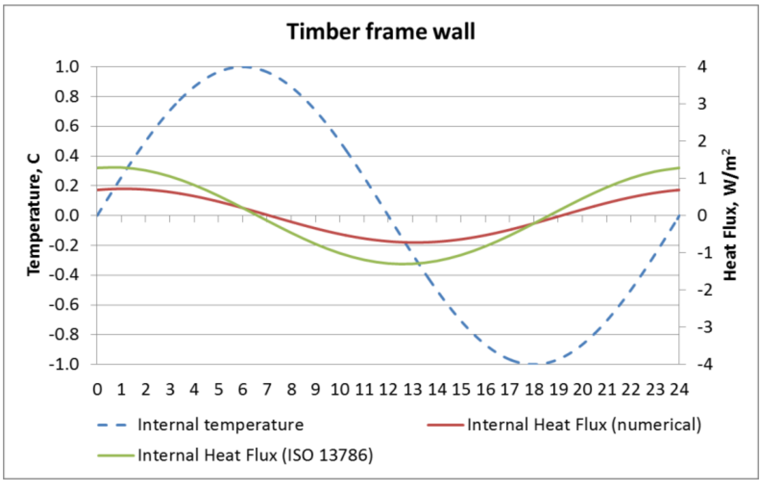


Figure 8-18: Heat flow variation on the internal surface of the timber frame wall calculated numerically and with the BS EN ISO 13786:2007 method from a cyclic temperature excitation at the same surface

The thermal admittance for each construction calculated both analytically and numerically is presented in Figure 8-19.

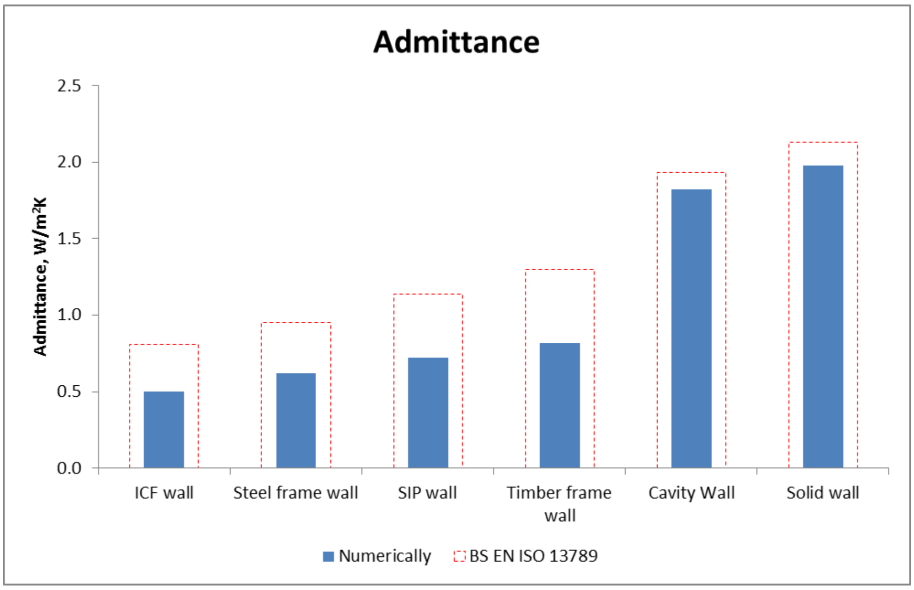


Figure 8-19: Cyclic variation of heat flows as a result of cyclic temperature excitation on the wall models examined

The solid wall appears to be the most responsive to the unit temperature excitation followed by the cavity wall. The admittance value for these walls was found to be 1.976 W/m^{2}K and 1.825 W/m^{2}K respectively using the FEA software. Next, was the steel frame wall with an admittance value of 0.937 W/m^{2}K followed by the timber frame wall with 0.928W/m^{2}K. The SIP wall had a very similar admittance value of 0.815 W/m^{2}K. Finally, the ICF wall was found to have the lowest cyclic heat flow variation with a thermal admittance value of 0.499 W/m^{2}K. It can be seen that the admittance values determined analytically were very similar for masonry cavity and the solid wall while they were somewhat different for the steel frame, the timber frame, SIP and the ICF wall.

The dynamic properties of the different constructions calculated numerically are presented in Table 8-1. It should be noted that the values in the table refer to the 'clear wall' performance, i.e. the repeating thermal bridges are accounted for.

Table 8-1: Dynamic thermal properties

Wall	Thermal Admittance, Y_{mm} (W/m²K)	Thermal Admittance, Y_{nn} (W/m²K)	Periodic thermal transmittance, Y_{mn} (W/m²K)	Heat Capacity, C_m (internal) J/K	Heat Capacity, C_n (external) J/K	Areal heat capacity, k_m (internal) J/m²k	Areal heat capacity, k_n (external) J/m²k	Decrement factor, f
Solid wall	1.975	0.932	0.023	68330	4960	27115	1968	0.153
Cavity wall	1.825	6.689	0.015	62720	231280	24889	91778	0.097
ICF wall	0.499	0.908	0.00225	17199	31396	6825	12459	0.015
SIP panel	0.815	1.135	0.075	25650	36759	10179	14587	0.498
Timber frame	0.928	0.896	0.117	28033	27061	11124	10738	0.781
Steel frame	0.937	0.464	0.146	26852	11567	10656	4590	0.975

8.6.2 Pulse excitation

The response of the walls at both surfaces under a pulse temperature excitation is presented here. The unit response function (URF) of the six constructions on the internal side to the unit pulse temperature excitation on the same side is presented in Figure 8-20 below. The respective URF graph on the external side of the construction from the temperature pulse at the opposite side is presented in Figure 8-21.

With regards to the response at the internal surface, it can be seen that the solid wall appears to be the most responsive construction, absorbing a peak of approximately 5W/m^2 followed by the timber frame wall, the masonry cavity wall and the steel frame wall with a peak of approximately 2.7 W/m^2 to 3.0 W/m^2. The SIP and the ICF wall absorbed the least amount of heat during this transient. With regards to readmitting the heat back to the interior space, again the solid wall was found to the most responsive releasing a peak of approximately 3.5 W/m^2 followed by the timber frame wall and the steel frame wall. It can be seen that the cavity wall released the least amount of heat, approximately 1W/m^2 suggesting that most of the heat absorbed by the wall was stored at the internal layers of the construction.

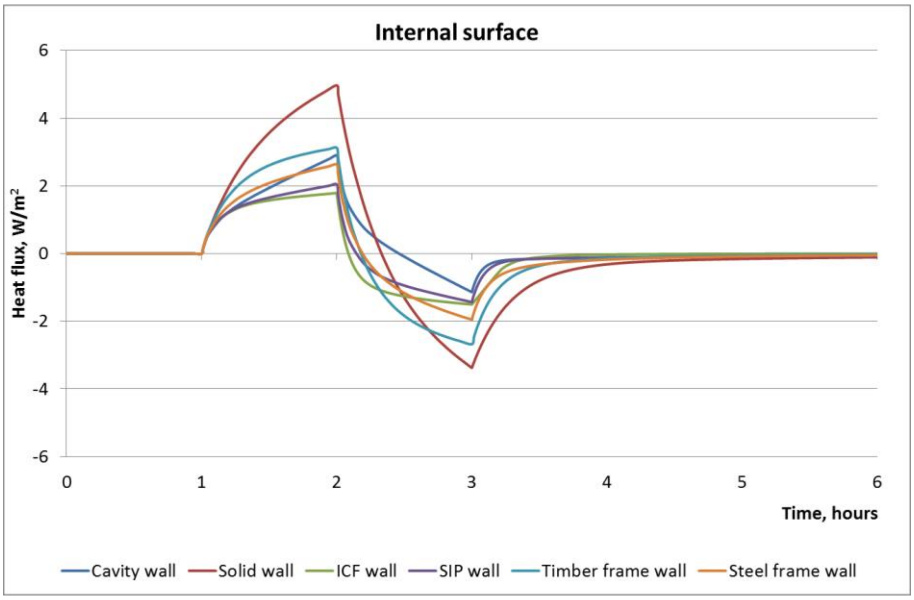


Figure 8-20: Unit response function of the internal surface six wall constructions to a unit pulse temperature excitation on the same side

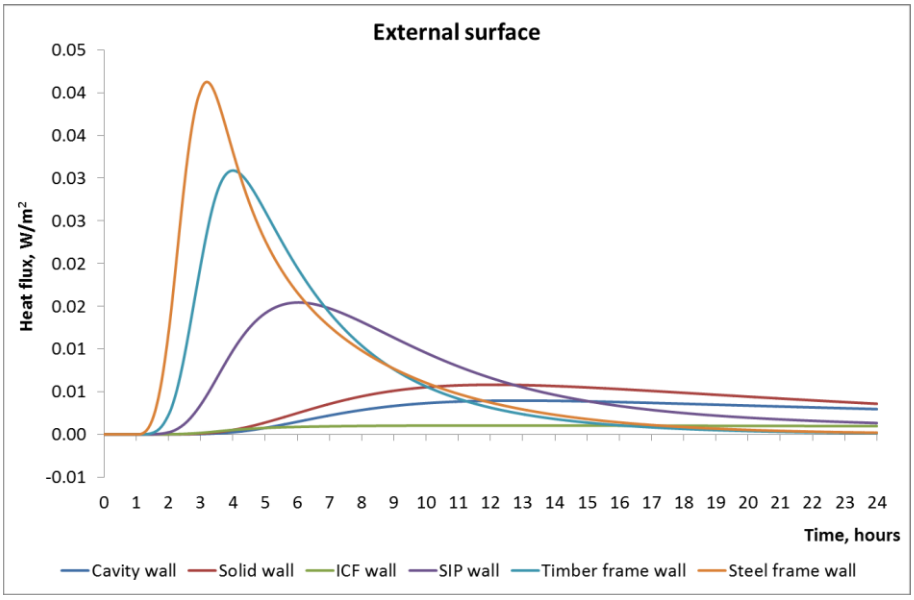


Figure 8-21: Unit response function of the external surface six wall constructions to a unit pulse temperature excitation on the internal side

The response of the walls at the external side shows that the steel frame wall loses all the heat within 24 hours of the temperature pulse. The amount heat exiting the outside surface of the wall peaks at approximately 0.04 W/m^2 roughly 1.5 hours after the temperature pulse peak suggesting very small buffering time. The timber frame wall also had very fast response releasing the maximum amount of heat (0.03 W/m^2) approximately two hours after the peak of the pulse occurred. Similarly to the steel frame wall, the heat transient in the timber frame is completed within 24 hours from the temperature excitation. The SIP wall appears to have a slower response to the timber and steel frame constructions with the peak amount of heat exiting the wall surface of approximately 0.02 W/m^2 occurring 4 hours after the pulse maximum. Within the first 24 hours of the temperature excitation most, but not all, of the heat transfer was completed.

In contrast, the solid wall and the cavity wall had significantly slower response. The peak heat flow at the surface of the solid wall occurred approximately 11 hours after the temperature peaked while in the case of the cavity wall no such distinctive peak amount of heat flow exiting the wall surface can be determined. The ICF wall was found to have the slowest response of the three. During the first 24 hours, the heat transient was not completed in any of these three walls with large amount of heat still left to be released.

8.6.3 Actual weather analysis

In order to evaluate the results of the two methods for the characterisation of the transient response of building elements presented in the previous paragraphs, namely the sinusoidal and the pulse excitation, the next step of the analysis considered the performance of the building elements under actual observed internal and external conditions. An appropriate thermal load was applied at both sides of the wall constructions and the resulting heat flows were recorded.

The scope of this work is to examine the ability of building elements to regulate elevated internal temperatures. Therefore, the period with the highest recorded temperatures was chosen as the applied thermal load at the external surface of the wall. With regards to the internal thermal load, the recorded internal temperatures at the living room of the Tarmac Code 4 house for the same period were applied.

The warmest week of the monitoring period was between the 22nd and the 27th of July 2014. Peak temperatures during that week were consistently between 26°C and 28°C with minimum temperature between 15°C and 16°C. Internal temperatures were between approximately 23.5°C and 25.5°C. The external and internal temperature profiles for that period are shown in Figure 8-22. The resulting heat flows for the different constructions in response to the applied external and internal temperature excitations are presented in Figure 8-23.

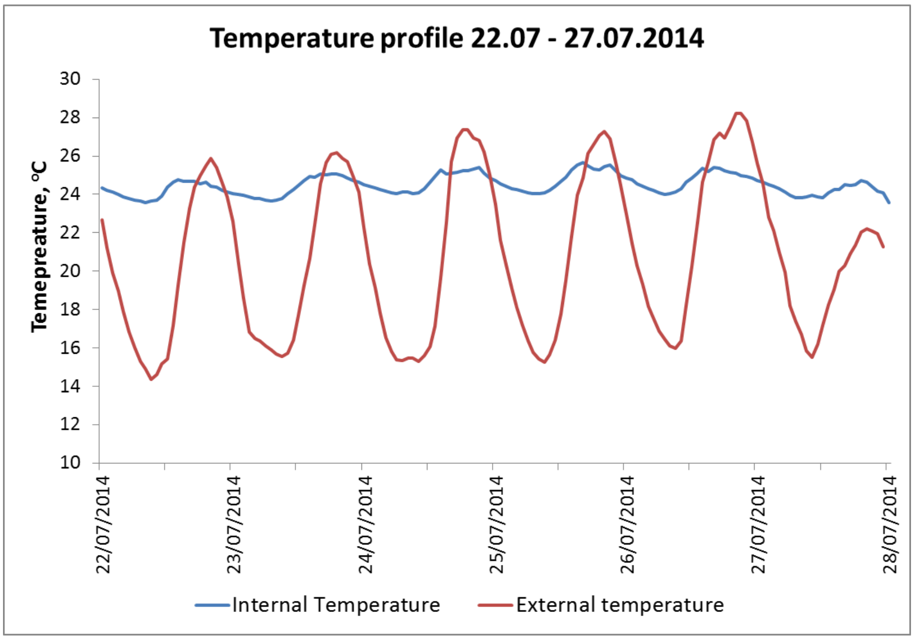


Figure 8-22: Internal and External temperature profiles for the period 22.07 – 27.07.2014

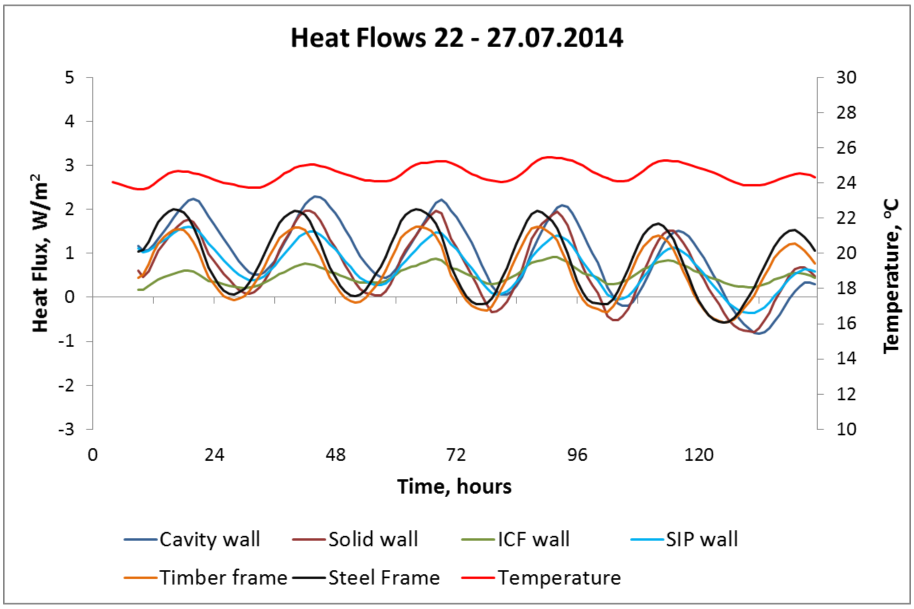


Figure 8-23: Resulting heat flows at the internal side of the six wall constructions for the period 22.07 – 247.07.2014

It can be seen that there is a phase difference between the peak heat flux entering the surface of the timber and steel frame and the rest of the constructions. The steel frame and timber frame walls had a faster response on the internal temperature excitation. The response of the cavity wall appears to have the largest time delay of all the constructions, while the solid wall, the SIP and ICF wall were found to have comparable responses with the peaks and lows of heat flux occurring at approximately the same time.

With regards to the heat balance of the walls, the cavity wall absorbed the largest amount of heat during the course of the period examined. On average approximately 0.97 W/m^2 were absorbed by the cavity wall on a daily basis. The steel frame wall was ranked second in terms of net heat balance; it was found to absorb slightly lower amount of heat than the cavity wall, 0.87 W/m^2 on average per day. The SIP wall absorbed on average 0.73 W/m^2 and the solid wall 0.69 W/m^2. The timber frame wall absorbed on average 0.61 W/m^2 and the ICF wall 0.49W/m^2.

The performance of the solid wall considering the net heat balance was poor. However, it can be seen that the peak heat flux entering the surface of the solid wall is comparable to that of the cavity and the steel frame walls and higher than that of the SIP wall. In terms of heat flux fluctuation it was found that on average the solid wall and the steel frame wall had the highest values of diurnal variation; 3.12 and 3.15 W/m^2 respectively. Therefore, the fact that the net heat balance on the wall surface suggests that the solid wall is able to absorb only small amounts of heat is due to the fact that the solid wall is also releasing heat; more so than the rest of the constructions. The cavity wall and the timber frame wall were found to have slightly lower fluctuation; 2.6 and 2.8 W/m^2.

The SIP wall fluctuation was approximately 1.9 W/m^2 while the ICF wall had the smallest average value of approximately 1 W/m^2.

The time delay of the solid wall heat flux (approximately five to six hours compared to the steel frame one) also suggests that the performance of the wall could be more favourable than the steel frame wall, as the heat is being released to space when the zone temperature is lower. Similarly, the cavity wall heat flow had a larger time delay compared to the timber frame construction.

Heavyweight solid wall

The analysis may have showed that the admittance value was not able to provide reliable estimates on the performance of all the building systems examined. It should be noted that the wall constructions examined seemingly had large relative differences in the admittance value. However, this difference was not great in absolute terms. The range of Y-values was between approximately 0.5 W/m^{2}K and 2W/m^{2}K. Hens (2013) argued that for a building element to be effective at regulating the internal zone temperature it should have an admittance of approximately 4W/m^{2}K.

For this reason, a hypothetical construction was also examined. The wall structure was a heavyweight solid wall, identical to the Tarmac Code 6 solid wall examined earlier but considering heavyweight blocks instead of aircrete blocks. The resulting admittance value of the wall was numerically calculated to 7.8 W/m^{2}K. The relative performance of the heavyweight solid wall against the solid wall (Y=1.98 W/m^2) and the steel frame wall (Y=0.94W/m^2) is shown in Figure 8-24.

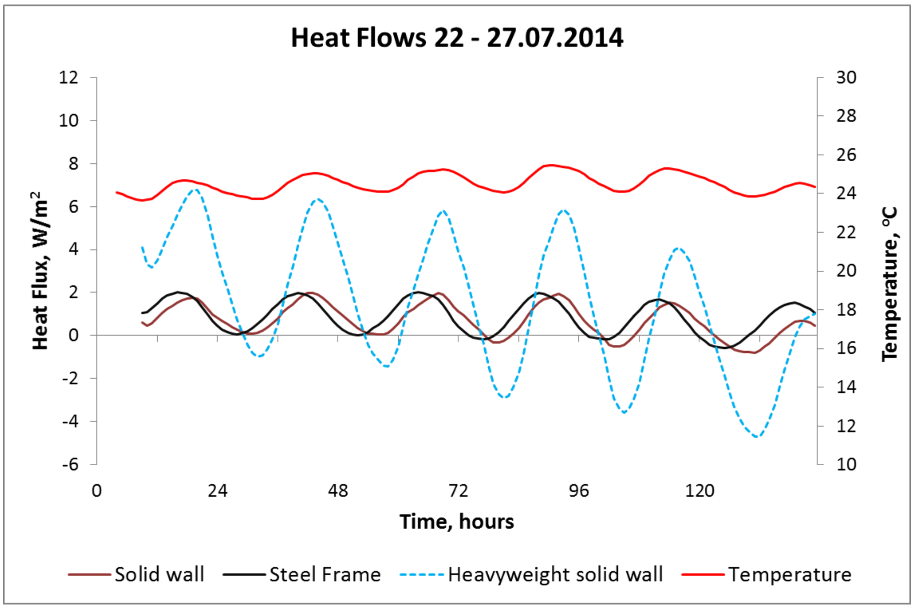


Figure 8-24: Resulting heat flows at the internal side of the heavyweight solid wall compared to the solid and steel frame wall for the period 22.07 – 24.07.2014

It appears that the heavyweight wall is significantly more responsive than the other two walls, absorbing and releasing significant more heat than the other two constructions. The average daily heat flux variation was approximately three times higher than that of the other constructions. On average the heavyweight wall absorbed 1.53W/m^2, significantly more than the solid wall (average rate of 0.69W/m^2) and the steel frame that had a heat flux rate of 0.87W/m^2. In addition, the heavyweight wall also presents similar time delay than the solid wall, making it overall a preferential option for regulating the internal conditions in a zone.

8.7 Conclusions and suggestions for further work

The study presented in this chapter focused on the dynamic performance of six commonly used MMC walls. The thermal response of the walls was examined under specific temperature excitations, sinusoidal and pulse temperature, and under actual weather and internal temperature conditions. This was performed in order to evaluate first the heat flows under the set conditions considered by the common methodologies widely used to predict the transient performance of building elements, and then compare the findings with the performance of these walls under actual operating conditions.

The dynamic properties of the constructions as defined in the ISO 13786:2007 were calculated numerically with the use of appropriate Finite Element Analysis software and analytically using the Dynamic Properties Calculator software. The admittance value, which is the most common property used to predict the heat exchange between the surface of a building element and the adjacent zone and is considered a measure of the thermal inertia, was calculated both numerically and analytically. The two methods provided very similar results in the case of the masonry solid and the cavity wall; however, somewhat different results for the rest of the constructions were produced. It should be noted that the differences were found on very low values of admittance, i.e. a small absolute error would lead to a more significant discrepancy. Nevertheless, in both cases the analysis showed that the solid wall and the cavity wall were the constructions with the highest levels of thermal admittance while the rest of the constructions had low values of thermal admittance.

With regards to the pulse temperature excitation the resulting heat flows at both surfaces of the walls were examined. The investigation of heat flow at the external surface of the wall suggested that the timber frame, steel frame and SIP wall had a much faster response than the ICF, masonry cavity and solid wall. After 24 hours, the heat transient had been completed in the former constructions; due to heat storage inside the masonry walls and the ICF, heat flux was still being released by these three walls.

Examining the heat flows under the fixed temperature excitations led to the derivation of very clear conclusions regarding the response of the constructions. However, actual operating conditions, where the temperature varies in both surfaces of the walls, are significantly more complex than the sinusoidal and pulse excitations which consider steady temperature at one of the surfaces. It was found that in terms of net heat balance the cavity wall was absorbing the largest amount of heat on average, while the steel frame wall absorbed marginally less amount of heat. The net heat flux on the internal surface of the timber frame wall suggested that it absorbed on average more heat than the cavity wall. The SIP panel and the ICF wall were found to have the lowest amount of average heat flux entering their surfaces.

The results of the analysis showed that the daily heat flux variation under actual temperature conditions was very similar in walls with large relative differences in admittance values; the masonry solid ($Y = 1.975\ W/m^2K$, $\kappa = 27.1\ kJ/m^2K$) and the steel frame wall ($Y = 0.937\ W/m^2K$, $\kappa = 10.6\ kJ/m^2K$) had almost the same variation in the resulting heat flux; the cavity ($Y = 1.825\ W/m^2K$, $\kappa = 24.9\ kJ/m^2K$) and timber frame ($Y = 0.928\ W/m^2K$, $\kappa = 11.1\ kJ/m^2K$) also had very similar performance.

However, the two masonry constructions presented a larger time delay which is preferential as these walls present the ability to regulate the peak temperatures and release the excessive heat at time when the zone temperature is lower. The thermal admittance as a metric to characterise heat flow variation was not found suitable for all constructions. The time delay at the wall response therefore appears to have significant value at the predicted performance of the wall.

It should also be noted that the ICF wall was the only construction that was found to be constantly absorbing heat, without releasing any heat to space. This suggests that the ICF wall would be a more suitable solution in applications that benefit from long-term heat storage.

Examining a hypothetical construction with significantly higher admittance value than the other constructions ($Y = 7.18W/m^2K$) showed that the heavyweight option had preferential performance compared to the other options. It released and absorbed much larger amount of heat than the other constructions, with an associated time delay in its response. It appeared that in this case, the argument made by Hens (2013) was valid.

This seems to be also in accordance with the suggestions made by Kendrick et al. (2012) that constructions commonly used in the UK do not offer high levels of available thermal mass. The three masonry constructions examined did not present significantly different performance compared to the three lightweight constructions, namely the timber frame, steel frame and SIP walls. Yet, the admittance value for all six walls did not range significantly. Therefore it is proposed for future work that a sensitivity analysis is performed in order to identify the resulting heat exchange of a building element to the surrounding zone as a function of the admittance value and determine whether there is a limit in the admittance value that results in significant difference in the heat flows as Hens (2013) suggested. Furthermore, it is recommended for future work to perform these tests in a laboratory setting and evaluate the response of actual physical components.

CHAPTER 9. CONCLUSIONS AND FUTURE WORK

The use of Modern Methods of Construction is expected to increase significantly in the future as these methods have significant advantages compared to traditional masonry construction methods. However, specific concerns regarding the overheating potential of these methods exist and may restrict their growth in the future. It was therefore considered timely to investigate the thermal performance of MMC. The work presented aimed at the following:

- Investigate whether dwellings built with MMC are likely to suffer from overheating now or in the future;
- Assess whether the risk of overheating of houses built with MMC was higher than that of dwellings built with modern masonry construction methods;
- Evaluate the thermal performance of non-traditional (i.e. not masonry) elements and their effectiveness in reducing the overheating risk of MMC constructions without adding significant weight to the structure;
- Investigate the actual as-built performance of MMC and modern masonry building elements through gathering temperature and heat flow monitoring data; and
- Assess the dynamic characteristics of various constructions and evaluate their ability to estimate the thermal response of the construction elements under actual operating conditions.

9.1 Conclusions

The parametric study was conducted to investigate the overheating risk of the Nottingham H.O.U.S.E. and the potential of two PCM boards and a gypsum board to provide additional levels of thermal mass without increasing significantly the weight of the structure. Several zones of the house were found to suffer from high temperatures while the use of materials to provide additional levels of thermal mass were found able to reduce the overheating occurrence.

The materials examined were found to have varying levels of effectiveness in regulating internal temperatures. The use of up to three layers of Rigidur H reduced the occurrence of elevated temperatures by approximately 2 percent in absolute terms compared to plasterboard; a relative improvement of 15% up to 67% in the different zones. Despite the fact that concrete was found to be slightly more effective than Rigidur H (when considering the same number of layers) it was found that adding two layers of Rigidur had a profound effect in reducing overheating, more so than one layer of concrete. The PCM boards were the most effective components and they managed to reduce overheating significantly or in some cases eliminate it. These results were promising and can be used to inform designers on alternative construction components when assessing the performance of different construction methods. These are solutions that may easily be incorporated to existing MMC components (such as the timber frame walls examined) and improve their thermal performance.

The next step monitoring the internal ambient zone temperatures in two houses in the Green Street development, one built with timber frame construction and the other with modern masonry construction. The results suggested that timber frame construction, and it would not be unreasonable to assume that most MMC with similar levels of thermal mass, will experience elevated temperatures in the future climate to a great extent. This was in accordance with the general perception that MMC are likely to face overheating problems. In the current climate, overheating was barely an issue in just one zone; nevertheless comfort temperatures were exceeded for approximately 12% up to 16% of time in the different zones.

In comparison, modern masonry construction also had very slight overheating issue in one zone in the current climate. Temperatures above the comfort level were also exceeded but this was for fairly shorter periods (up to 42% relative improvement in some cases) than when timber frame construction was considered. With regards to future climate, it was seen that the performance of modern masonry cavity wall construction was very similar to that of timber frame. The occurrence of elevated temperatures above the CIBSE overheating thresholds set for specific zones considering the use of timber frame walls and masonry cavity walls was very similar for the two cases. Masonry construction presented slightly reduced levels of overheating, up to 12% improved performance compared to timber frame, but that was limited in certain zones and climate.

Examining the internal temperatures solely however presented certain limitations as it did not allow assessing the effect of the building elements on the resulting indoor temperatures. The monitoring study of the two dwellings in Green Street showed that the internal temperatures were also greatly affected by parameters such as building use and internal gains, occupancy rate, ventilation patterns and building design.

Therefore, the next step of the analysis involved monitoring the heat flows at the surface of the building elements. Building components of different constructions found in the houses of the Creative Energy Homes (CEH) project, MMC and modern masonry, were monitored for a period ranging from twelve to eighteen months. In addition, the in situ performance of PCM boards was also assessed in practice. The two ceiling elements that were fitted with PCM boards were found to store more heat than the respective internal wall elements that were finished with conventional plasterboard. However, they were found in practice to store increased amounts of heat at a larger temperature range than expected based on the product specifications. This was more prominent in the Smartboard that was covered by plasterboard suggesting that the method of installation affected the performance of the PCM board.

The analysis of the heat flows occurring at the external walls did not show a great difference in the performance of the different building elements; apart from the SIP wall that was the least responsive the rest of the constructions did not present clear differences. In terms of net heat balance, the masonry walls (cavity, solid and ICF wall) were found to store more heat than the respective panellised (steel frame, timber frame and SIP wall) constructions on a daily basis. However, the timber and steel frame constructions were found to absorb comparable amounts of heat to the masonry walls, large amount of which they were releasing back to space. Again, it was found that any direct comparison of the different constructions would be subject to the significantly different conditions found in each dwelling. The houses examined had significantly different design and geometry, occupancy profile and subsequent building use. For this reason, the external wall constructions were then examined under the same fixed conditions with the use of FEA software.

The FEA analysis of the six wall constructions found at the CEH houses aimed at evaluating the dynamic characteristics of the building elements and determine whether these characteristics were able to estimate the response of the walls under normal operating conditions. It was found that the admittance value, Y, and the areal heat capacity, κ, the most common properties used to evaluate the thermal inertia of constructions, were not able to predict the performance of the wall constructions in all cases. It should be noted that despite the fact that some of the constructions were considered heavyweight and some lightweight - the terms regard the weight of the structure rather than the available thermal mass - the difference in the admittance value was not large in absolute values. All constructions investigated had a much lower value with the highest values reaching approximately $2W/m^2K$.

A hypothetical heavyweight alternative of the solid block wall was also examined to assess these arguments. The heavyweight wall had an admittance value of $7.18W/m^2K$. It was found that the heavyweight wall was the most effective construction in storing the excess heat from space, both in terms of net heat balance and in terms of daily heat fluctuation. In other words it was able to store approximately twice as much heat as the other walls in absolute values. Furthermore, it was also able to store and release almost three times the amount of heat on average on a daily basis compared to the rest of the constructions examined.

The following overarching findings were derived from this work:

- Overheating is an issue that dwellings built with MMC will experience in the future and may also experience in present climate. The levels of overheating of these houses built with MMC, however, will not be significantly different than that of houses built with modern masonry methods. For this reason the use of MMC should not be ignored on the basis of their higher risk of overheating.
- Non-traditional materials are able to provide additional levels of thermal mass and can be readily incorporated to existing panellised structures. If these solutions are taken into account at the design stage, any difference between the performance of MMC and masonry construction will be reduced even further.
- Thermal mass is an effective strategy to regulate internal elevated temperatures. In order to benefit fully from the potential of thermal mass as a strategy to regulate internal temperatures, however, masonry constructions should be in thermal contact to the internal space.
- Evidence on the long-term performance of PCM boards in situ under normal operating conditions was presented for the first time. The ceiling elements with PCM boards were found to store more heat than conventional boards. It was found that the increased heat storage due to phase change occurs at larger than expected temperature range.
- The metrics commonly used to characterise the thermal inertia of constructions were not able to deliver an accurate estimate of the predicted response of all constructions examined. The dynamic thermal properties reflected on the performance of some but not all constructions. However, the admittance did provide a valid estimate of a heavyweight alternative.

9.2 Suggestions for future work

Quantifying the dynamic response of building elements in situ is a complex task. This work is the first to report findings from the long term monitoring of actual building systems. It is of great importance that more such long-term studies are conducted in order to gain more confidence on the performance of MMC onsite. The limitations found in this study can be used to improve future studies. The following are suggested:

- Where possible housing units of identical design and different construction should be selected for monitoring. This will eliminate the effect of the design and geometry on the thermal response of the zones and elements.
- An integrated monitoring approach should be considered where parameters such as zone occupancy, window opening, ventilation rates and temperatures on the adjacent zones are accounted for, in order to determine the relative effect of the building use parameters on the element heat flows. The use of wireless sensors to monitor adjacent zones will solve the problem of damaging the construction.
- Where possible large scale monitoring studies should be conducted. Monitoring a large number of dwellings will eliminate any differences in the building use by reporting on the average performance of the constructions.
- Further monitoring studies of the actual in situ performance of components incorporating PCM are proposed in order to verify the findings of this study. In addition, further monitoring studies on the in situ performance of MMC building elements are suggested.
- Conducting a sensitivity analysis to identify whether a minimum level of thermal inertia is required in order for these metrics to provide an accurate estimation is also suggested.
- Finally, apart from the need for monitoring studies there is also need for laboratory testing as well. Rigorous physical testing in a climate chamber setting in order to verify the results of the Finite Element Analysis is recommended for further work.

It is understood that the proposed suggestions for future work will require significant resources. However, these studies are necessary to provide designers with reliable recommendations in order to deliver design solutions that will enhance the thermal comfort of occupants and mitigate the levels of overheating in the future.

REFERENCES

ALAWADHI, E. 2016. *Finite Element Simulations Using ANSYS,* Boca Raton, CRC Press.

AMOAKO-ATTAH, J. & JAHROMI, A.-B. 2015. Method comparison analysis of dwellings' temperatures in the UK. *Engineering Sustainability,* 168**,** 11.

ARCC CN. 2012. *Adaptation and Resilience in a Changing Climate – Coordination Network* [Online]. Available: http://www.arcc-cn.org.uk/ [Accessed 5th January 2013].

ARES, E. 2016. Zero Carbon Homes - Briefing Paper Number 6678.

ARUP 2010. Dynamic Thermal Property Calculator v.1.0. MPA The Concrete Centre.

ARUP RESEARCH AND DEVELOPMENT AND BILL DUNSTER ARCHITECTS 2005. UK Housing and Climate Change: Heavyweight vs lightweight construction. London: Ove Arup and Partners Ltd.

ASHRAE 2002. Guideline 14-2002: Measurement of Energy and Demand Savings. Atlanta, Georgia: ASHRAE.

ASHRAE 2009. Chapter 19: Energy estimating and modeling methods. *2009 ASHRAE Handbook: Fundamentals.* SI ed. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE 2010. ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy. SI ed. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE 2013. Chapter 18: Nonresidential cooling and heating load calculations. *2013 ASHRAE Handbook: Fundamentals.* SI ed. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ATHIENITIS, A. K. & SANTAMOURIS, M. 2002. *Thermal Analysis and Design of Passive Solar Buildings,* London, James & James (Science Publishers) Ltd.

ATTMA 2010. Technical Standard L1 - Measuring Air Permeability of Building Envelopes (Dwellings). Northampton: The Air Tightness Testing and Measurement Association.

BAILEY, D. J. 2015. *A performance evaluation of mainstream timber frame and traditional masonry housing in the UK.* Doctor of Philosophy, The University of Nottingham.

BALARAS, C. A. 1996. The role of thermal mass on the cooling load of buildings. An overview of computational methods. *Energy and Buildings,* 24**,** 1-10.

BALOCCO, C., GRAZZINI, G. & CAVALERA, A. 2008. Transient analysis of an external building cladding. *Energy and Buildings,* 40**,** 1273-1277.

BANHAM, J., GRAEF, R., FAULKNER, K. & MAC DONALD, M. 2012. Building the Homes and Communities Britain Needs.

BARKER 33 CROSS-INDUSTRY GROUP. 2006. *Modern Methods of Construction: An examination of the barriers to the greater use of Modern Methods of Construction in the provision of new housing and the mechanisms to overcome them - executive summary of final report* [Online]. Available: http://www.constructingexcellence.org.uk/pdf/hforum/MMC_Final_Executive_Summary.pdf [Accessed 21st October 2012].

BARKER, K. 2004. Review of Housing Supply - Delivering Stability: Securing our Future Housing Needs. Norwich.

BARLOW, J. & OZAKI, R. 2005. Building mass customised housing through innovation in the production system: lessons from Japan. *Environment and Planning A,* 37**,** 9-20.

BARNARD, N., CONCANNON, P. & JAUNZENS, D. 2001. Modelling the performance of thermal mass. London.

BASF 2006. Micronal PCM Smartboard - Intelligent Temperature Management in an Extremely Lightweight Approach. Ludwigshafen, Germany: BASF.

BASF 2008. Micronal PCM - Intelligent Temperature Management for Buildings. Ludwigshafen, Germany: BASF SE.

BASF no date-a. Building a Sustainalble Future: The BASF House - UK Project. BASF plc.

BASF no date-b. Project Reference Reducing CO_2 in buildings - Energy Efficient Housing. BASF plc.

BATES, L. 2015. 2013 UK Greenhouse Gas Emissions, Final Figures. London.

BEIZAEE, A., LOMAS, K. J. & FIRTH, S. K. 2013. National survey of summertime temperatures and overheating risk in English homes. *Building and Environment,* 65**,** 1-17.

BERNSTEIN, H. M., GUDGEL, J. & LAQUIDARA-CARR, D. 2011. Prefabrication and Modularization. *Smart Market Report: increasing Productivity in the Construction Industry.* Bedford, MA.

BRITISH GYPSUM 2012. Rigidur for Offsite applications: Product Data Sheet. British Gypsum Saint Gobain.

BROWN, W. C. & STEPHENSON, D. G. 1993. A guarded hot box procedure for determining the dynamic response of full-scale wall specimens - Part I. *ASHRAE Transactions***,** 10.

BSI 1996. BS EN ISO 8990:1996 - Thermal insulation - Determination of steady-state thermal transmission properties - Calibrated and guarded hot box. London: BSI Standards Limited.

BSI 1999. BS EN 13187:1999 Thermal performance of buildings - Qualitative detection of thermal irregularities in building envelopes - Infrared method. London: BSI Standards Limited.

BSI 2001. BS EN ISO 13829: 2001 - Standard Thermal Performance of Buildings -Determination of air permeability of buildings - Fan pressurisation method. London: BSI Standards Limited.

BSI 2005. BS EN ISO 7730:2005 - Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. London: BSI Standards Limited.

BSI 2007a. BS EN 15251:2007 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. London: BSI Group.

BSI 2007b. BS EN ISO 10211:2007 Thermal bridges in building construction — Heat flows and surface temperatures — Detailed calculations (ISO 10211:2007). London: BSI Group.

BSI 2007c. BS EN ISO 13786:2007 – Thermal performance of building components – Dynamic thermal characteristics – Calculation methods. London: BSI Group.

BSI 2014. BS ISO 9869-1:2014 - Thermal Insulation - Building Elements - In-situ measurement of thermal resistance and thermal transmittance - Part 1: Heat flow meter method. London: BSI Standards Limited.

BUILDOFFSITE 2012. Buildoffsite Review 2012 The business case for offsite. London.

CABINET OFFICE 2011. Government Construction Strategy. London: Cabinet Office.

CIBSE 2007. *Guide A: Environmental Design,* London, Chartered Institution of Building Services Engineers.

CIBSE. 2013. *CIBSE Weather Data - Current, Future, Combined & DSYs for London* [Online]. CIBSE. [Accessed 10th of June 2015 2015].

CIBSE 2015a. *Building performance modelling AM11:2015,* London, CIBSE publications.

CIBSE 2015b. *Guide A: Environmental Design,* London, Chartered Institution of Building Services Engineers.

CIBSE JOURNAL 2013. Simulation gets real. *CIBSE Journal.* Cambridge: Cambridge Publishers Ltd.

CLARKE, J. A. 2001. *Energy simulation in building design* Oxford Butterworth-Heinemann.

Climate Change Act 2008 (c.27). London: The Stationary Office.

CLIMATE EAST MIDLANDS & NOTTINGHAMSHIRE COUNTY COUNCIL 2011. A summary of the Local Climate Impacts Profile. Climate East Midlands, Nottingham City Council.

COLEY, D., KERSHAW, T., EAMES, M., COX, P., STEPHENSON, D., STAINFORTH, D., HARRISON, S., MORTON, T. & BUTLER, D. 2011. PROMETHEUS: The Use of Probabilistic Climate Change Data to Future-Proof Design Decisions in the Building Sector.

COUNCIL OF THE EUROPEAN UNION 2002. 2002/358/EC: Council Decision of 25 April 2002 concerning the approval, on behalf of the European Community, of the Kyoto Protocol to the United Nations Framework Convention on Climate Change and the joint fulfilment of commitments thereunder.

CUTLAND CONSULTING LIMITED 2012. Low and Zero Carbon Homes: Understanding the Performance Challenge. Watford, UK: NHBC Foundation and IHS BRE Press.

DAVIES, I. 2009. Sustainable Construction Timber Sourcing and Specifying Local Timber. Edinburgh: Forestry Commission Scotland.

DCLG 2015. Table 209: permanent dwellings completed, by tenure and country. *In:* 209, L. T. (ed.). Department for Communities and Local Government.

DE SAULLES, T. 2012. *Thermal Mass Explained,* Camberley, Surrey, Concrete Centre.

DECC 2011. The Carbon Plan: Delivering our low carbon future. London: Department of Energy and Climate Change.

DECC 2014. The Government's Standard Assessment Procedure for Energy rating of Dwellings 2012 edition. Garston: BRE.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT 2006. Building a Greener Future: Towards Zero Carbon Development - Consultation. Wetherby: Communities and Local Government Publications.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT 2008a. The Code for Sustainable Homes - Setting the standard in sustainability for new homes. Wetherby: Communities and Local Government Publications.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT 2008b. Innovative Construction Products and Techniques. Wetherby.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT 2010a. Code for Sustainable Homes: Technical Guide. London: Communities and Local Governement Publications.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT 2010b. Household Projections, 2008 - 2033, England. *Housing Statistical Release.* London, National Statistics: Communities and Local Government.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT 2012. Investigation into Overheating in Homes: Literature Review London: Department for Communities and Local Government.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT 2014a. Affordable Homes Programme to transform the way we build.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT 2014b. Code for Sustainable Homes Technical Guide - Code Addendum (2014) England. London: Department for Communities and Local Government.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT 2014c. Housing Zones Prospectus. London: Department of Communities and Local Government.

DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT 2015. 2012-based Household Projections: England 2012 - 2037. *Housing Statistical Release.* London: Communities and Local Government.

DEPARTMENT OF ENERGY AND CLIMATE CHANGE 2009. The UK Low Carbon Transition PLan: National strategy for climate and energy. Norwich: The Stationary Office.

DETAIL GREEN 2009. Saving 120 tonnes of CO_2. *Detail Green.* Munich: Institut für internationale Architektur-Dokumentation GmbH & Co. KG.

DIAMOND, S., DAS BHAUMIK, C., MYLONA, A. & VIRK, G. 2015. Assessing overheating risk - Evidence Review. London.

DJONGYANG, N., TCHINDA, R. & NJOMO, D. 2010. Thermal comfort: A review paper. *Renewable and Sustainable Energy Reviews,* 14**,** 2626-2640.

DUSKA, M., BARTAK, M., DRKAL, F. & HENSEN, J. L. M. 2006. Analytical approach to transient heat conduction in cooling load calculations. *Proceedings of the 17th Int. Air-conditioning and Ventilation Conference.* Prague: STP - Society of Environmental Engineering.

EAMES, M., KERSHAW, T. & COLEY, D. 2011. On the creation of future probabilistic design weather years from UKCP09. *Building Services Engineering Research and Technology,* 32**,** 127-142.

EDSL 2009. Tas Theory Manual. EDSL Documentation.

EDSL 2010. Tas 9.2.1 Dynamic Thermal Analysis Software. Milton Keynes, UK: Environmental Design Solutions Ltd. .

EDSL. 2015a. *Leading the field...* [Online]. Environmental Design Solutions Limited. [Accessed 23rd January 2016].

EDSL. 2015b. *Tas Engineering* [Online]. Environmental Design Solutions Limited. [Accessed 23rd January 2016].

EDSL. 2015c. *Validation* [Online]. Environmental Design Solutions Limited. [Accessed 23rd January 2016].

EGAN, J. 1998. Rethinking Construction. Norwich, UK.

EMMITT, S. & GORSE, C. 2014. *Barry's introduction to construction of buildings,* Chichester, John Wiley and Sons, Ltd.

ENERGY SAVING TRUST 2005a. Building energy efficient buildings using modern methods of construction. London: EST and BRE.

ENERGY SAVING TRUST 2005b. Reducing overheating - A designer's guide. *Energy Efficiency Best Practice in Housing.* London: Energy Saving Trust.

ENGSTRÖM, S., SARDÉN, Y. & STEHN, L. Towards improving client-contractor communication in industrialised building. *In:* DAINTY, A., ed. Procs 25th Annual ARCOM Conference, 7-9 September 2009 2009a Nottingham, UK. Association of Researchers in Construction Management, 21-30.

ENGSTRÖM, S., STEHN, L. & SARDÉN, Y. Competitive impact of industrialised building - in search for explanations to the current state. *In:* DAINTY, A., ed. Procs 25th Annual ARCOM Conference, 7-9 September 2009 2009b Nottingham, UK. Association of Researchers in Construction Management, 413-24.

FAWCETT, R., ALLISON, K. & CORNER, D. 2005. Using modern methods of construction to build homes more quickly and efficiently. London: National Audit Office.

FEIST, W. 2007. Passivhaus Planning Package - PHPP (Version 1.0) [Software]. Darmstadt, Germany: Passivhaus Institut.

FEIST, W., PFLUGER, R., KAUFMANN, B., SCHNIEDERS, J. & KAH, O. 2007. *Passive House Planning Package 2007,* Darmstadt, Passivhaus Institut.

FERRARI, S. & ZANOTTO, V. 2013. The thermal performance of walls under actual service conditions: Evaluating the results of climatic chamber tests. *Construction and Building Materials,* 43**,** 309-316.

FERTIGHAUSWELT. 2014. *Fertighauswelt* [Online]. [Accessed 14 Jan 2014].

FORD, B., WILSON, R., GILLOTT, M., IBRAHEEM, O., SALMERON, J. & SANCHEZ, F. J. 2012. Passive downdraught evaporative cooling: performance in a prototype house. *Building Research & Information,* 40**,** 290-304.

FORTMEYER, R. 2011. *Why Not Timber High-Rises?* [Online]. Melbourne: Niche Media Pty Ltd. Available: http://www.australiandesignreview.com/features/1966-why-not-timber-high-risesr [Accessed 03 March 2014].

GAZE, C., ROSS, K., NOLAN, E., NOVAKOVIC, O. & CARTWRIGHT, P. 2007a. Modern Methods of Construction (MMC) in housing: Drivers and barriers to their use. IP3/07 ed. Garston, Watford.

GAZE, C., ROSS, K., NOWAK, F. & NOLAN, E. 2007b. Modern Methods of Construction (MMC) in housing: Planning for manufactured housing. IP3/07 Part 2 ed. Garston, Watford.

GEMINI DATALOGGERS LTD. 2016. *Tinytag Ultra 2 Data Loggers* [Online]. Gemini Dataloggers Ltd. [Accessed 23 February 2016].

GETHING, B. 2010. Design for future climate: Opportunities for adaptation in the built environment. Swindon: Technology Strategy Board.

GETHING, B. & PUCKETT, K. 2013. *Design for Climate Change,* London, RIBA Publishing

GILLOTT, M., RODRIGUES, L. & SPATARU, C. 2010a. Low-carbon housing design informed by research. *Proceedings of the Institution of Civil Engineers-Engineering Sustainability,* 163**,** 77-87.

GILLOTT, M., RODRIGUES, L. T. & SPATARU, C. 2010b. Low-carbon housing design informed by research. *Proceedings of the ICE - Engineering Sustainability* [Online], 163. Available: http://www.icevirtuallibrary.com/content/article/10.1680/ensu.2010.163.2.77.

GUPTA, R. & GREGG, M. 2012. Using UK climate change projections to adapt existing English homes for a warming climate. *Building and Environment,* 55**,** 20-42.

HACKER, J., CAPON, R. & MYLONA, A. 2009. Use of Climate Change Scenarios for Building Simulation: The CIBSE Future Weather Years. London: Chartered Institution of Building Services Engineers (CIBSE).

HACKER, J., HOLMES, M., BELCHER, S. & DAVIES, G. 2005a. *Climate change and the indoor environment: impacts and adaptation,* London, The Chartered Institute of Building Services Engineers.

HACKER, J. N., BELCHER, S. E. & CONNELL, R. K. 2005b. Beating the Heat: keeping UK buildings cool in a warming climate. *UKCIP Briefing Report.* Oxford: UKCIP.

HACKER, J. N., DE SAULLES, T. P., MINSON, A. J. & HOLMES, M. J. 2008. Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change. *Energy and Buildings,* 40**,** 375-384.

HAQUE, E. & HAMPSON, P. 2014. Modelling phase change in a 3D thermal transient analysis. *The International Journal of Multiphysics,* 8**,** 19.

HENS, H. 2013. *Performance based building design,* Berlin, Ernst & Sohn.

HENSEN, J. L. M. & RADOSEVIC, M. 2004. Teaching building performance simulation - some quality assurance issues and experiences. *PLEA 2004 - 21st International Conference on Passive and Low Energy Architecture.* Eidhoven, Netherlands.

HM GOVERNMENT 2010. Approved Document L1A: Conservation of fuel and power in new dwellings. 2010 Edition ed. London: NBS.

HM GOVERNMENT 2013a. Approved Document L1A: Conservation of fuel and power in new dwellings. 2013 Edition ed. London: NBS.

HM GOVERNMENT 2013b. Construction 2025 Industrial Strategy: government and indystry in parthership *In:* SKILLS, D. F. B. I. A. (ed.).

HOLMANS, A. 2013. New Estimates of Housing Demand and Need in England, 2011 to 2031. *Town and Country Planning Tomorrow.* London.

HOMES AND COMMUNITIES AGENCY 2014. Affordable Homes Programme 2015 - 2018 Prospectus. London: Homes and Communities Agency.

HULME, J., BEAUMONT, A. & SUMMERS, C. 2013. Energy Follow-Up Survey 2011 - Report 7: Thermal comfort and overheating.

IGLOO. 2013. *Blueprint Project Nottingham: Green Street in the Meadows* [Online]. Igloo. Available: http://www.igloo.uk.net [Accessed 25th June 2014].

INFRASTRUCTURE AND PROJECTS AUTHORITY 2016. Government Construction Strategy 2016-2020. *In:* AUTHORITY, I. A. P. (ed.).

JANKOVIC, L. 2012. *Designing zero carbon buildings using dynamic simulation methods,* Abingdon, Routledge.

JENKINS, G. J., MURPHY, J. M., SEXTON, D. M. H., LOWE, J. A., JONES, P. & KILSBY, C. G. 2009. UK Climate Projections: Briefing Report. version 2 ed. Exeter, UK.

JOHNSTON, D., MILES-SHENTON, D., FARMER, D. & WINGFIELD, J. 2013. Whole House Heat Loss Test Method (Coheating). Leeds Metropolitan Univeristy.

KENDRICK, C., OGDEN, R., WANG, X. & BAICHE, B. 2012. Thermal mass in new build UK housing: A comparison of structural systems in a future weather scenario. *Energy and Buildings,* 48**,** 40-49.

KIAMBA, L. 2016. *Optimising Environmental Design Strategies to Improve Thermal Performance in Office Buildings in Kenya.* Doctor of Philosophy Ph.D., University of Nottingham.

KNAUF 2013. Knauf Comfortboard 23 Gypsum board GBK with latent heat storage for sustainable temperature management. Knauf.

KOSNY, J., YARBROUGH, D., CHILDS, P. & SYED, A. M. 2007. How the Same Wall Can Have Several Different R-values: Relations Between Amount of Framing and Overall Thermal Performance in Wood and Steel-Framed Walls. *Thermal Performance of the Exterior Envelopes of Whole Buildings X International Conference.* Clear Water, Florida: Oak Ridge National Laboratory.

LATHAM, M. 1994. Constructing the Team - Final Report. London, UK.

LESSING, J. 2006. *Industrialised House-Building Concept and Processes.* PhD Licentiate Thesis, Lund UniversitY.

LEWIS, S. 2014. *PHPP Illustrated - A Designer's Companion to the Passivhaus Planning Package,* Newcastle upon Tyne, RIBA publishing.

LINNER, T. & BOCK, T. 2012. Evolution of large-scale industrialisation and service innovation in Japanese prefabrication industry. *Construction Innovation: Information, Process, Management,* 12**,** 156-178.

LOMAS, K. J. & KANE, T. 2013. Summertime temperatures and thermal comfort in UK homes. *Building Research & Information,* 41**,** 259-280.

LOWENSTEIN, O. 2008. Towering Timber. *The Architect's Journal.* London: Architects' Journal

LU, N. 2007. *Investigation of the designers' and general contractors' perceptions of offsite construction techniques in the United States construction industry.* Doctor of Education Clemson University.

LU, N. & BAUSMAN, D. C. 2009. Comparative Study on Offsite Construction Techniques in the U.S. Building Construction. *SC 45th Annual International Conference Proceedings.* Gainesville FL: University of Florida.

LYRIAN, D., SOEBARTO, V. & WILLIAMSON, T. Assessing the simulation capability of the AccuRate engine in modelling massive construction elements. *In:* WURTZ, E., ed. Proceedings pf BS2013: 13th Conference of International Building Performance Simulation Association, 2013 Chambéry, France. 2709-2715.

MAHAPATRA, K., GUSTAVSSON, L. & HEMSTRÖM, K. 2012. Multi-storey wood-frame buildings in Germany, Sweden and the UK. *Construction Innovation: Information, Process, Management,* 12**,** 62-85.

MAPSTON, M. & WESTBROOK, C. 2010. Prefabricated building untis and modern methods of construction. *In:* HALL, M. R. (ed.) *Materials for energy efficiency and thermal comfort in buildings.* Cambridge: Woodhead Publishing LImited and CRC Press LLC.

MARK GROUP 2013. Mark Group Ecohouse - Energy saving technologies shaping efficient future living. Mark Group Ltd.

MARSHALL, D., WORTHING, D., HEATH, R. & DANN, N. 2014. *Understanding Housing Defects,* New York, Routledge.

MARTÍN, K., FLORES, I., ESCUDERO, C., APAOLAZA, A. & SALA, J. M. 2010. Methodology for the calculation of response factors through experimental tests and validation with simulation. *Energy and Buildings,* 42**,** 461-467.

MCLEOD, R., MEAD, K. & STANDEN, M. 2010. Passivhaus primer: Designer's guide - Aguide for the design team and local authorities. Watford: BRE.

MEAD, K. & BRYLEWSKI, R. 2010. Passivhaus primer: Introduction - An aid to understanding the key principles of the Passivhaus Standard. Watford: BRE.

MET OFFICE. 2015a. *Midlands Climate* [Online]. HMSO. Available: http://www.metoffice.gov.uk/climate/uk/regional-climates/mi [Accessed 23rd February 2016].

MET OFFICE. 2015b. *Nottingham Climate* [Online]. HMSO. Available: http://www.metoffice.gov.uk/public/weather/climate/gcrjm8jf7 [Accessed 23rd February 2016].

MILES, J. & WHITEHOUSE, N. 2013. Offsite Housing Review. London: Construction Industry Council.

MINISTRY OF LAND INFRASTRUCTURE TRANSPORT AND TOURISM. 2014. *Data of the Current Survey on Construction Statistics* [Online]. Construction Research and Statistics Office. Available: http://www.mlit.go.jp/toukeijouhou/chojou/stat-e.htm [Accessed 13 Jan 2014 2014].

MPA - THE CONCRETE CENTRE 2011. Thermal Performance: Part L1A. Camberley, Surrey: MPA - The Concrete Centre.

MYLONA, A. 2012. The use of UKCP09 to produce weather files for building simulation. *Building Services Engineering Research & Technology,* 33**,** 12.

MYLONA, A., MAVROGIANNI, A., DAVIES, M. & WILKINSON, P. 2015. Defining overheating - Evidence Review. London.

NADIM, W. & GOULDING, J. S. 2010. Offsite production in the UK: the way forward? A UK construction industry perspective. *Construction Innovation: Information, Process, Management,* 10**,** 181 - 202.

NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES 2009. Advancing the Competitiveness and Efficiency of the U.S. Construction Industry. Washington DC.

NATURAL SCOTLAND 2013. Scotland's Sustainable Housing Strategy. Edinburgh: The Scottish Government.

NG, S.-C., LOW, K.-S. & TIOH, N.-H. 2011. Newspaper sandwiched aerated lightweight concrete wall panels—Thermal inertia, transient thermal behavior and surface temperature prediction. *Energy and Buildings,* 43**,** 1636-1645.

NHBC FOUNDATION 2012. Overheating in new homes: A review of the evidence. Milton Keynes: IHS BRE Press.

NICOL, F., HUMPHREYS, M. & ROAF, S. 2012. *Adaptive thermal comfort: Principles and practice,* Oxon, Routledge.

NICOL, F. & SPIRES, B. 2013. TM52 The Limits of Thermal Comfort: Avoiding Overheating in European Buildings. London.

NICOL, S., BEER, C. & SCOTT, C. 2014. The age and construction of English homes - A guide to ageing the English housing stock. Watford.

O'CONNOR, N. & CAPON, R. 2015. Overheating in Homes - The Big Picture Full Report. London.

ORME, M. & PALMER, J. 2003. *Control of Overheating in Future Housing - Design Guidance for Low Energy Strategies,* St Albans, FaberMaunsell Ltd. .

ORME, M., PALMER, J. & IRVING, S. 2003. Control of overheating in well-insulated housing. Available: www.cibse.org/pdfs/7borme.pdf [Accessed 03 January 2013].

PALMER, S. 2000. Sustainable Homes: Timber Frame Housing. Middlesex: Sustainable Homes.

PAN, W., GIBB, A. & DAINTY, A. 2005. Offsite Modern Methods of Construction in Housebuilding: Perspectives and Practices of Leading UK Housebuilders. Loughborough: Loughborough University.

PAN, W., GIBB, A. G. F. & DAINTY, A. R. J. 2008. Leading UK housebuilders' utilisation of offsite modern methods of construction. *Building Research & Information,* 36**,** 56-67.

PARLIAMENTARY OFFICE OF SCIENCE AND TECHNOLOGY 2003. Modern methods of housebuilding. *POSTnote.* London: The Parliamentary Office of Science and Technology.

PARSONS, K. 2010. Thermal Comfort in Buildings. *In:* HALL, M. R. (ed.) *Materials for energy efficiency and thermal comfort in buildings.* Cambridge: Woodhead Publishing LImited and CRC Press LLC.

PASSIPEDIA. 2012. *The Passive House - definition* [Online]. passipedia.org. Available: http://www.passipedia.org/passipedia_en/doku.php?id=basics:the_passive_house_-_definition&rev=1353407677 [Accessed 7th September 2012].

PASSIVHAUS TRUST. 2015. *What is Passivhaus?* [Online]. Passivhaus Trust. Available: http://www.passivhaustrust.org.uk/what_is_passivhaus.php#2 [Accessed 26th March 2015].

PEACOCK, A. D., JENKINS, D. P. & KANE, D. 2010. Investigating the potential of overheating in UK dwellings as a consequence of extant climate change. *Energy Policy,* 38**,** 3277-3288.

PEARSON, C. 2011. Thermal Imaging of Building Fabric - BG 39-2011. Bracknell: BSRIA.

PIDDINGTON, J., GARRETT, H. & NOWAK, T. 2013. Housing in the UK: National Comparisons in typology, condition and cost of poor housing. Bracknell.

PLANNING PORTAL. 2015. *Current Legislation - Introduction* [Online]. Available: http://www.planningportal.gov.uk/buildingregulations/buildingpolicyandlegislation/currentlegislation/introduction [Accessed 4th March 2015].

RAVIKUMAR, M. & SRINIVASAN, P. 2008. Natural cooling of building using Phase Change Material. *International Journal of Engineering and Technology,* 5**,** 10.

RHODES, C. 2015. Construction Industry: Statistics and Policy - Briefing Paper Number 01432.

RICHARDS PARTINGTON ARCHITECTS 2012. Understanding overheating - where to start: An introduction for house builders and designers Milton Keynes: NHBC Foundation.

RIGIPS SAINT GOBAIN 2012. Alba balance efficient room temperature management with innovative PCM plasterboards. Mägenwil, Switzerland: Rigips, AG.

ROAF, S., CRICHTON, D. & NICOL, F. 2009. *Adapting Buildings and Cities for Climate Change - A 21st Century Survival Guide,* Oxford, Architectural Press.

RODGERS, J. L. & NICEWANDER, W. A. 1988. Thirteen Ways to Look at the Correlation Coefficient. *The American Statistician,* 42**,** 8.

RODRIGUES, L. 2009. *An investigation into the use of thermal mass to improve comfort in British housing.* Doctor of Philosophy Ph.D., University of Nottingham.

RODRIGUES, L., GARRATT, T. & EBBS, N. 2012. Is added sustainability equal to added value? *Energy Conversion and Management,* 63**,** 203-207.

RODRIGUES, L. & GILLOTT, M. 2011. The summer performance of the BASF House. *In:* BODART, M. & EVRARD, A. (eds.) *PLEA 2011 - 27th International Conference on Passive and Low Energy Architecture.* Louvain-la-Neuve, Belgium: Presses universitaires de Louvain.

RODRIGUES, L., GILLOTT, M. & SOUGKAKIS, V. 2013a. The Use of Thermal Mass to Mitigate Overheating in an Affordable Low-Energy Pre-fabricated Timber House *SET 2013 - 12th International Conference on Sustainable Energy Technologies.* (In Press.).

RODRIGUES, L., GILLOTT, M. & TETLOW, D. 2013b. Summer Overheating in Future Weather Scenarios in a Super Insulated Steel Frame Urban House.

RODRIGUES, L. & NIKIFORIADIS, F. 2013. A Comparative Study of the Climate Resilience of Timber Frame and Masonry Homes of Similar Designs in the UK. *12th International Conference on Sustainable Energy Technologies (SET 2013).* Hong Kong: In Press.

RODRIGUES, L., SOUGKAKIS, V. & GILLOTT, M. 2015. Investigating the potential of adding thermal mass to mitigate overheating in a super-insulated low-energy timber house. *International Journal of Low-Carbon Technologies*.

RODRIGUES, L., TETLOW, D., GILLOTT, M. & SOUGKAKIS, V. 2014. Chapter 10: The Application of Phase Change Materials to Improve the Climate Resilience of a Low-Energy Prototype House. *In:* DINCER, I., MIDILLI, A. & KUCUK, H. (eds.) *Progress in Sustainable Energy Technologies Vol II: Creating Sustainable Development.* Switzerland: Springer International Publishing.

RODRIGUES, L. T. & GILLOTT, M. 2013. Climate resilience of a low-energy prototype house. *Proceedings of the ICE - Engineering Sustainability* [Online], 166. Available: http://www.icevirtuallibrary.com/content/article/10.1680/ensu.12.00009.

RODRIGUES, L. T., GILLOTT, M. & TETLOW, D. 2013c. Summer overheating potential in a low-energy steel frame house in future climate scenarios. *Sustainable Cities and Society,* 7**,** 1-15.

ROSS, K. 2002. Non-traditional housing in the UK - A brief review. Garston, Watford.

ROSS, K. 2005. *Modern Methods of House Construction: A Surveyor's Guide,* Watford, Bre Trust.

ROSS, K., CARTWRIGHT, P. & NOVAKOVIC, O. 2006. A guide to modern methods of consrtuction. *In:* FOUNDATION, N. (ed.). London: IHS BRE Press.

ROYAPOOR, M. & ROSKILLY, T. 2015. Building model calibration using energy and environmental data. *Energy and Buildings,* 94**,** 109-120.

SAINT-GOBAIN 2014. An Exemplar of Low-Energy Offsite Manufactured Housing: Nottingham H.O.U.S.E. Coventry: Saint-Gobain.

SCOTTISH GOVERNMENT 2012. GREENER HOMES INNOVATION SCHEME £10 million Innovation Fund. Scottish Governemnt.

SMITH, S., HAIRSTANS, R., MACDONALD, R. & SANNA, F. 2013. Strategic Review of the Offsite Construction Sector in Scotland Summary Report. Edinburgh.

SOUGKAKIS, V., RODRIGUES, L., NAZER, H. & GILLOTT, M. 2014. Comparing the thermal performance of timber frame vs masonry low-energy dwellings in the UK today and in the future. *SET 2014 - 13th International Conference on Sustainable Energy Technologies.* Geneva, Switzerland: In Press.

SPITLER, J. D. 2011. Chapter 5: Thermal load and energy performance prediction. *In:* HENSEN, J. L. M. & LAMBERTS, R. (eds.) *Building Performance Simulation for Design and Operation.* 1 ed. Florence: Taylor and Francis.

SPITLER, J. D. 2014. *Load calculation applications manual* Atlanta, Ga, ASHRAE.

SPITLER, J. D., FISHER, D. E. & PEDERSEN, C. O. 1997. The Radiant Time Series Cooling Load Calculation Procedure. *ASHRAE Transactions,* 103**,** 14.

STIRLING, C. 2003. *Off-site Construction: An Introduction,* BRE.London, Building Research Establishment Scotland.

SVIRSKAITĖ, J. 2011. Eco materials for construction Study visit II.

TARMAC UK LTD. 2008. *Tarmac Homes Project - Making the Code simple, affordable and repeatable* [Online]. Tarmac UK Ltd,. Available: http://www.tarmachomesproject.co.uk/ [Accessed 30 September 2014 2014].

The Climate Change Act 2008 (2020 Target, Credit Limit and Definitions) Order 2009 (S.I. 2009/1258). London: The Stationary Office.

THE SECRETARY OF STATE FOR COMMUNITIES AND LOCAL GOVERNMENT 2007. Homes for the future: more affordable, more sustainable. *In:* GOVERNMENT, D. F. C. A. L. (ed.). London: TSO (The Stationary Office).

THE UNIVERSITY OF NOTTINGHAM. 2016a. *Creative Energy Homes - BASF Research House Gallery* [Online]. Available: http://www.nottingham.ac.uk/creative-energy-homes/houses/basf-research-house/gallery.aspx [Accessed 16th December 2013].

THE UNIVERSITY OF NOTTINGHAM. 2016b. *Creative Energy Homes [online]* [Online]. Available: http://www.nottingham.ac.uk/creative-energy-homes/creative-energy-homes.aspx [Accessed 16th December 2013].

THELANDERSSON, S., AASHEIM, E. & RANTA-MAUNUS, A. New timber construction in Nordic countries. Proceedings of the 8th World Conference on Timber Engineering, 2004 Lahtis, Finland. 1-8.

TUBELO, R. 2016. *The application of the 'fabric first' approach to improve thermal comfort and energy efficiency in affordable housing in Southern Brazil.* Doctor of Philosophy Ph.D., University of Nottingham.

TUDOR, R. 2013. A Practical Guide to Building Thermal Modelling BG 48/2013. Bracknell: BSRIA.

UK CLIMATE PROJECTIONS. 2009a. *UKCP09 Climate Change Projections* [Online]. Rotherham: Environment Agency. Available: http://ukclimateprojections.defra.gov.uk/23189 [Accessed 12th December 2012].

UK CLIMATE PROJECTIONS. 2009b. *Weather Generator* [Online]. Rotherham: Environment Agency. Available: http://ukclimateprojections.defra.gov.uk/23261 [Accessed 15th December 2012].

UKCIP & SCCIP. no date. *Assessing the differences: UKCIP02 & UKCP09* [Online]. UK climate projections. Available: http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=76750&filetype=pdf [Accessed 6th June 2015].

ULGEN, K. 2002. Experimental and theoretical investigation of effects of wall's thermophysical properties on time lag and decrement factor. *Energy and Buildings,* 34**,** 273-278.

VELRAJ, R. & DANIEL, G. 2014. Passive Solar Heating Or Cooling For Residential Building Using PCM

International Journal of Advanced Research in Civil,Structural,Environmental and Infrastructure Engineering and Developing, 2**,** 9.

VENABLES, T., BARLOW, J. & GANN, D. 2004. *Manufacturing Excellence: UK Capacity in Offsite Manufacturing,* London, Innovation Studies Centre.

VOKES, C., BRENNAN, J., BAYLISS, M. & BECK, H. 2013. Technology and Skills in the Construction Industry - Evidence Report 74. London: UK Commission for Employment and Skills.

WAGHORN, M., SUTTIE, E. & SUTTON, A. 2015. Delivering sustainable, low energy housing with softwood timber frame. *Information Paper.* Building Research Establishment (BRE).

WANG, X., KENDRICK, C., OGDEN, R., WALLIMAN, N. & BAICHE, B. 2013. A case study on energy consumption and overheating for a UK industrial building with rooflights. *Applied Energy,* 104**,** 337-344.

WAUGH THISTLETON ARCHITECTS. 2014. *Murray Grove The world's largest modern timber residential building [online]* [Online]. Waugh Thistleton Architects. Available: http://www.waughthistleton.com/project.php?name=murray [Accessed 03 May 2014].

WEBB, N., BROOMFIELD, M., BROWN, P., BUYS, G., CARDENAS, L., MURRELLS, T., PANG, Y., PASSANT, N., THISTLETHWAITE, G. & WATTERSON, J. 2014. UK Greenhouse Gas Inventory, 1990 to 2012: Annual Report for submission under the Framework Convention on Climate Change.

WHITE, J. 2014. *An investigation into the parameters that contribute to the gap between the designed and as-built thermal performance of British housing.* PhD Thesis, The University of Nottingham.

WOLSTENHOLME, A. 2009. Never Waste a Good Crisis - A Review of Progress since Rethinking Construction and Thoughts for Our Future. London.

ZCH 2012. Overheating in new homes - A review of the evidence NF46. Milton Keynes.

ZCH 2014. Rowner Research Project Phase One - Design Strategy. London.

ZERO CARBON HUB 2010. Carbon Compliance for tomorrow's new homes: Overview of findings and recommendations. *Carbon Compliance for tomorrow's new homes.* London: NHBC Foundation.

ZERO CARBON HUB 2014a. Closing the Gap Between Design and As-built Performance - Evidence Review Report. London.

ZERO CARBON HUB 2014b. Zero Carbon Homes and Nearly Zero Energy Buidings - UK Building Regulations and EU Directives. London: Zero Carbon HUb.

ZERO CARBON HUB. 2015a. *Performance Gap* [Online]. Zero Carbon Hub. Available: http://www.zerocarbonhub.org/current-projects/performance-gap [Accessed 20th April 2015].

ZERO CARBON HUB. 2015b. *Zero Carbon Policy* [Online]. London: Zero Carbon Hub. Available: http://www.zerocarbonhub.org/zero-carbon-policy/zero-carbon-policy [Accessed 5th March 2015].

ZERO CARBON HUB 2016. Assessing overheating risk - leaflet. London: Zero Carbon HUb.

ZERO CARBON HUB & NHBC FOUNDATION 2013. Zero carbon strategies for tomorrow's new homes. Milton Keynes.

ZHU, G.-H., GAO, X.-G., LI, K., HU, J.-P. & HE, J.-S. 2010. Finite element simulation of temperature fields of gypsum wallboard in heat pump drying process. *Zhongnan Daxue Xuebao (Ziran Kexue Ban)/Journal of Central South University (Science and Technology),* 41**,** 1828-1833.

APPENDIX A – NOTTINGHAM H.O.U.S.E CONSTRUCTIONS

In this section the build-up of the external walls and roofs and the thermal properties of the materials used in the parametric analysis of Chapter 4 for each case examined are presented.

<u>Case 0 – Plast</u>

Opaque Construction | Name: External Wall_plast | Description: External wall thermowod cladding

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.600	0.400	0.920	0.900	0.101	5.110

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1plast\20	10.0	0.16	0.0	11.000	960.0	837.0	PLASTERBOARD *4
2	ISOVER multima...	235.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	9.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER RKL Fa...	50.0	0.031	0.0	1.500	24.0	920.0	Glass wool insulation pa...
5	am1cav\5	36.0	0.0	1.25	1.000	0.0	0.0	50MM AIR (HORIZONT...
6	Thermowood	18.0	0.107	0.0	11.420	545.0	2390.0	Thermowood 18mm

Figure A-1 External wall build-up and material properties for Case 0 - Plast

Opaque Construction | Name: eiling_plasterboard | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.900	0.400	0.950	0.900	0.074	39.308

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1plast\20	12.5	0.16	0.0	11.000	960.0	837.0	PLASTERBOARD *4
2	ISOVER multima...	175.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	15.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
5	Ply	10.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
6	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
7	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
8	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
9	ISOVER multima...	37.5	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
10	Hofatex UD	80.0	0.049	0.0	5.000	260.0	2100.0	80 mm Hofatex sarking ...
11	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD

Figure A-2: Roof build-up and material properties for Case 0 – Plast

Case 1 – Rig

Opaque Construction | Name: External Wall_Rigic | Description: External wall thermowod cladding

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.600	0.650	0.920	0.900	0.101	5.107

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	Rigidur H	10.0	0.2	0.0	6.800	1200.0	1100.0	GYPSUM FIBRE CONC...
2	ISOVER multima...	235.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	9.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER RKL Fa...	50.0	0.031	0.0	1.500	24.0	920.0	Glass wool insulation pa...
5	am1cav\5	36.0	0.0	1.25	1.000	0.0	0.0	50MM AIR (HORIZONT...
6	Thermowood	18.0	0.107	0.0	11.420	545.0	2390.0	Thermowood 18mm

Figure A-3: External wall build-up and material properties for Case 1 – Rig

Opaque Construction | Name: Ceiling_Rigidur1 | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.900	0.650	0.950	0.900	0.074	39.258

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	Rigidur H	12.5	0.2	0.0	6.800	1200.0	1100.0	GYPSUM FIBRE CONC...
2	ISOVER multima...	175.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	15.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
5	Ply	10.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
6	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
7	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
8	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
9	ISOVER multima...	37.5	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
10	Hofatex UD	80.0	0.049	0.0	5.000	260.0	2100.0	80 mm Hofatex sarking ...
11	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD

Figure A-4: Roof build-up and material properties for Case 1 –Rig

Case 1 – Con

Opaque Construction | Name: External Wall_conc | Description: External wall thermowod cladding

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.600	0.650	0.920	0.900	0.101	5.112

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1concd\7	10.0	1.4	0.0	34.000	2100.0	840.0	DENSITY 2 CONCRET...
2	ISOVER multima...	235.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	9.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER RKL Fa...	50.0	0.031	0.0	1.500	24.0	920.0	Glass wool insulation pa...
5	am1cav\5	50.0	0.0	1.01	1.000	0.0	0.0	50MM AIR (HORIZONT...
6	Thermowood	18.0	0.107	0.0	11.420	545.0	2390.0	Thermowood 18mm

Figure A-5: External wall build-up and material properties for Case 1 – Con

Opaque Construction	Name	Ceiling_concrete1	Description	

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.900	0.650	0.950	0.900	0.074	39.086

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1concd\7	12.5	1.4	0.0	34.000	2100.0	840.0	DENSITY 2 CONCRET...
2	ISOVER multima...	175.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	15.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
5	Ply	10.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
6	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
7	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
8	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
9	ISOVER multima...	37.5	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
10	Hofatex UD	80.0	0.049	0.0	5.000	260.0	2100.0	80 mm Hofatex sarking ...
11	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD

Figure A-6: Roof build-up and material properties for Case 1 –Con

<u>Case 2 – Rig</u>

Opaque Construction	Name	External Wall_Rigic	Description	External wall thermowood cladding

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.600	0.650	0.920	0.900	0.1	5.122

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	Rigidur H	20.0	0.2	0.0	6.800	1200.0	1100.0	GYPSUM FIBRE CONC...
2	ISOVER multima...	235.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	9.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER RKL Fa...	50.0	0.031	0.0	1.500	24.0	920.0	Glass wool insulation pa...
5	am1cav\5	36.0	0.0	1.25	1.000	0.0	0.0	50MM AIR (HORIZONT...
6	Thermowood	18.0	0.107	0.0	11.420	545.0	2390.0	Thermowood 18mm

Figure A-7: External wall build-up and material properties for Case 2 – Rig

Opaque Construction	Name	Ceiling_Rigidur2	Description	

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.900	0.650	0.950	0.900	0.074	39.461

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	Rigidur H	25.0	0.2	0.0	6.800	1200.0	1100.0	GYPSUM FIBRE CONC...
2	ISOVER multima...	175.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	15.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
5	Ply	10.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
6	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
7	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
8	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
9	ISOVER multima...	37.5	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
10	Hofatex UD	80.0	0.049	0.0	5.000	260.0	2100.0	80 mm Hofatex sarking ...
11	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD

Figure A-8: Roof build-up and material properties for Case 2 – Rig

Case 2 – Con

Opaque Construction | Name: External Wall_conc | Description: External wall thermowood cladding

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.600	0.650	0.920	0.900	0.101	5.114

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1concd\7	20.0	1.4	0.0	34.000	2100.0	840.0	DENSITY 2 CONCRET...
2	ISOVER multima...	235.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	9.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER RKL Fa...	50.0	0.031	0.0	1.500	24.0	920.0	Glass wool insulation pa...
5	am1cav\5	50.0	0.0	1.01	1.000	0.0	0.0	50MM AIR (HORIZONT...
6	Thermowood	18.0	0.107	0.0	11.420	545.0	2390.0	Thermowood 18mm

Figure A-0-9: External wall build-up and material properties for Case 2 – Con

Opaque Construction | Name: Ceiling_concrete2 | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.900	0.650	0.950	0.900	0.074	39.115

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1concd\7	25.0	1.4	0.0	34.000	2100.0	840.0	DENSITY 2 CONCRET...
2	ISOVER multima...	175.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	15.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
5	Ply	10.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
6	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
7	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
8	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
9	ISOVER multima...	37.5	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
10	Hofatex UD	80.0	0.049	0.0	5.000	260.0	2100.0	80 mm Hofatex sarking ...
11	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD

Figure A-10: Roof build-up and material properties for Case 1 –Con

Case 3 – Rig

Opaque Construction | Name: External Wall_Rigic | Description: External wall thermowood cladding

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.600	0.650	0.920	0.900	0.1	5.138

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	Rigidur H	30.0	0.2	0.0	6.800	1200.0	1100.0	GYPSUM FIBRE CONC...
2	ISOVER multima...	235.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	9.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER RKL Fa...	50.0	0.031	0.0	1.500	24.0	920.0	Glass wool insulation pa...
5	am1cav\5	36.0	0.0	1.25	1.000	0.0	0.0	50MM AIR (HORIZONT...
6	Thermowood	18.0	0.107	0.0	11.420	545.0	2390.0	Thermowood 18mm

Figure A-11: External wall build-up and material properties for Case 3 – Rig

Opaque Construction | Name: Ceiling_Rigidur3 | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.900	0.650	0.950	0.900	0.073	39.667

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	Rigidur H	37.5	0.2	0.0	6.800	1200.0	1100.0	GYPSUM FIBRE CONC...
2	ISOVER multima...	175.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	15.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
5	Ply	10.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
6	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
7	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
8	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
9	ISOVER multima...	37.5	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
10	Hofatex UD	80.0	0.049	0.0	5.000	260.0	2100.0	80 mm Hofatex sarking ...
11	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD

Figure A-12: External wall build-up and material properties for Case 3 – Rig

Case 3 – Con

Opaque Construction | Name: External Wall_conc | Description: External wall thermowod cladding

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.600	0.650	0.920	0.900	0.101	5.116

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1concd\7	30.0	1.4	0.0	34.000	2100.0	840.0	DENSITY 2 CONCRET...
2	ISOVER multima...	235.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	9.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER RKL Fa...	50.0	0.031	0.0	1.500	24.0	920.0	Glass wool insulation pa...
5	am1cav\5	50.0	0.0	1.01	1.000	0.0	0.0	50MM AIR (HORIZONT...
6	Thermowood	18.0	0.107	0.0	11.420	545.0	2390.0	Thermowood 18mm

Figure A-13: External wall build-up and material properties for Case 3 – Con

Opaque Construction | Name: Ceiling_concrete3 | Description:

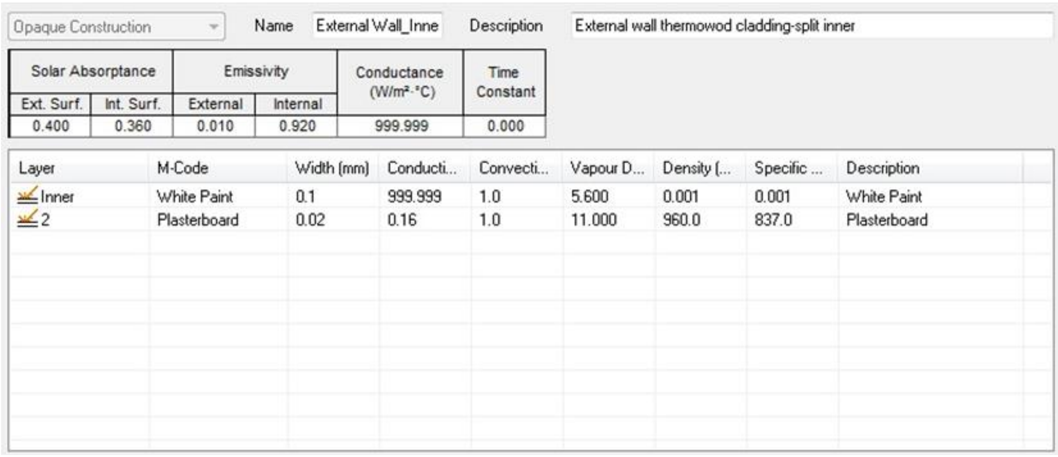
Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.900	0.650	0.950	0.900	0.074	39.144

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1concd\7	37.5	1.4	0.0	34.000	2100.0	840.0	DENSITY 2 CONCRET...
2	ISOVER multima...	175.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
3	Ply	15.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
4	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
5	Ply	10.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
6	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
7	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
8	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
9	ISOVER multima...	37.5	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
10	Hofatex UD	80.0	0.049	0.0	5.000	260.0	2100.0	80 mm Hofatex sarking ...
11	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD

Figure A-14: Roof build-up and material properties for Case 3 – Con

Cases with PCM (Case1-Alb23, Case2-Alb23, Case1-Alb26, Case2-Alb26)

The use of PCM materials was simulated by Tas was as follows: the building element were the PCM layer(s) was to be inserted was broken automatically in three parts, one external to the PCM board (s), one internal and one adiabatic PCM layer between the two layers. The internal and external layer for the external wall and roof are presented below.

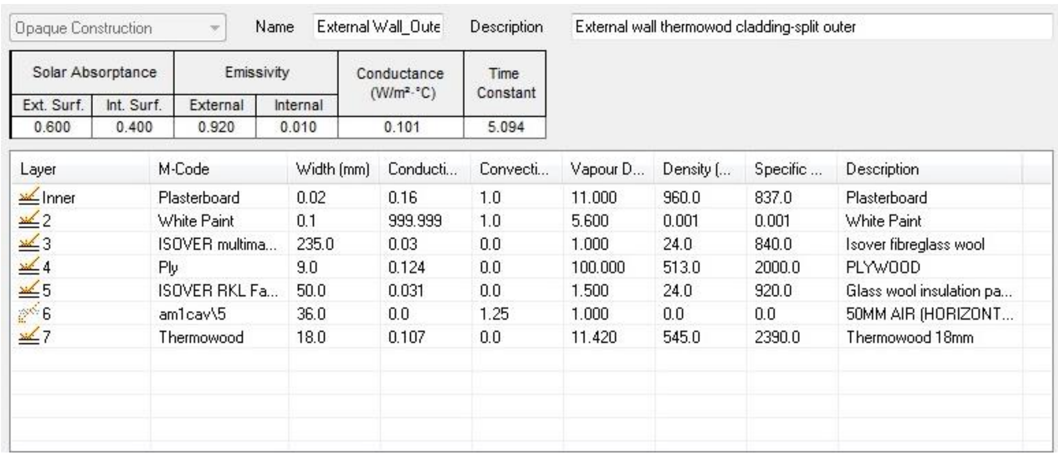


Opaque Construction — Name: External Wall_Inne — Description: External wall thermowod cladding-split inner

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.360	0.010	0.920	999.999	0.000

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	White Paint	0.1	999.999	1.0	5.600	0.001	0.001	White Paint
2	Plasterboard	0.02	0.16	1.0	11.000	960.0	837.0	Plasterboard

Figure A-15: Build-up and material properties for the external part of the external wall for cases: Case1-Alb23, Case2-Alb23, Case1-Alb26, Case2-Alb26



Opaque Construction — Name: External Wall_Oute — Description: External wall thermowod cladding-split outer

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.600	0.400	0.920	0.010	0.101	5.094

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	Plasterboard	0.02	0.16	1.0	11.000	960.0	837.0	Plasterboard
2	White Paint	0.1	999.999	1.0	5.600	0.001	0.001	White Paint
3	ISOVER multima...	235.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
4	Ply	9.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
5	ISOVER RKL Fa...	50.0	0.031	0.0	1.500	24.0	920.0	Glass wool insulation pa...
6	am1cav\5	36.0	0.0	1.25	1.000	0.0	0.0	50MM AIR (HORIZONT...
7	Thermowood	18.0	0.107	0.0	11.420	545.0	2390.0	Thermowood 18mm

Figure A-16: Build-up and material properties for the internal part of the external wall for cases: Case1-Alb23, Case2-Alb23, Case1-Alb26, Case2-Alb26

Opaque Construction | Name: Ceiling_Inner | Description: -split inner

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.360	0.010	0.920	999.999	0.000

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	White Paint	0.1	999.999	1.0	5.600	0.001	0.001	White Paint
2	Plasterboard	0.02	0.16	1.0	11.000	960.0	837.0	Plasterboard

Figure A-17: Build-up and material properties for the external part of the roof for cases: Case1-Alb23, Case2-Alb23, Case1-Alb26, Case2-Alb26

Opaque Construction | Name: Ceiling_Outer | Description: -split outer

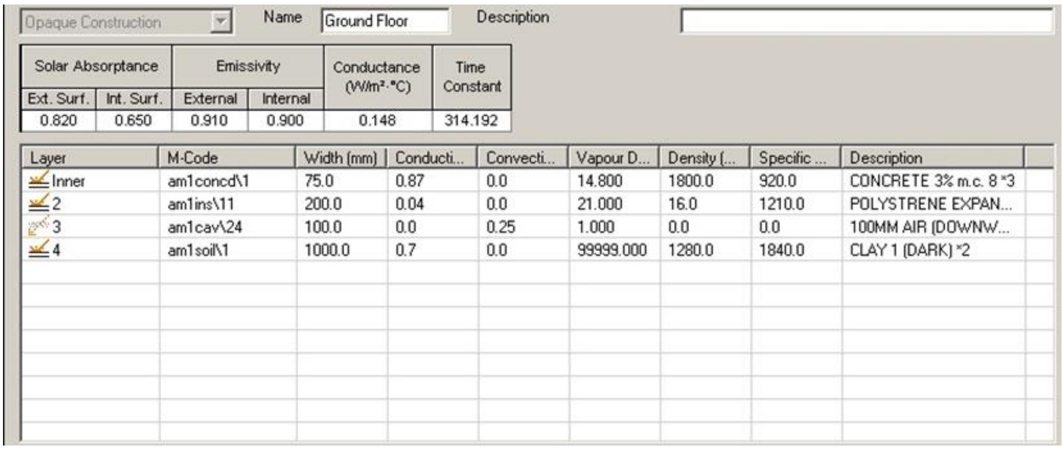
Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.900	0.400	0.950	0.010	0.074	39.058

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	Plasterboard	0.02	0.16	1.0	11.000	960.0	837.0	Plasterboard
2	White Paint	0.1	999.999	1.0	5.600	0.001	0.001	White Paint
3	ISOVER multima...	175.0	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
4	Ply	15.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
5	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
6	Ply	10.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
7	Ply	12.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD
8	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
9	ISOVER Roofine...	50.0	0.035	0.0	1.200	80.0	670.0	GLASSWOOL insulation
10	ISOVER multima...	37.5	0.03	0.0	1.000	24.0	840.0	Isover fibreglass wool
11	Hofatex UD	80.0	0.049	0.0	5.000	260.0	2100.0	80 mm Hofatex sarking ...

Figure A-18: Build-up and material properties for the internal part of the roof for cases: Case1-Alb23, Case2-Alb23, Case1-Alb26, Case2-Alb26

APPENDIX B – GREEN STREET CONSTRUCTIONS

The build-up of the envelope elements and the thermal properties of the materials of Unit 8 (timber) and Unit 31(masonry) of Green Street as well as the 'masonry extra' construction are presented here.

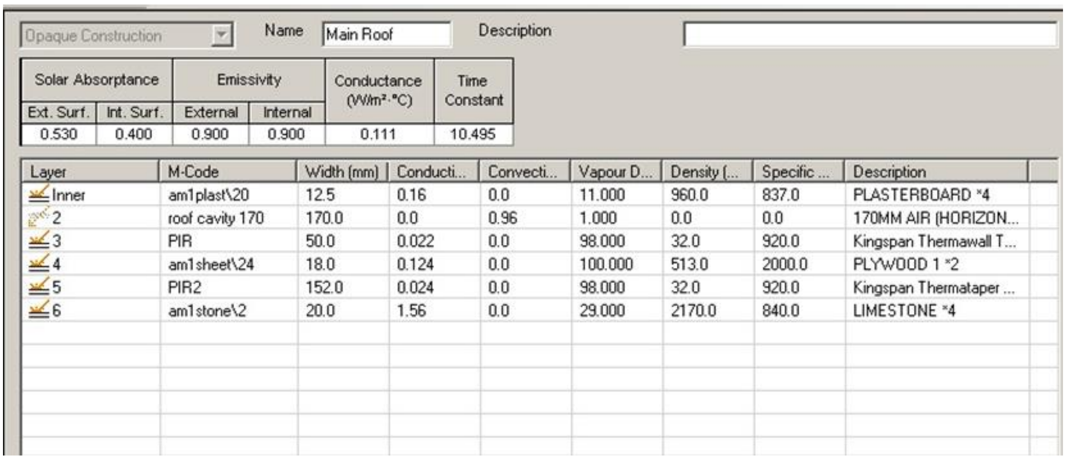


Opaque Construction | Name: Ground Floor | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.820	0.650	0.910	0.900	0.148	314.192

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1concd\1	75.0	0.87	0.0	14.800	1800.0	920.0	CONCRETE 3% m.c. 8 *3
2	am1ins\11	200.0	0.04	0.0	21.000	16.0	1210.0	POLYSTRENE EXPAN...
3	am1cav\24	100.0	0.0	0.25	1.000	0.0	0.0	100MM AIR (DOWNW...
4	am1soil\1	1000.0	0.7	0.0	99999.000	1280.0	1840.0	CLAY 1 (DARK) *2

Figure B-1: Build-up and thermal properties of materials of the floor element (common to all cases)

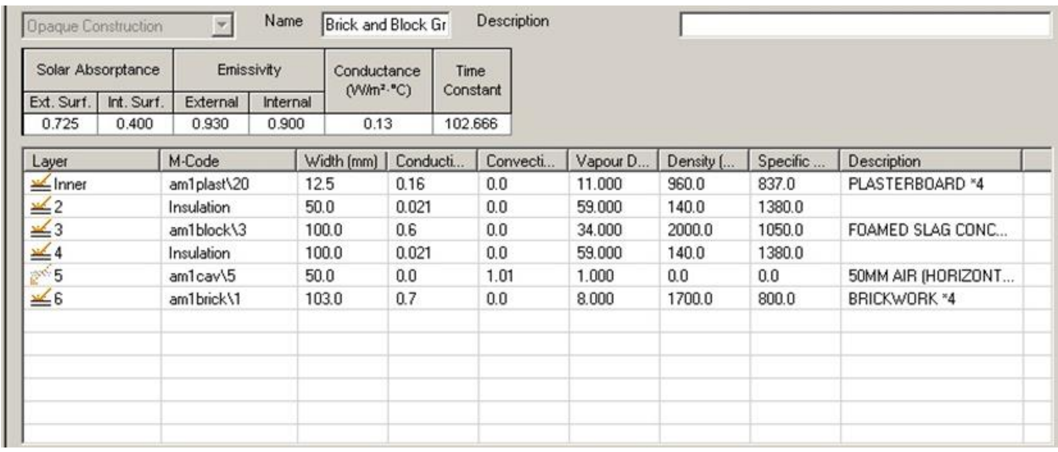


Opaque Construction | Name: Main Roof | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.530	0.400	0.900	0.900	0.111	10.495

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1plast\20	12.5	0.16	0.0	11.000	960.0	837.0	PLASTERBOARD *4
2	roof cavity 170	170.0	0.0	0.96	1.000	0.0	0.0	170MM AIR (HORIZON...
3	PIR	50.0	0.022	0.0	98.000	32.0	920.0	Kingspan Thermawall T...
4	am1sheet\24	18.0	0.124	0.0	100.000	513.0	2000.0	PLYWOOD 1 *2
5	PIR2	152.0	0.024	0.0	98.000	32.0	920.0	Kingspan Thermataper ...
6	am1stone\2	20.0	1.56	0.0	29.000	2170.0	840.0	LIMESTONE *4

Figure B-2: Build-up and thermal properties of materials of the roof element (common to all cases)

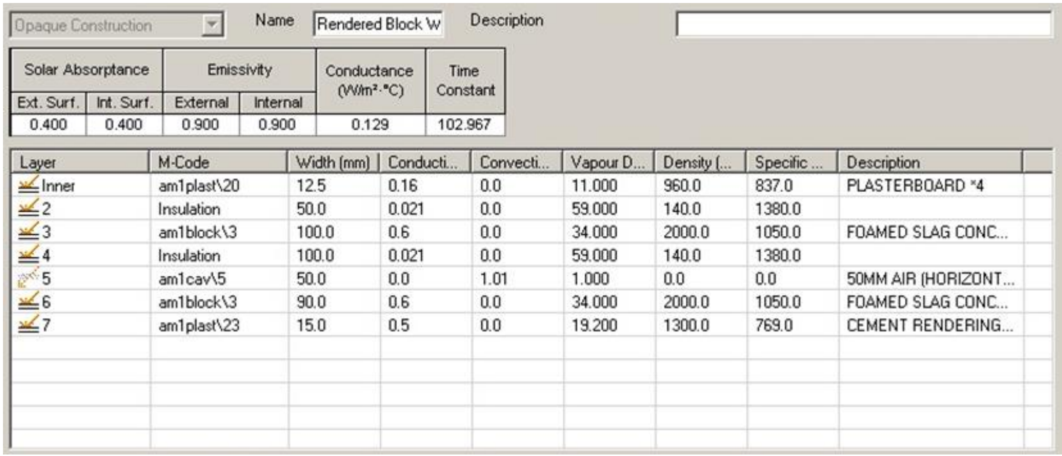


Opaque Construction | Name: Brick and Block Gr | Description:

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.725	0.400	0.930	0.900	0.13	102.666

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1plast\20	12.5	0.16	0.0	11.000	960.0	837.0	PLASTERBOARD *4
2	Insulation	50.0	0.021	0.0	59.000	140.0	1380.0	
3	am1block\3	100.0	0.6	0.0	34.000	2000.0	1050.0	FOAMED SLAG CONC...
4	Insulation	100.0	0.021	0.0	59.000	140.0	1380.0	
5	am1cav\5	50.0	0.0	1.01	1.000	0.0	0.0	50MM AIR (HORIZONT...
6	am1brick\1	103.0	0.7	0.0	8.000	1700.0	800.0	BRICKWORK *4

Figure B-3: Build-up and thermal properties of materials of the brick and block masonry wall (Unit 31)

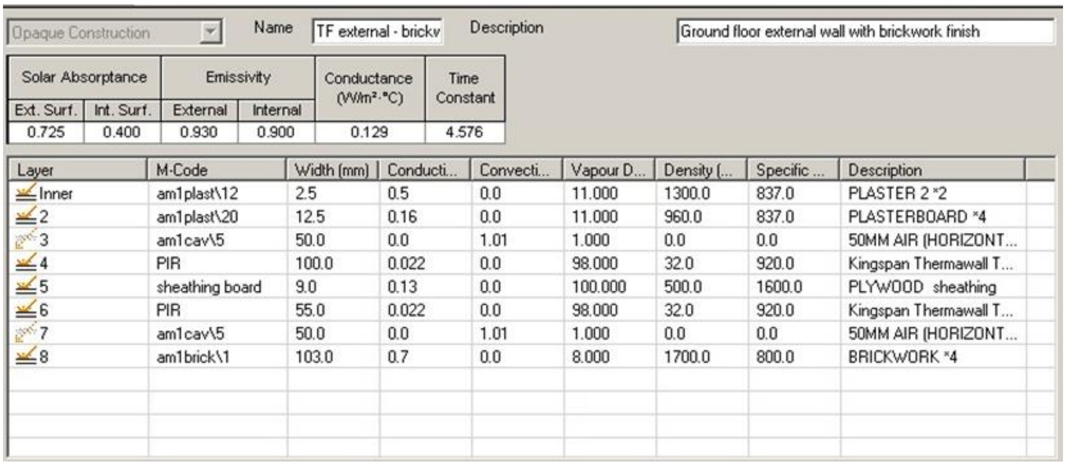


Opaque Construction	Name	Rendered Block W	Description	

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	0.129	102.967

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1plast\20	12.5	0.16	0.0	11.000	960.0	837.0	PLASTERBOARD *4
2	Insulation	50.0	0.021	0.0	59.000	140.0	1380.0	
3	am1block\3	100.0	0.6	0.0	34.000	2000.0	1050.0	FOAMED SLAG CONC...
4	Insulation	100.0	0.021	0.0	59.000	140.0	1380.0	
5	am1cav\5	50.0	0.0	1.01	1.000	0.0	0.0	50MM AIR (HORIZONT...
6	am1block\3	90.0	0.6	0.0	34.000	2000.0	1050.0	FOAMED SLAG CONC...
7	am1plast\23	15.0	0.5	0.0	19.200	1300.0	769.0	CEMENT RENDERING...

Figure B-4: Build-up and thermal properties of materials of rendered block cavity wall (Unit 31)

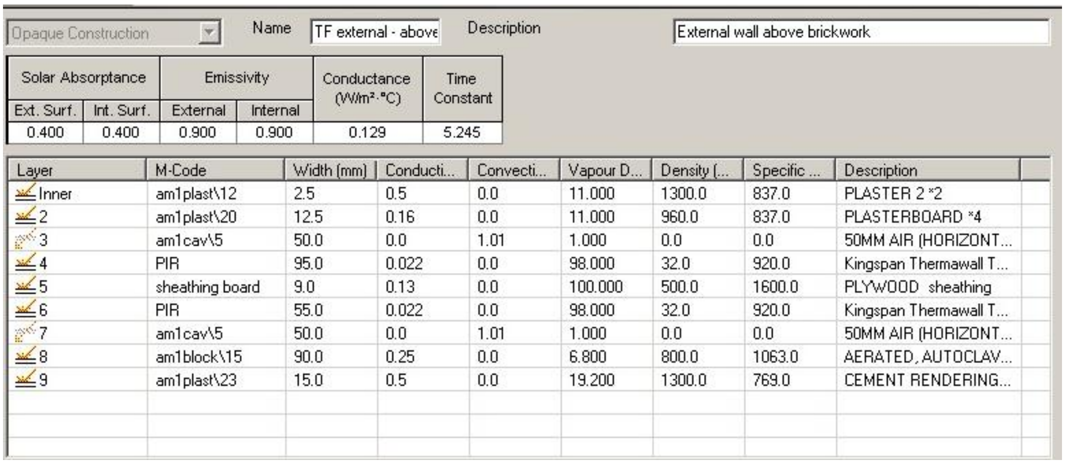


Opaque Construction	Name	TF external - brickv	Description	Ground floor external wall with brickwork finish

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.725	0.400	0.930	0.900	0.129	4.576

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1plast\12	2.5	0.5	0.0	11.000	1300.0	837.0	PLASTER 2 *2
2	am1plast\20	12.5	0.16	0.0	11.000	960.0	837.0	PLASTERBOARD *4
3	am1cav\5	50.0	0.0	1.01	1.000	0.0	0.0	50MM AIR (HORIZONT...
4	PIR	100.0	0.022	0.0	98.000	32.0	920.0	Kingspan Thermawall T...
5	sheathing board	9.0	0.13	0.0	100.000	500.0	1600.0	PLYWOOD sheathing
6	PIR	55.0	0.022	0.0	98.000	32.0	920.0	Kingspan Thermawall T...
7	am1cav\5	50.0	0.0	1.01	1.000	0.0	0.0	50MM AIR (HORIZONT...
8	am1brick\1	103.0	0.7	0.0	8.000	1700.0	800.0	BRICKWORK *4

Figure B-5: Build-up and thermal properties of materials of the timber frame wall with outer brick layer (Unit 8)



Opaque Construction	Name	TF external - above	Description	External wall above brickwork

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	0.129	5.245

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1plast\12	2.5	0.5	0.0	11.000	1300.0	837.0	PLASTER 2 *2
2	am1plast\20	12.5	0.16	0.0	11.000	960.0	837.0	PLASTERBOARD *4
3	am1cav\5	50.0	0.0	1.01	1.000	0.0	0.0	50MM AIR (HORIZONT...
4	PIR	95.0	0.022	0.0	98.000	32.0	920.0	Kingspan Thermawall T...
5	sheathing board	9.0	0.13	0.0	100.000	500.0	1600.0	PLYWOOD sheathing
6	PIR	55.0	0.022	0.0	98.000	32.0	920.0	Kingspan Thermawall T...
7	am1cav\5	50.0	0.0	1.01	1.000	0.0	0.0	50MM AIR (HORIZONT...
8	am1block\15	90.0	0.25	0.0	6.800	800.0	1063.0	AERATED, AUTOCLAV...
9	am1plast\23	15.0	0.5	0.0	19.200	1300.0	769.0	CEMENT RENDERING...

Figure B-6: Build-up and thermal properties of materials of the timber frame wall with render finish (Unit 8)

Opaque Construction | Name: TF external to terra | Description: External wall to terraces

Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	0.127	4.636

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1plast\12	2.5	0.5	0.0	11.000	1300.0	837.0	PLASTER 2 *2
2	am1plast\20	12.5	0.16	0.0	11.000	960.0	837.0	PLASTERBOARD *4
3	am1cav\40	40.0	0.0	1.25	1.000	0.0	0.0	40MM AIR (HORIZONT...
4	PIR	100.0	0.022	0.0	98.000	32.0	920.0	Kingspan Thermawall T...
5	sheathing board	9.0	0.13	0.0	100.000	500.0	1600.0	PLYWOOD sheathing
6	PIR	60.0	0.022	0.0	98.000	32.0	920.0	Kingspan Thermawall T...
7	am1cav\4	20.0	0.0	1.27	1.000	0.0	0.0	20MM AIR (HORIZONT...
8	am1sheet\17	10.0	0.135	0.0	3.840	800.0	1300.0	PARTICLE BOARD ME...
9	am1plast\23	15.0	0.5	0.0	19.200	1300.0	769.0	CEMENT RENDERING...

Figure B-7: Build-up and thermal properties of materials of the timber frame wall with render finish facing the terrace (Unit 8)

Opaque Construction | Name: Block Wall_plaster | Description:

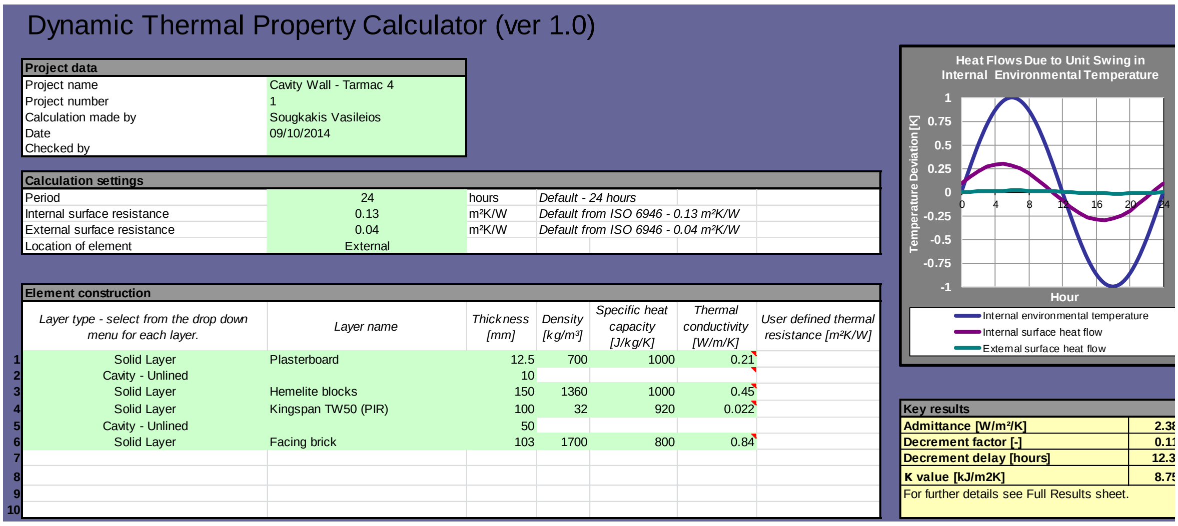
Solar Absorptance		Emissivity		Conductance (W/m²·°C)	Time Constant
Ext. Surf.	Int. Surf.	External	Internal		
0.400	0.400	0.900	0.900	0.13	7.719

Layer	M-Code	Width (mm)	Conducti...	Convecti...	Vapour D...	Density (...	Specific ...	Description
Inner	am1plast\14	13.0	0.53	0.0	11.000	1570.0	837.0	PLASTER 4 *4
2	am1block\3	100.0	0.6	0.0	34.000	2000.0	1050.0	FOAMED SLAG CONC...
3	Insulation	150.0	0.021	0.0	59.000	140.0	1380.0	
4	am1cav\5	50.0	0.0	1.01	1.000	0.0	0.0	50MM AIR (HORIZONT...
5	am1block\3	90.0	0.6	0.0	34.000	2000.0	1050.0	FOAMED SLAG CONC...
6	am1plast\23	15.0	0.5	0.0	19.200	1300.0	769.0	CEMENT RENDERING...

Figure B-8: Build-up and thermal properties of materials of the 'masonry extra' external wall

APPENDIX C – CREATIVE ENERGY HOMES CONSTRUCTIONS

The thermal properties of the 19 building elements monitored at the Creative Energy Homes site as calculated by the Dynamic Thermal Properties Calculator are presented below.



Dynamic Thermal Property Calculator (ver 1.0)

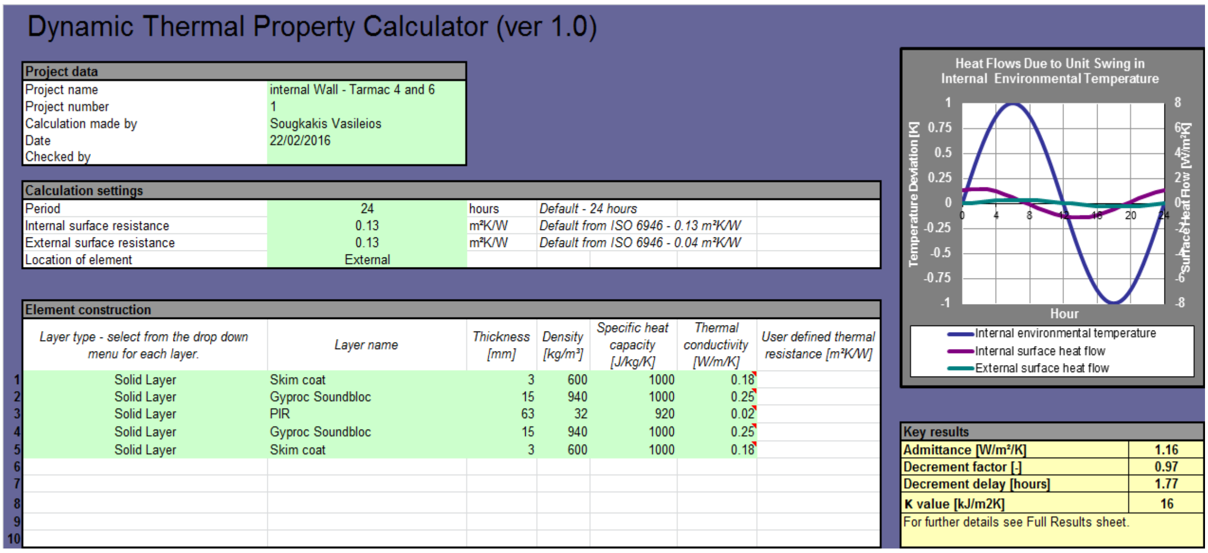
Project data	
Project name	Cavity Wall - Tarmac 4
Project number	1
Calculation made by	Sougkakis Vasileios
Date	09/10/2014
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.04	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	Plasterboard	12.5	700	1000	0.21	
2	Cavity - Unlined		10				
3	Solid Layer	Hemelite blocks	150	1360	1000	0.45	
4	Solid Layer	Kingspan TW50 (PIR)	100	32	920	0.022	
5	Cavity - Unlined		50				
6	Solid Layer	Facing brick	103	1700	800	0.84	
7							
8							
9							
10							

Key results	
Admittance [W/m²/K]	2.38
Decrement factor [-]	0.11
Decrement delay [hours]	12.3
K value [kJ/m2K]	8.75
For further details see Full Results sheet.	

Figure C-1: Build-up and thermal properties of the Tarmac Code 4 cavity wall



Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	internal Wall - Tarmac 4 and 6
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	Skim coat	3	600	1000	0.18	
2	Solid Layer	Gyproc Soundbloc	15	940	1000	0.25	
3	Solid Layer	PIR	63	32	920	0.02	
4	Solid Layer	Gyproc Soundbloc	15	940	1000	0.25	
5	Solid Layer	Skim coat	3	600	1000	0.18	
6							
7							
8							
9							
10							

Key results	
Admittance [W/m²/K]	1.16
Decrement factor [-]	0.97
Decrement delay [hours]	1.77
K value [kJ/m2K]	16
For further details see Full Results sheet.	

Figure C-2: Build-up and thermal properties of the internal wall common in the Tarmac Code 4 and Code 6

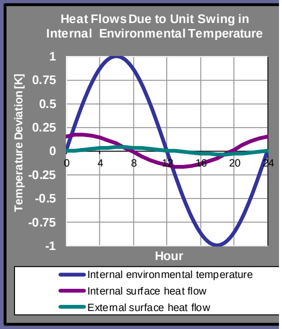
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Timber Floor - Tarmac 4
Project number	1
Calculation made by	Sougkakis Vasileios
Date	09/10/2014
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.1	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.1	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	Plasterboard	12.5	700	1000	0.21	
2	Solid Layer	Chipboard	22	430	1260	0.067	
3	Solid Layer	mineral quilt	100	12	1030	0.042	
4	Cavity - Unlined	Render	120				
5	Solid Layer	Decking	10	500	1600	0.13	
6							
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	**1.38**
Decrement factor [-]	**0.96**
Decrement delay [hours]	**1.75**
K value [kJ/m2K]	**8.75**
For further details see Full Results sheet.	

Figure C-3: Build-up and thermal properties of the Tarmac Code 4 internal ceiling

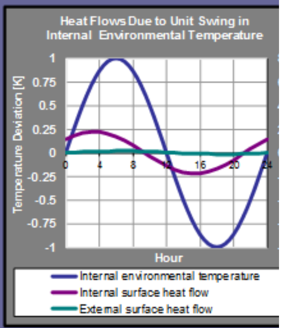
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Solid Wall - Tarmac 6
Project number	1
Calculation made by	Sougkakis Vasileios
Date	09/10/2014
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.04	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	plaster (lightweight)	13	600	1000	0.18	
2	Solid Layer	Durox supabloc	215	460	1000	0.11	
3	Solid Layer	EPS insulation	150	23	1470	0.035	
4	Solid Layer	Render	13	1800	1000	1	
5							
6							
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	**1.78**
Decrement factor [-]	**0.14**
Decrement delay [hours]	**12.3**
K value [kJ/m2K]	**48**
For further details see Full Results sheet.	

Figure C-4: Build-up and thermal properties of the Tarmac Code 6 solid wall

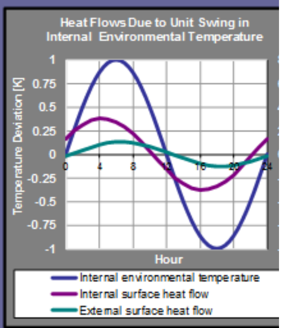
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Internal floor - Tarmac 6
Project number	1
Calculation made by	Sougkakis Vasileios
Date	09/10/2014
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.1	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.1	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	plaster (lightweight)	10	600	1000	0.18	
2	Solid Layer	Precast prestressed hollowcore con	150	880	840	0.48	
3	Solid Layer	Truflow screed	150	2050	1200	1.9	
4	Solid Layer	Floor finish	10	500	1600	0.13	
5							
6							
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	**3.05**
Decrement factor [-]	**0.19**
Decrement delay [hours]	**9.26**
K value [kJ/m2K]	**72.5**
For further details see Full Results sheet.	

Figure C-5: Build-up and thermal properties of the Tarmac Code 6 internal floor

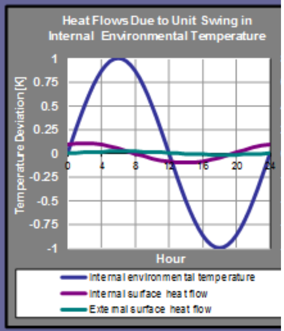
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	ICF - BASF ground
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.04	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Cavity - Unlined		25				
3	Solid Layer	Neopor EPS insulation	95	25	1450	0.03	
4	Solid Layer	cast concrete	158	2100	1000	1.33	
5	Solid Layer	Neopor EPS insulation	95	25	1450	0.03	
6	Solid Layer	external render (lime,sand)	12	1600	1000	0.8	
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	0.8
Decrement factor [-]	0.0
Decrement delay [hours]	9.5
K value [kJ/m2K]	10
For further details see Full Results sheet.	

Figure C-6: Build-up and thermal properties of the BASF ICF wall

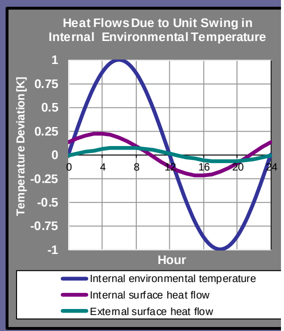
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Internal block wall - BASF ground
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Cavity - Unlined		25				
3	Solid Layer	Concrete block	100	630	1000	0.15	
4	Cavity - Unlined		25				
5	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
6							
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	1.7
Decrement factor [-]	0.6
Decrement delay [hours]	5.3
K value [kJ/m2K]	41.5
For further details see Full Results sheet.	

Figure C-7: Build-up and thermal properties of the BASF internal block wall

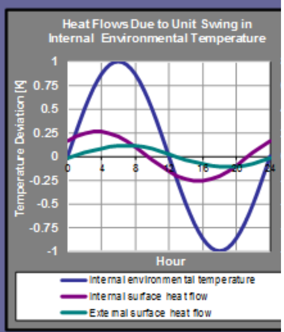
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	SIP Roof - BASF
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Solid Layer	PCM Smartboard	15	800	1200	0.18	
3	Solid Layer	OSB	18	500	1600	0.13	
4	Cavity - Unlined	I-joists	200				
5	Solid Layer	OSB	18	500	1600	0.13	
6	Solid Layer	Carpet	10	200	1300	0.6	
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	2.1
Decrement factor [-]	0.9
Decrement delay [hours]	2.5
K value [kJ/m2K]	38.8
For further details see Full Results sheet.	

Figure C-8: Build-up and thermal properties of the BASF internal ceiling

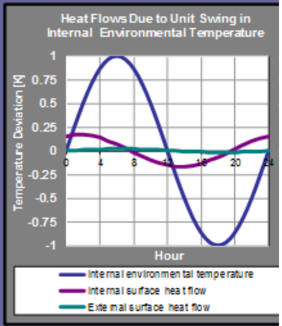
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	SIP - BASF ground
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.04	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Cavity - Unlined		25				
3	Solid Layer	OSB	11	500	1600	0.13	
4	Solid Layer	Polyurethane insulation	140	24	1590	0.023	
5	Solid Layer	OSB	11	500	1600	0.13	
6	Cavity - Unlined		10				
7	Solid Layer	steel cladding	12	1	1	1	
8							
9							
10							



Key results	
Admittance [W/m²/K]	1.3
Decrement factor [-]	0.8
Decrement delay [hours]	3.7
K value [kJ/m2K]	18.8
For further details see Full Results sheet.	

Figure C-9: Build-up and thermal properties of the BASF SIP wall

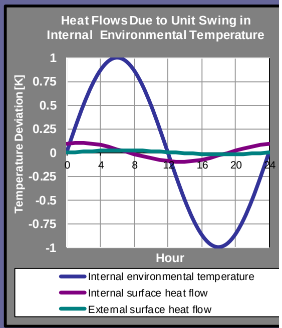
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Interanl partition timber frame - BASF ground
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Cavity - Unlined		25				
3	Solid Layer	PIR insulation	100	32	920	0.02	
4	Cavity - Unlined		25				
5	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
6							
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	0.7
Decrement factor [-]	0.9
Decrement delay [hours]	1.7
K value [kJ/m2K]	10.0
For further details see Full Results sheet.	

Figure C-10: Build-up and thermal properties of the BASF internal wall

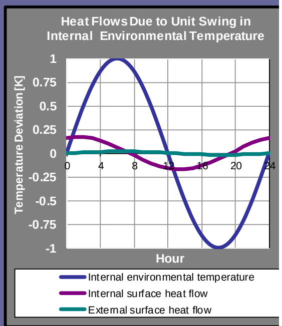
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	SIP Roof - BASF
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.1	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.04	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Cavity - Unlined		25				
3	Solid Layer	OSB	11	500	1600	0.13	
4	Solid Layer	Polyurethane insulation	130	24	1590	0.023	
5	Solid Layer	OSB	23	500	1600	0.13	
6	Cavity - Unlined		10				
7	Solid Layer	steel cladding	12	1	1	1	
8							
9							
10							



Key results	
Admittance [W/m²/K]	1.3
Decrement factor [-]	0.8
Decrement delay [hours]	4.1
K value [kJ/m2K]	18.8
For further details see Full Results sheet.	

Figure C-11: Build-up and thermal properties of the BASF SIP roof

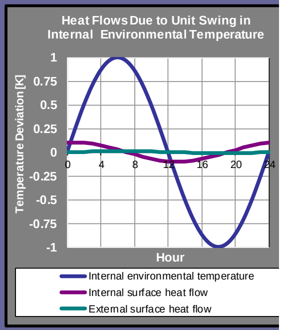
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Internal partition timber frame - Nottingham HOUSE
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.04	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Solid Layer	Isover Multimax 30	245	18	840	0.03	
3	Solid Layer	Sheathing ply	9	500	1600	0.13	
4	Solid Layer	RKL façade (glasswool)	50	18	840	0.03	
5	Cavity - Unlined		50				
6	Solid Layer	Timber cladding	18	500	1600	0.13	
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	0.8
Decrement factor [-]	0.6
Decrement delay [hours]	5.4
K value [kJ/m2K]	10
For further details see Full Results sheet.	

Figure C-12: Build-up and thermal properties of the Nottingham H.O.U.S.E. timber frame wall

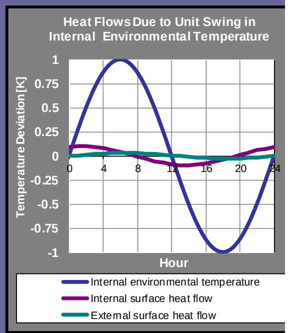
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Internal partition timber frame - Nottingham HOUSE
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
Solid Layer	PIR	72	32	920	0.02	
Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	



Key results	
Admittance [W/m²/K]	0.7
Decrement factor [-]	0.9
Decrement delay [hours]	1.2
K value [kJ/m2K]	10
For further details see Full Results sheet.	

Figure C-13: Build-up and thermal properties of the Nottingham H.O.U.S.E. timber frame internal wall

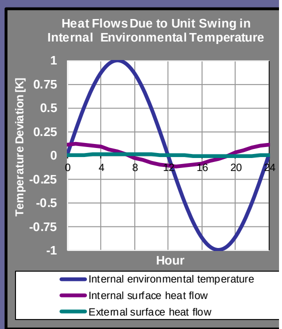
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Internal partition timber frame - Nottingham HOUSE
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.04	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	plasterboard (standard)	15	800	1000	0.21	
2	Solid Layer	Isover Multimax 30	195	18	840	0.03	
3	Solid Layer	Plywood sheathing	15	500	1600	0.13	
4	Solid Layer	Roofine P35	50	18	840	0.035	
5	Solid Layer	Plywood sheathing	22	500	1600	0.13	
6	Solid Layer	Roofine P35	100	18	840	0.035	
7	Solid Layer	Glassfibre insulation	37.5	18	840	0.035	
8	Solid Layer	Hofatex sarking board	80	260	2100	0.049	
9	Solid Layer	Ply	12	500	1600	0.13	
10							



Key results	
Admittance [W/m²/K]	0.9
Decrement factor [-]	0.0
Decrement delay [hours]	16.4
K value [kJ/m2K]	12.0
For further details see Full Results sheet.	

Figure C-14: Build-up and thermal properties of the Nottingham H.O.U.S.E. roof

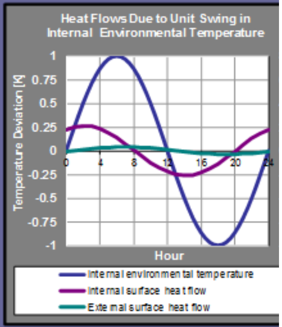
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Interanl partitionsteel frame - Mark Group Sunspace
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Solid Layer	cement particle board	12.5	1200	1500	0.23	
3	Solid Layer	rockwool	90	25	1030	0.038	
4	Solid Layer	cement particle board	12.5	1200	1500	0.23	
5	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
6							
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	2.1
Decrement factor [-]	0.8
Decrement delay [hours]	3.5
K value [kJ/m2K]	32.5
For further details see Full Results sheet.	

Figure C-15: Build-up and thermal properties of the Mark Group house steel frame internal wall

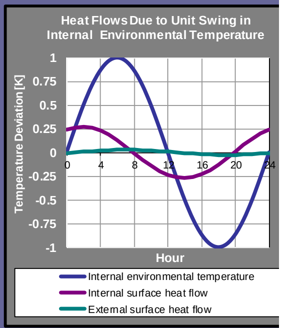
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Interanl partitionsteel frame - Mark Group Sunspace
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	PCM board	12.5	800	1000	0.23	
2	Solid Layer	cement particle board	12.5	1200	1500	0.23	
3	Solid Layer	rockwool	140	25	1030	0.038	
4	Cavity - Unlined	cement particle board	50				
5	Solid Layer	cement particle board	12.5	1200	1500	0.23	
6	Solid Layer	carpet	10	200	1300	0.6	
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	2.1
Decrement factor [-]	0.8
Decrement delay [hours]	3.5
K value [kJ/m2K]	32.5
For further details see Full Results sheet.	

Figure C-16: Build-up and thermal properties of the Mark Group house steel frame internal ceiling

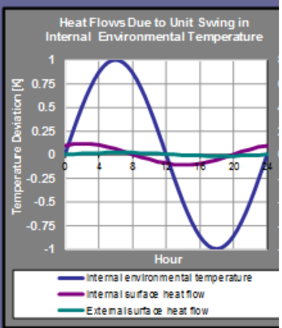
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Interanl partitionsteel frame - Mark Group Sunspace
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.13	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.04	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Solid Layer	rockwool	90	25	1030	0.038	
3	Solid Layer	cement particle board	12.5	1200	1500	0.23	
4	Solid Layer	extruded polystyrene	150	40	1400	0.035	
5	Solid Layer	render	5	1800	1000	1	
6							
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	0.8
Decrement factor [-]	0.2
Decrement delay [hours]	7.2
K value [kJ/m2K]	10.0
For further details see Full Results sheet.	

Figure C-17: Build-up and thermal properties of the Mark Group house steel frame external wall

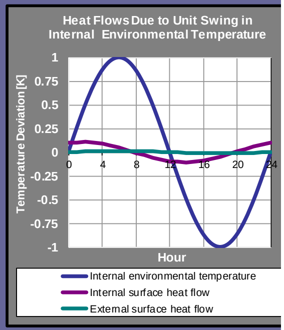
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	External Roof steel frame - Mark Group Office
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.13	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.04	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Solid Layer	rockwool	120	25	1030	0.038	
3	Solid Layer	cement particle board	12.5	1200	1500	0.23	
4	Solid Layer	PIR	120	32	920	0.02	
5	Solid Layer	roof tile	5	1800	1000	1	
6							
7							
8							
9							
10							

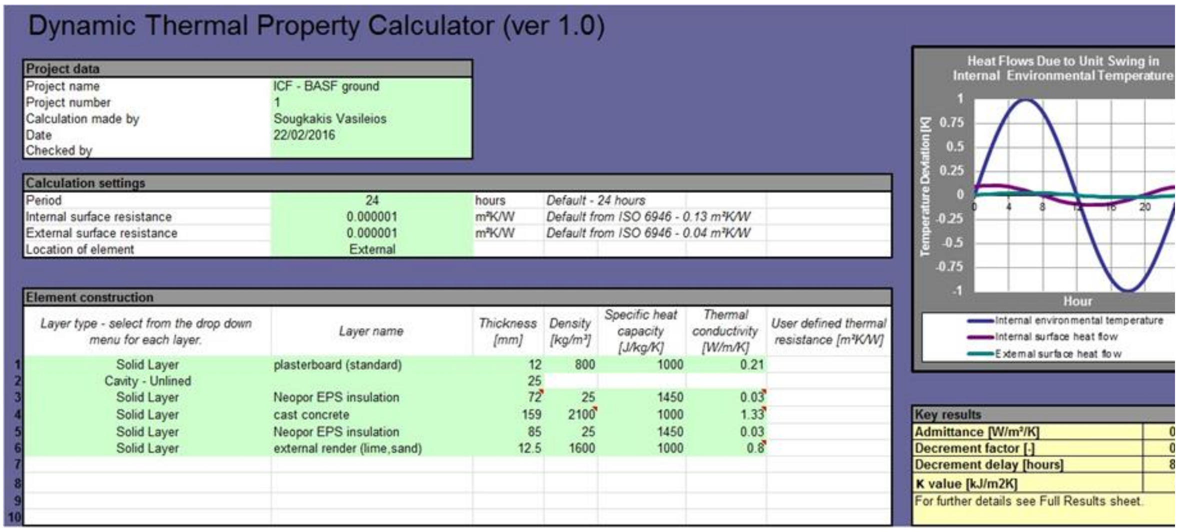


Key results	
Admittance [W/m²/K]	**0.8**
Decrement factor [-]	**0.2**
Decrement delay [hours]	**7.1**
K value [kJ/m2K]	**10.0**
For further details see Full Results sheet.	

Figure C-18: Build-up and thermal properties of the Mark Group house steel frame roof

APPENDIX D – FINITE ELEMENT ANALYSIS CONSTRUCTIONS

The thermal properties of the building elements examined in Chapter 7 as calculated by the Dynamic Thermal Properties Calculator (ver1.0) are presented below.



Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	ICF - BASF ground
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

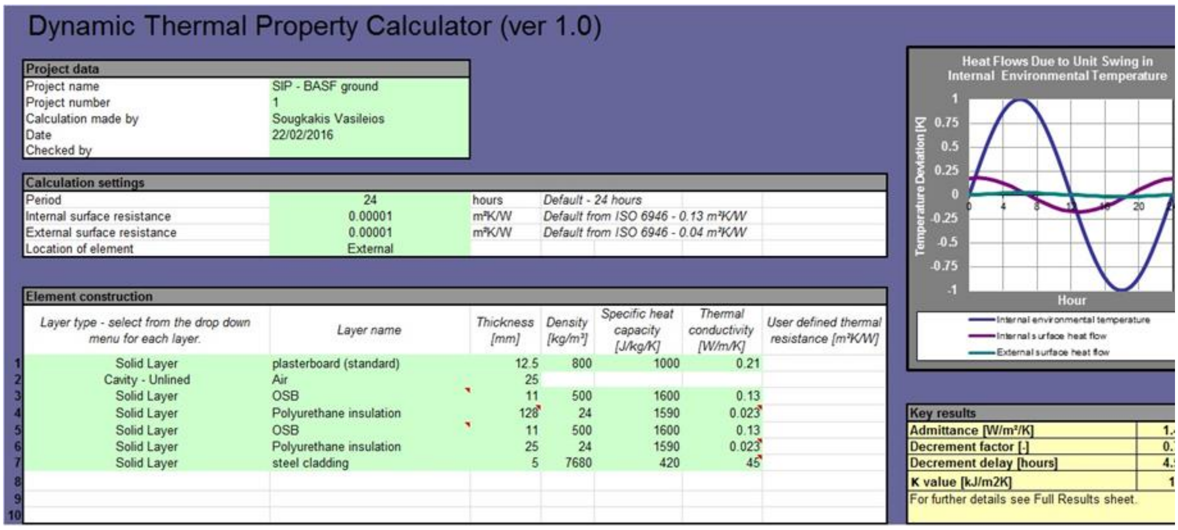
Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.000001	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.000001	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	plasterboard (standard)	12	800	1000	0.21	
2	Cavity - Unlined		25				
3	Solid Layer	Neopor EPS insulation	72	25	1450	0.03	
4	Solid Layer	cast concrete	159	2100	1000	1.33	
5	Solid Layer	Neopor EPS insulation	85	25	1450	0.03	
6	Solid Layer	external render (lime,sand)	12.5	1600	1000	0.8	
7							
8							
9							
10							

Key results	
Admittance [W/m²/K]	0
Decrement factor [-]	0
Decrement delay [hours]	8
K value [kJ/m2K]	
For further details see Full Results sheet.	

Figure D-1: Build-up and thermal properties of the ICF wall



Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	SIP - BASF ground
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.00001	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.00001	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	plasterboard (standard)	12.5	800	1000	0.21	
2	Cavity - Unlined	Air	25				
3	Solid Layer	OSB	11	500	1600	0.13	
4	Solid Layer	Polyurethane insulation	128	24	1590	0.023	
5	Solid Layer	OSB	11	500	1600	0.13	
6	Solid Layer	Polyurethane insulation	25	24	1590	0.023	
7	Solid Layer	steel cladding	5	7680	420	45	
8							
9							
10							

Key results	
Admittance [W/m²/K]	1.
Decrement factor [-]	0.
Decrement delay [hours]	4.
K value [kJ/m2K]	1
For further details see Full Results sheet.	

Figure D-2: Build-up and thermal properties of the SIP wall

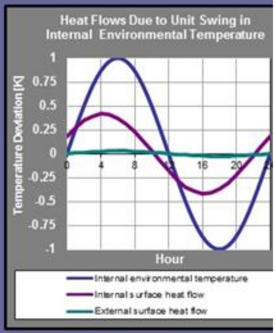
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Cavity Wall - Tarmac 4
Project number	1
Calculation made by	Sougkakis Vasileios
Date	09/10/2014
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.00001	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.00001	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	Plasterboard	12.5	700	1000	0.21	
2	Cavity - Unlined		10				
3	Solid Layer	Hemelite blocks	150	1360	1000	0.45	
4	Solid Layer	Kingspan TW50 (PIR)	80	32	920	0.022	
5	Cavity - Unlined		50				
6	Solid Layer	Facing brick	103	1700	800	0.84	
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	3.
Decrement factor [-]	0.
Decrement delay [hours]	10.
K value [kJ/m2K]	9
For further details see Full Results sheet.	

Figure D-3: Build-up and thermal properties of the cavity wall

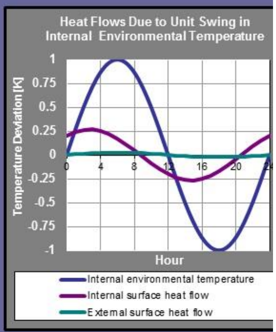
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Solid Wall - Tarmac 6
Project number	1
Calculation made by	Sougkakis Vasileios
Date	09/10/2014
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.00001	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.00001	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	plaster (lightewight)	13	600	1000	0.18	
2	Solid Layer	Durox supabloc	215	460	1000	0.11	
3	Solid Layer	EPS insulation	133	23	1470	0.035	
4	Solid Layer	Render	13	1800	1000	1	
5							
6							
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	2.
Decrement factor [-]	0.
Decrement delay [hours]	11.
K value [kJ/m2K]	4
For further details see Full Results sheet.	

Figure D-4: Build-up and thermal properties of the solid wall

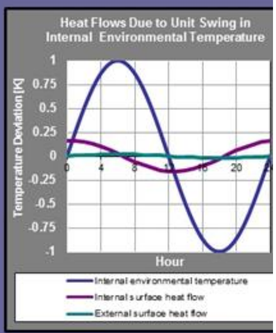
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Timber Frame
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	Default - 24 hours
Internal surface resistance	0.00001	m²K/W	Default from ISO 6946 - 0.13 m²K/W
External surface resistance	0.00001	m²K/W	Default from ISO 6946 - 0.04 m²K/W
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	Layer name	Thickness [mm]	Density [kg/m³]	Specific heat capacity [J/kg/K]	Thermal conductivity [W/m/K]	User defined thermal resistance [m²K/W]
1	Solid Layer	Rigidur H	12.5	1200	1100	0.2	
2	Solid Layer	Isover Multimax 30	217.5	18	840	0.04	
3	Solid Layer	Sheathing ply	9	500	1600	0.13	
4	Solid Layer	RKL façade (glasswool)	5	18	840	0.03	
5	Cavity - Unlined		20				
6	Solid Layer	Timber cladding	18	500	1600	0.13	
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	1.
Decrement factor [-]	0.
Decrement delay [hours]	2.
K value [kJ/m2K]	1
For further details see Full Results sheet.	

Figure D-5: Build-up and thermal properties of the timber frame wall

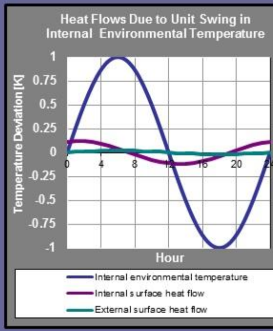
Dynamic Thermal Property Calculator (ver 1.0)

Project data	
Project name	Steel frame
Project number	1
Calculation made by	Sougkakis Vasileios
Date	22/02/2016
Checked by	

Calculation settings			
Period	24	hours	*Default - 24 hours*
Internal surface resistance	0.00001	m²K/W	*Default from ISO 6946 - 0.13 m²K/W*
External surface resistance	0.00001	m²K/W	*Default from ISO 6946 - 0.04 m²K/W*
Location of element	External		

Element construction

	Layer type - select from the drop down menu for each layer.	*Layer name*	*Thickness [mm]*	*Density [kg/m³]*	*Specific heat capacity [J/kg/K]*	*Thermal conductivity [W/m/K]*	*User defined thermal resistance [m²K/W]*
1	Solid Layer	Plasterboard	12.5	800	1000	0.21	
2	Solid Layer	mineral wool	100	25	1030	0.038	
3	Solid Layer	OSB	11	500	1600	0.13	
4	Solid Layer	PIR insulation external	77	32	920	0.022	
5	Solid Layer	render	5	1600	1000	0.8	
6							
7							
8							
9							
10							



Key results	
Admittance [W/m²/K]	0.
Decrement factor [-]	0.
Decrement delay [hours]	4.
K value [kJ/m2K]	1

For further details see Full Results sheet.

Figure D-6: Build-up and thermal properties of the steel frame wall