Loughborough University
Centre for Innovative and Collaborative Construction Engineering

A Computational and Empirical Analysis of the Thermal Performance of Insulating Concrete Formwork

Eirini Mantesi

Aggregate Industries UK Ltd
Bardon Hall, Bardon Drive, Copt Oak Road Markfield
LE67 9PJ

Centre for Innovative and Collaborative Construction Engineering
Department of Architecture, Building & Civil Engineering
Loughborough University
Loughborough
Leicestershire, LE11 3TU

A COMPUTATIONAL AND EMPIRICAL ANALYSIS OF THE THERMAL PERFORMANCE OF INSULATING CONCRETE FORMWORK

By
Eirini Mantesi

A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

July 2018

Aggregate Industries UK Ltd
Bardon Hall, Bardon Drive, Copt Oak Road
Markfield
LE67 9PJ

Centre for Innovative and Collaborative Construction Engineering
Department of Architecture, Building & Civil Engineering
Loughborough University
Loughborough
Leicestershire, LE11 3TU

To my parents,
Kondylia and George Mantesis,
who have always been
a great source of inspiration.
Thank you!

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to several people that have supported me, directly or indirectly, throughout the duration of this EngD project.

To begin with, I would like to thank my academic supervisors, Prof Jacqui Glass, Dr Christina Hopfe and Prof Malcolm Cook, for their tremendous help and support. During these four years, they have provided meaningful advice and guidance, they were always the first to talk to in times of distress, they promoted me and my work in every possible way, and they helped increase my self-esteem, as a young researcher. They far exceeded their strict responsibilities as project supervisors, and I genuinely feel grateful to have met and worked with them.

Secondly, I would like to express my deep appreciation to my industrial supervisor, Mr Richard Wilks, and my colleague, Mr Ron Lang, whose experience provided me with invaluable guidance during each stage of the project. Moreover, I would like to thank the head of sustainability department at Aggregate Industries, Mrs Donna Hunt, for financially supporting the monitoring project and for introducing me to people to promote my research. I'd like to express my gratitude to the owners of Twiga Lodge, Mr Ronny and Mrs Barbara Karlsson, for their kindness to offer their house as a case study for this research and for their warm hospitality during my visits to collect the data. I would like to thank Mr Vincent Smedley for advising and installing the monitoring equipment. This EngD project would not have been possible without funding from the Engineering and Physical Sciences Research Council (EPSRC) and Aggregate Industries UK Ltd, as well as the support of the Centre for Innovative and Collaborative Construction Engineering at Loughborough University.

I would faithfully like to thank my life partner, Dr Antonios Kyparissiadis, for being by my side through the good and the bad, for supporting me emotionally and making me believe in myself. I would also like to thank him for proofreading the thesis and for all those hours we spent studying together, making the whole process significantly more fun!

I would like to express my thanks to my friends, Dr Sotiria Kogou, Ms Irini Laura Verbist and Ms Katerina Xenikou for their precious emotional support throughout these years and for all those interesting research-related (or not) conversations we had, sharing our thoughts, concerns and ideas. Moreover, I would like to thank my friend and colleague Mr Konstantinos Mourkos, for all the hours we spent discussing, brainstorming and working together. Our collaboration made the, otherwise lonely, process of undertaking a PhD a lot more enjoyable.

Last but certainly not least, I would like to acknowledge the contribution of my family; I would never have made it here without their love, encouragement and emotional support. A big thank you goes to my siblings, Despoina and Dimitris Mantesis, for always being next to me (despite "any gaps in geography") and to my four nephews, George, Dimitris, Little George and Elias for all the happy breaks I had over those years talking to them on Skype.

ABSTRACT

The research presented in this EngD thesis focused on Insulated Concrete Formwork (ICF), a site-based, Modern Method of Construction (MMC). An ICF wall consists of modular prefabricated Expanded Polystyrene Insulation (EPS) hollow blocks and cast in situ concrete. The blocks are assembled on site and the concrete is poured into the void. Once the concrete has cured, the insulating formwork stays in place permanently, providing very low U-values and high levels of airtightness. ICF is often thought of as just an insulated panel acting thermally as a lightweight structure. There is a view that the internal layer of insulation isolates the thermal mass of the concrete from the internal space and interferes with thermal interaction. Despite evidence of ICF's enhanced thermal storage capacity (compared to a lightweight timber-frame panel with equivalent insulation), there is still a gap in understanding when attempting to quantify the effect of the thermal mass within ICF.

Using computational analysis (Building Performance Simulation - BPS) and empirical evaluation (monitoring data), the aim of the EngD research was to analyse the aspects that affect the thermal performance of ICF; to develop an understanding about its thermal behaviour and its response to dynamic heat transfer; and, to investigate how the latter is affected by the inherent thermal inertia of the concrete core.

An initial inter-model comparison using different state-of-the-art simulation tools showed a high range of variability in their simulation results for the same ICF building (up to 57% difference in the predictions provided by nine BPS tools). However, further analysis indicated that this discrepancy was mostly attributed to the modelling decisions of the user (intentional or unintentional – i.e. relying on the default settings of the tools without appreciating the sensitivity of the model), rather than the actual capabilities of the tools. Once the simulation models were calibrated with information from the monitoring project, BPS tools were able to predict with good accuracy the performance of ICF. In terms of internal air temperatures, the difference between simulation predictions and monitoring results was less than RMSE = 0.25^{o}C during warm weather and around RMSE = 0.45^{o}C during cold weather. The error between simulation and reality in the annual heating energy demand was found to be very low and equal to RMSE = 0.6kWh, indicating that the calibrated simulation models were able to predict the energy consumption of the building accurately.

Nevertheless, despite the good agreement between simulation predictions and monitoring results, the analysis indicated there was still a level of modelling uncertainty allied to the representation of solar radiation, and ICF was found to be affected by the availability of solar radiation.

The combined results of the empirical evaluation to an in-depth computational analysis showed that in terms of energy consumption and internal thermal condition, an ICF building behaves mostly as a heavyweight structure. The concrete core of ICF is not as thermally decoupled from the internal space as it is commonly expected. The thermal inertia of the concrete in ICF reduces the dynamic heat transmission of the wall, resulting ultimately in a relatively stable internal environment (up to 37% reduced heat losses were evident in the ICF building when compared to a lightweight structure with equal levels of insulation).

KEY WORDS

ICF; Thermal Mass; Building Performance Simulation; Inter-model Comparison; Modelling Uncertainty; Sensitivity Analysis; Thermal Monitoring; Empirical Validation; Calibrated Simulation; Dynamic Heat Transmission;

PREFACE

The Engineering Doctorate (EngD) programme is a four-year research degree equivalent to the traditional PhD, being better suited to the needs of industry. The EngD is part-funded by the Engineering and Physical Sciences Research Council (EPSRC) and its aim is to develop engineers who are capable of demonstrating innovation in the application of knowledge to the engineering sector (CICE, 2014). The focus of an EngD project is usually on one or more significant engineering problems with an industrial context.

The work conducted as part of this EngD was managed by the Centre for Innovative and Collaborative Construction Engineering (CICE) at Loughborough University and sponsored by Aggregate Industries UK Ltd, one of the largest heavyweight building materials producer/suppliers in UK, and member of LafargeHolcim Group.

This thesis presents the findings of the EngD project, it includes the main discourse and it is supported by four publications, two conference papers and two journal papers (three more conference papers have been published as part of this project but are not included in this thesis for reasons of brevity).

The main discourse is divided into five Chapters:

- The first chapter presents the background to knowledge and explains the aims and objectives of the research.
- The second chapter consists of a critical review to current literature on the subject area.
- The third chapter explains the methodology and the research methods employed in the specific EngD project.
- Chapter four describes the research undertaken and consists of a number of specific work packages, each addressing individual objectives within the overall aim of the research.

- The fifth and final chapter discusses the findings and the implications of the research in respect to existing knowledge and with relevance to the industrial sponsor and the wider industry.

Four of the seven publications are included in Appendices A to D. For ease of reference, these papers have been numbered 1-4. Each one presents specific work items within the overall programme. References to the papers are made throughout the discourse.

ACRONYMS AND ABBREVIATIONS

ACH	Air Changes per Hour
ANN	Artificial Neural Network
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BESTEST	Building Energy Simulation Test
BPS	Building Performance Simulation
BRE	Building Research Establishment
BS	Building Simulation
BSO	Building Simulation and Optimization
CCRA	Climate Change Risk Assessment
CICE	Centre of Innovative and Collaborative Engineering
CO_2	Carbon Dioxide
CV-RMSE	Covariance of Root Mean Squared Error
D_f	Decrement Factor
DHW	Domestic Hot Water
DOE	Department of Energy
DSA	Differential Sensitivity Analysis
EBC	Energy in Buildings and Communities
EngD	Doctorate of Engineering
EPS	Expanded Polystyrene
EPSRC	Engineering and Physical Sciences Research Council
Eq	Equation
EU	European Union
GBP	Great Britain Pound
GHG	Greenhouse Gas
GUI	Graphical User Interface
HTF	Hygrothermal Facility
HTM	High Thermal Mass
HVAC	Heating, Ventilation and Air Conditioning
IBPSA	International Building Performance Simulation Association
ICF	Insulating Concrete Formwork
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPMVP	International Performance Measurement and Verification Protocol
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LHS	Latin Hypercube Sampling
LTM	Low Thermal Mass
MBE	Mean Biased Error
MCA	Monte Carlo Analysis
MMC	Modern Methods of Construction

MPA	Mineral Product Association
MVHR	Mechanical Ventilation Heat Recovery
N.B.	Nota Bene
NCM	National Calculation Methodology
NPPF	National Planning Policy Framework
NRMSE	Normalised Root Mean Square Error
OAT	One at a Time
PhD	Doctorate of Philosophy
PV	Photovoltaic
R&D	Research and Development
RCP	Representative Concentration Pathways
RMSE	Root Mean Squared Error
RMX	Ready-Mix Concrete
SA	Sensitivity Analysis
SRRC	Standard Rank Regression Coefficient
TMY	Typical Meteorological Year
UA	Uncertainty Analysis
UHI	Urban Heat Island
UK	United Kingdom
UKCP	United Kingdom Climate Projections
UN	United Nations
USA	United States of America
W	Watts
WP	Work Package

LETTERS

c	Specific Heat Capacity
d	Thickness
λ	Thermal Conductivity
μ	Mean Value
ρ	Density
σ	Standard Deviation

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PAPERS

The following papers have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the course of the research. The first four publications are included in the Appendices of this thesis.

PUBLICATION 1 – CONFERENCE PAPER (APPENDIX A)

Mantesi, E., Hopfe, C. J., Glass, J., Cook, M. J. 2016. Investigating the Impact of Modelling Uncertainty on the Simulation of ICF for Buildings, In *3rd Building Simulation and Optimization Conference BSO2016. Newcastle, UK, 12-14 September 2016, Conference Proceedings.* URI: https://dspace.lboro.ac.uk/2134/21972.

PUBLICATION 2 – JOURNAL PAPER (APPENDIX B)

Mantesi, E., Hopfe, C. J., Cook, M. J., Glass, J., Strachan, P. 2018. The Modelling Gap: Quantifying the Discrepancy in the Representation of Thermal Mass in Building Simulation, *Building and Environment* 131, 74-98, doi: 10.1016/j.buildenv.2017.12.017.

PUBLICATION 3 – CONFERENCE PAPER (APPENDIX C)

Mourkos, K., Mantesi, E., Hopfe, C. J., Cook, M., Glass, J., Goodier, C. 2017. The Role of Fabric Performance in the Seasonal Overheating of Dwellings, In *15th International Building Performance Simulation Association, Building Simulation Conference, San Francisco, USA, 07-09 August 2017, Conference Proceedings.* URI: https://dspace.lboro.ac.uk/2134/25188.

PUBLICATION 4 – JOURNAL PAPER (APPENDIX D)

Mantesi, E., Hopfe, C. J., Mourkos, K., Glass, J., Cook, M. J. 2019. Empirical and Computational Evidence for Thermal Mass Assessment: The Example of Insulating Concrete Formwork, *Energy and Buildings* 188-198, 314-332, doi: doi.org/10.1016/j.enbuild.2019.02.021.

PUBLICATION 5 – CONFERENCE PAPER (NOT INCLUDED IN THESIS)

Mantesi, E., Cook, M. J., Glass, J., Hopfe, C. J. 2015. Review of the Assessment of Thermal Mass in Whole Building Performance Simulation Tools, In *14th International Building Performance Simulation Association, Building Simulation Conference, BS2015, Hyderabad, India, 07-09 December 2015, Conference Proceedings.*
URI: https://dspace.lboro.ac.uk/2134/19228.

PUBLICATION 6 – CONFERENCE PAPER (NOT INCLUDED IN THESIS)

Mantesi, E., Hopfe, C. J., Glass, J., Cook, M. J. 2015. Assessment of ICF Energy Saving Potential in Whole Building Performance Simulation Tools, In *14th International Building Performance Simulation Association, Building Simulation Conference, BS2015, Hyderabad, India, 07-09 December 2015, Conference Proceedings.* URI: https://dspace.lboro.ac.uk/2134/19229.

PUBLICATION 7 – CONFERENCE PAPER (NOT INCLUDED IN THESIS)

Lei, W., Mantesi, E., Hopfe, C. J. 2017. Uncertainty Analysis of the Thermal Performance of Insulated Concrete Formwork in Comparison to Heavyweight & Lightweight Wall Configurations, In *7th Masters Conference: People and Buildings. London, UK, 22nd September 2017, Conference Proceedings.*

1 BACKGROUND TO THE RESEARCH

This chapter is the introduction to the EngD research project. It discusses the background to research, and provides an overview of the research context, which points to the research justification. Moreover, the emerging research problem is specified to explain the overarching research aim and objectives. A brief summary of the industrial sponsor is given, acknowledging the reasons for supporting this EngD. The thesis structure is described, and a thesis map is included to show how each chapter addresses the research aim and objectives.

1.1 IMPLICATIONS OF A CHANGING FUTURE CLIMATE

The purpose of this section is to summarise the available evidence regarding the key risks associated with climate change, with particular focus on the impacts of future climate on the built environment.

Climate change is defined as the expected change in climate elements, such as temperature, pressure, winds (Dessler, 2012), and is a consequence of the rising concentration of Greenhouse Gases (GHG) in the atmosphere, mainly caused by human activities. The most direct impact of climate change is the increase of global temperature maxima, which is also expected to result in significant changes in the weather patterns and in increased frequency of extreme weather events (such as heat-waves, flooding, cold snaps and others) (NHBC Foundation, 2012; DEFRA, 2012; Committee on Climate Change, 2016).

The Intergovernmental Panel on Climate Change (IPCC) estimates that the global surface temperature change for the end of 21st century (2081-2100) is projected to exceed 1.5^{o}C (relative to 1850-1900), under the medium to high Representative Concentration Pathways (RCP)[1](IPCC, 2014).

[1] RCPs refer to time series of emissions and concentrations scenarios of the full range of greenhouse gases (GHGs) and aerosols, and are used as a basis for the climate predictions and projections extending up to 2100.

According to the United Kingdom Climate Projections[2] (UKCP, n.d.), under a medium emissions scenario, average summer temperatures are estimated to rise up to 2.8^{o}C by 2050s, reaching up to 5.4^{o}C by 2080s (in Southern England) (compared to 1961-1990 levels) (McLeod et al., 2013; Vardoulakis et al., 2015; Kovats & Osborn, 2017).

1.1.1 NATIONAL AND INTERNATIONAL POLICIES FOR CLIMATE CHANGE

In an attempt to combat the impact of climate change, governments have set targets to reduce energy consumption and CO_2 emissions. A number of national and international policies and programmes have been introduced over the last two decades. The Kyoto protocol was adopted in December 1997 and entered in force in February 2005. It is an international agreement among the United Nations (UN) setting GHG emission targets. In the first period, all parties participating in the Kyoto Protocol set targets to reduce GHG emissions to an average of 5% against 1990 levels. After the Doha amendment in 2012, Parties were further committed to an even higher reduction, equal to 18% (below 1990 level) for the eight-year period between 2013 and 2020 (UNFCCC, n.d.).

In line with the Kyoto Protocol, the European Parliament and Council published the Directive 10/31/EU on energy efficiency of building (European Parliament and Council, 2010). Under the Directive, all EU countries were required to use energy in buildings more efficiently and set a long-term commitment to maintain the global temperature rise below 2^{o}C by simultaneously reducing their overall GHG emissions by at least 20% below 1990 levels. In November 2016,

[2] The most up-to-date evidence for projected changes in the UK climate are from the 2009 UK Climate Projections (UKCP09). A project to update the projections is underway and is expected to release results in 2018 (UKCP18) (Committee on Climate Change, 2016).

.

the commission proposed an update to the Directive, including a further reduction of GHG emissions by 30% by 2030 (European Commission, n.d.).

In the Climate Conference of December 2015, in Paris, 195 countries (representing more than 87% of global GHG emissions) agreed to the first universal, legally-binding global climate deal, referred to as *Paris Climate Accord* (European Commission, n.d.). The aim of the Paris Accord is to prevent more than a 1.5^{o}C increase in global temperatures and achieve a net zero emissions target by the end of this century (Committee on Climate Change, 2016). Although inspiring, there are concerns about its success. Meeting the objectives of the agreement is highly dependent on the assumption that member states, especially those considered as high polluters (such as USA[3], China, Japan, Brazil, EU, Russia, India), will drive their own carbon reduction targets voluntarily, without any binding enforcement mechanism (Victor et al., 2017). Research has shown that current national initiatives are failing to meet the pledges made as part of Paris Accord goals (Rogelj et al., 2016; Victor et al., 2017).

In 2008, the Climate Change Act was passed in the UK Parliament (Parliament of the United Kingdom, 2008). Through the Act, the Committee on Climate Change and the Adaptation Sub-Committee were established to help assess and manage risks associated to climate change, to set objectives and introduce policies, aiming to review their outcome every five years. The first Climate Change Risk Assessment (CCRA) was published in January 2012, followed by the first UK National Adaptation Programme in July 2013. The second CCRA is now available since January 2017. The fifth Chapter of the second CCRA is focused particularly on people and the

[3] In June 2017 USA president Donald Trump announced the intention of US to leave the Paris Accord after November 2020, when it is the earliest date possible according to the article 28 of the agreement (United States of America: Communication, 2017)

built environment. The second National Adaptation Programme is expected in the summer of 2018 (Committee on Climate Change, 2016).

There is growing concern on the implications of climate change and the risks they will pose to people, communities, buildings, infrastructure and businesses. Among the different national and international policies, a significant amount of efforts is directed towards reducing the energy consumption and the CO_2 emissions in the build environment.

1.1.2 IMPACTS OF CLIMATE CHANGE ON THE BUILT ENVIRONMENT

The impact of climate change on the built environment has been the focus of much scientific research over the past decades (Jenkins et al., 2011; DCLG, 2012; Beizaee et al., 2013; McLeod et al., 2013; Jones et al., 2016; Lomas & Porritt, 2017). In Europe, 40% of the total energy consumption and 36% of the total CO_2 emissions derive directly from the built environment (European Parliament and Council, 2010). Residential buildings alone use about 60% of the total energy consumption attributed to the building sector (Foucquier et al., 2013).

Chapter 5 of the CCRA summarises the key risks of climate change associated with people and the built environment (Kovats & Osborn, 2017). Among others, the authors have identified:

- The risk of overheating in buildings
- Flooding risks
- The increasing ambient temperatures due to Urban Heat Island (UHI) effect
- Water supply and drainage problems

A large portion of homes in England and in Europe are said to be vulnerable to overheating under future climatic scenarios, but also during current climatic conditions (Mavrogianni et al., 2012; Dengel & Swainson, 2012; Beizaee et al., 2013; Van Hooff et al., 2014). This is particularly important and it is partly attributed to the increasing ambient temperatures due to global warming, but also to the rigorous building regulations that focus on the reduction of fabric heat losses by increasing thermal resistance and air-tightness (Davies & Oreszczyn, 2012; Mavrogianni et al., 2012; McLeod & Hopfe, 2013; Vardoulakis et al., 2015; Committee on Climate Change, 2016; Jones et al., 2016; Lomas & Porritt, 2017).

There is an expected shift in energy use (decrease in heating demand, increase in cooling demand) which is also expected to affect the efficiency of passive design systems in maintaining comfortable thermal conditions (Crawley, 2008; De Wilde & Coley, 2012). At present, 3% of UK homes have mechanical air-conditioning for active cooling (Khare et al., 2015), while the majority of English dwellings rely on passive cooling to remove excess heat from the interior (e.g. natural ventilation). However, this percentage is expected to increase in the future (Peacock et al., 2010; McLeod et al., 2013), resulting ultimately in increased GHG emissions attributed to the domestic sector (Jones et al., 2016). Williams et al. (2012) developed a methodology that allows estimation of building lifecycle GHG emissions at early stage design, accounting for future climate projections. The analysis showed that GHG emission due to space cooling is expected to increase (i.e. between 26% - 70%, depending on the future emissions scenario). Despite any anticipated decrease in space heating demand, there is an overall expected net increase in GHG emissions. The latter indicates that energy efficient cooling systems, along with passive cooling design measures (such as solar shading, thermal mass, efficient window openings etc.), are important components in reducing cooling demand from buildings.

To adjust to the future changing climate, energy efficient buildings steer a new era of development, including new materials, innovative envelope technologies and advanced design ideas (Sadineni et al., 2011; Kolokotsa et al., 2011; Omrany et al., 2016).

1.1.3 Adaptation and Mitigation Strategies in Building Design

The thermal performance of buildings is highly affected by the climate to which they are exposed. Considering that the lifetime of a building is usually in the range between 50-100 years, it becomes apparent that combining adaptation and mitigation measures in building design is important to secure successful thermal performance in the future, but also reduced GHG emissions (De Wilde & Coley, 2012).

A number of different adaptation and mitigation strategies have been identified (Porritt et al., 2011; DCLG, 2012; De Wilde & Coley, 2012; Van Hooff et al., 2014). The most frequently mentioned are:

- Optimising building orientation (for new built development)
- Optimising glazing areas (windows to wall ratio)
- Applying solar shading (fixed or operable, vertical or horizontal)
- Windows upgrade (low emissivity double and triple glazing windows)
- Providing additional natural ventilation (in moderate climates - to help remove excess heat from the interior)
- Increasing the energy efficiency of appliances (A++ rating)
- Increasing the air-tightness of the fabric (reducing the amount of unwanted infiltration and thermal bridging)
- Increasing solar reflectivity of walls and roofs (lower exterior surface temperatures and lower heat flux from the exterior surface to indoor environment)
- Increasing the thermal resistance of the building fabric (application of external or internal insulation)
- Exploiting the thermal mass of the fabric (the thermal storage capacity of structural elements)

Among the different adaptation and mitigation building design measures this EngD project is particularly related to the last two points; increasing the thermal resistance of the building envelope, along with exploiting the fabric’s thermal mass as a passive design strategy.

1.2 UK HOUSING CRISIS AND THE USE OF MODERN METHODS OF CONSTRUCTION

Alongside carbon reduction targets, the UK government has to deal with the challenges imposed by the housing crisis. Between 1990-2010, population growth accelerated, while the corresponding number of completed dwellings per year decreased (Swann et al., 2012). The UK government is committed in the National Planning Policy Framework (NPPF) to facilitate the supply of housing, since a further increase of population by 10.2 million people is expected by 2033 (Swann et al., 2012; Troop, 2013).

The UK housing construction industry has been characterised as conservative, with very little changes in building design and layout over the past 100 years (Pan et al., 2007; Rodrigues, 2010). However, a recent industry survey conducted by the NHBC (NHBC Foundation, 2016) indicated that there is a noticeable turn toward lightweight and other off-site Modern Methods of Construction (MMC) due to their advantages in reducing cost, time, defects, health and safety risks and their environmental impact. MMC are defined as a number of mostly off-site innovative technologies in house building, moving work away from the construction site to the factory (Gibb, 1999).

1.2.1 INSULATING CONCRETE FORMWORK: A HEAVYWEIGHT MODERN METHOD OF CONSTRUCTION

This EngD research project focuses on one of the site-based MMC, namely the Insulated Concrete Formwork (ICF). The ICF wall system has several advantages; it shows an increased speed of construction, a significant structural strength and durability, better noise attenuation and others. With regards to its thermal performance, ICF can provide complete external and internal wall insulation, minimising the existence of thermal bridging, providing very low U-values and high levels of air-tightness if installed correctly (Rajagopalan et al., 2009).

The ICF wall component consists of modular prefabricated Expanded Polystyrene Insulation (EPS) hollow blocks and cast in situ concrete. The blocks are assembled on site and the concrete is poured into the void. Once the concrete has cured, the insulating formwork stays in place permanently. The resulting construction structurally resembles a conventional reinforced concrete wall.

Concrete is a high density material, therefore said to have high thermal mass (Shafigh et al., 2018). The thermal mass of the fabric can be used as a passive design strategy to reduce energy use for space conditioning (Al-Sanea et al., 2012; Slee et al., 2014; Navarro et al., 2016). The fundamental benefit of thermal mass is its ability to capture the internal, casual and solar heat gains, helping to moderate internal temperature swings and delaying the time at which peak load occurs (Al-Sanea et al., 2012; Reilly & Kinnane, 2017).

1.3 THE USE OF BUILDING PERFORMANCE SIMULATION FOR DESIGN SUPPORT

Over the past decades, computer-aided simulation of buildings has become widely available both in research and in industry (Wang & Zhai, 2016). Based on descriptions of the construction, occupancy patterns and HVAC systems, BPS tools can provide predictions on thermal performance and energy consumption of a building. However, there is often a discrepancy between expected energy performance during design stage and real energy performance after project completion (Foucquier et al., 2013). Moreover, there are often inconsistencies in simulation results when modelling an identical building using different BPS tools, referred to as modelling uncertainties (Hopfe & Hensen, 2011). These can lead to a lack of confidence in building simulation.

In order to rely on BPS prediction with a degree of confidence, it is important to represent the actual performance of a building as accurately as possible (Coakley et al., 2014; Fumo, 2014). Validation is a common practice to ensure the results from simulation programs are reliable

(Ryan & Sanquist, 2012; Fumo, 2014). A BPS model contains hundreds of input variables and parameters. Some researchers argue that it is impossible to completely validate a building model, but only to build confidence about the accuracy of the results (Ryan & Sanquist, 2012). Other studies have shown that if correct and up-to-date information is used in post-occupancy simulation, then BPS can provide relatively realistic results (Burman et al., 2012).

The empirical validation of BPS results relies on the comparison between the predictions provided by the different dynamic thermal simulation programs and the field measurements of the actual long-term energy use of a real building (Lomas et al., 1997; Judkoff & Neymark, 2011). By reconciling model outputs with measured data, it is feasible to achieve more accurate and reliable BPS results.

1.4 RESEARCH JUSTIFICATION

The following section aims to define the research problem, which emerges through studying the general subject domain, and to justify the significance and the need for this research.

It is widely accepted that the global climate is changing, and this will inevitably affect the whole built environment. As the different governments join their forces to reduce GHG emissions, building regulations become more and more stringent, with particular focus on improved building fabric performance (reduced infiltration, better insulation and optimal use of solar gains). Research has shown that super airtight and highly insulated constructions are at risk of overheating.

While the phenomenon of thermal mass to reducing energy consumption and maintaining comfortable conditions is thought to be reasonably well understood, there is a noticeable trend towards lightweight building structures, mainly due to their improved speed of construction, leading to increased instances of overheating and poor indoor comfort conditions. The problem becomes particularly evident in buildings with extended occupancy patterns, such as domestic and residential properties, many of which are occupied by vulnerable or low-income population groups. This, along with the increasing cost of energy, contribute to the growing issue of fuel poverty, a significant problem that requires immediate actions.

This EngD investigates the role of materials in contributing to energy demand reduction in buildings, principally through the effective deployment of thermal mass, with particular focus on ICF. ICF is often thought of as just an insulated panel acting thermally as a lightweight structure. There is a view that the internal layer of insulation isolates the thermal mass of the concrete from the internal space and interferes with thermal interaction. Although there is evidence supporting ICF's thermal storage capacity (Kosny et al., 2001b; Maref et al., 2010) in comparison to a light-weight timber-frame panel with equal levels of insulation, there is still a gap in understanding when attempting to quantify the effect of its thermal mass.

In Europe, ICF dates back since the late 1960's (Armstrong et al., 2011), yet it is often characterised as an innovative wall technology because it has only recently become more popular for use in residential and commercial construction. Additionally, an ICF building shows significantly increased speed of construction, compared to traditional construction methods; hence, it is often classed among the MMCs. To be able to support the commercial proposition of new materials and innovative building technologies, it is important to predict and communicate thermal behaviour and energy performance accurately.

In order to quantify the potential of ICF in energy consumption savings, it is crucial to calculate the dynamic heat transfer that occurs in and out of the building fabric. When assessing the energy consumption and thermal performances of heavyweight constructions where the dynamic thermal behaviour of the building fabric affects significantly the heat transfer and the thermal response of the building, the use of reliable dynamic Building Performance Simulation (BPS) is essential (Davies, 2004).

The purpose of the EngD project is to analyse the thermal performance of ICF in the UK climatic context. The main research problem associated to ICF is defined as follows:

> *Despite previous research conducted on ICF, there remains a gap in knowledge on its actual thermal performance. Moreover, there is a generally poor level of understanding of how to quantify the effect of its thermal mass and a lack of evidence verifying the accuracy of ICF simulation predictions.*

As such, there is scope to deliver a new evidence base that would allow a detailed comparison of monitoring data with simulation results, thereby empirically and computationally evaluate the thermal performance of ICF and its suitability for the UK housing construction industry.

1.5 RESEARCH AIM AND OBJECTIVES

The aim of the research is to analyse the aspects that affect the thermal performance of ICF construction method, to develop an understanding about the thermal behaviour of ICF and its response to dynamic heat transfer, and to investigate how the latter is affected by the inherent thermal inertia of the material's concrete core. The outcome would seek to inform the wider academic and industrial building energy community on the internal thermal conditions and the energy consumption of buildings using ICF.

The research objectives of this EngD project are the following:

1. To test and evaluate common dynamic Building Performance Simulation (BPS) tools in predicting ICF thermal and energy performance, and to identify the key modelling uncertainties that are associated to ICF simulation.
2. To monitor and analyse the actual energy consumption and thermal performance of an ICF building located in the UK and to scrutinise ICF's potential for indoor temperature control.

3. To empirically validate, with the use of real monitoring data, the accuracy of BPS simulation results in calculating the thermal performance of ICF.
4. To evaluate the level of uncertainty and the sensitivity of the model in the representation of ICF in BPS when considering the physical uncertainties of the wall material properties.
5. To investigate the thermal storage capacity of ICF concrete core and determine whether ICF can be characterised as a thermally heavyweight or lightweight structure.

1.6 THE INDUSTRIAL SPONSOR

Aggregate Industries UK Ltd is one of the largest heavyweight building materials producer/suppliers in UK. Its headquarters are located in Markfield, Leicestershire. It is a large company, with more than 4000 employees, more than 300 operational sites (in the UK) and an annual revenue of 1.2bn GBP (December 2017).

It was formed in 1997 after the merger of Bardon Group plc and Camas plc and acquired its current name of Aggregate Industries UK Ltd. In 2005, Aggregate Industries was acquired by Holcim Group. In 2015, Holcim merged with Lafarge and formed the LafargeHolcim group. LafargeHolcim is a multinational producer of cement, aggregates, ready-mix concrete (RMX) and asphalt, operating in more than 80 countries globally, employing around 80000 people, with an annual revenue (in 2017) of 26.13 billion Swiss franc (CHF) (LafargeHolcim, n.d.).

Aggregate Industries UK Ltd operations produce and supply a wide range of construction materials:

1. Aggregates
2. Cement
3. Ready-mix concrete and screed
4. Asphalt

5. Commercial and domestic landscaping
6. Building products/blocks

At the outset of the EngD project, the work undertaken was under the umbrella of the sustainability department. However, as the research progressed and due to several changes that occurred in the company's structure over the years, ICF now falls under the division of innovation and R&D.

The aim of the Innovation Department is to accelerate the development of new and innovative products and solutions. The research conducted on ICF fits into the category of "self-build" products. To be able to support the commercial proposition of innovative materials and building technologies (such as ICF), it is rather important to predict and communicate their thermal behaviour and energy performance accurately. Faced with a lack of empirical data, computer simulation can be used to provide quantitative data, supporting the decision-making process. The research conducted as part of this EngD was the first thorough investigation of the simulation of ICF and reflected on the effect of modelling uncertainties on ICF and thermal mass simulation. Moreover, a new evidence base was developed for the thermal storage capacity of ICF and its use in the UK housing construction industry, combining both computational data and monitoring results. Having all the benefits of a site-based MMC (such as improved speed of construction, reduced defects, decreased health and safety risks, among others), ICF could be a viable alternative to heavyweight housing construction. However, due to the lack of empirical knowledge on its thermal performance, ICF is commonly perceived as a thermally lightweight structure. There is a view that the internal layer of insulation isolates the thermal mass of ICF's concrete from the internal space and interferes with their thermal interaction. The results of this EngD will be exploited by Aggregate Industries UK Ltd to underpin their commercial proposition for the specific construction method.

Participating and supporting this EngD helped the sponsoring organisation to collect and access new data and ultimately to develop new understandings about the behaviour of ICF, which could eventually be used to inform building design and subsequent research in the area. The impact and the implications of the EngD project to the sponsoring organisation is thoroughly discussed in Section 5.3.

1.7 THESIS STRUCTURE

The EngD thesis is organised into five chapters. An overview of each chapter is provided below.

Chapter One – Background to the Research

The first chapter is the background to research. It provides an overview of the research context, and the research problem, aiming to justify the need for this research and to specify the emerging research aim and objectives. Furthermore, the chapter includes a brief presentation of the sponsoring company to acknowledge the reasons for supporting this EngD.

Chapter Two – Enhanced Fabric Performance and the Role of Advanced Building Modelling in Creating Energy Efficient Buildings

The second chapter is a literature review. It examines previous research studies conducted on ICF. Moreover, it investigates the relationship between thermal mass and ICF and it discusses the benefits and constraints of using computer-aided simulation for building design support.

Chapter Three – Adopted Methodology

Chapter three presents the research methodology adopted along with the specific research design used in order to meet the aim and objectives of this research. Methodological considerations are discussed, and a brief review of different research methods is conducted in order to justify the chosen approach. A research design map is included, summarising the key research processes employed for each of the different studies undertaken.

Chapter Four – Research Undertaken

Chapter four describes the research undertaken based on the adopted research design. It is divided into six sections related to six distinct work packages (WP). The chapter also refers to the publications produced during the EngD, which are included in the Appendices A – D.

Chapter Five – Findings and Implications

The final chapter summarises the main findings of the research, including the contribution to existing theory and practice, the impact of the research on the industrial sponsor and the wider industrial community. It includes a critical evaluation of the research, discussing the constraints and limitations of the project, along with recommendations for further research.

Fig.1.1 shows how the overarching aim and research objectives are addressed in specific sections and chapters and how they are linked to the academic outputs (published papers).

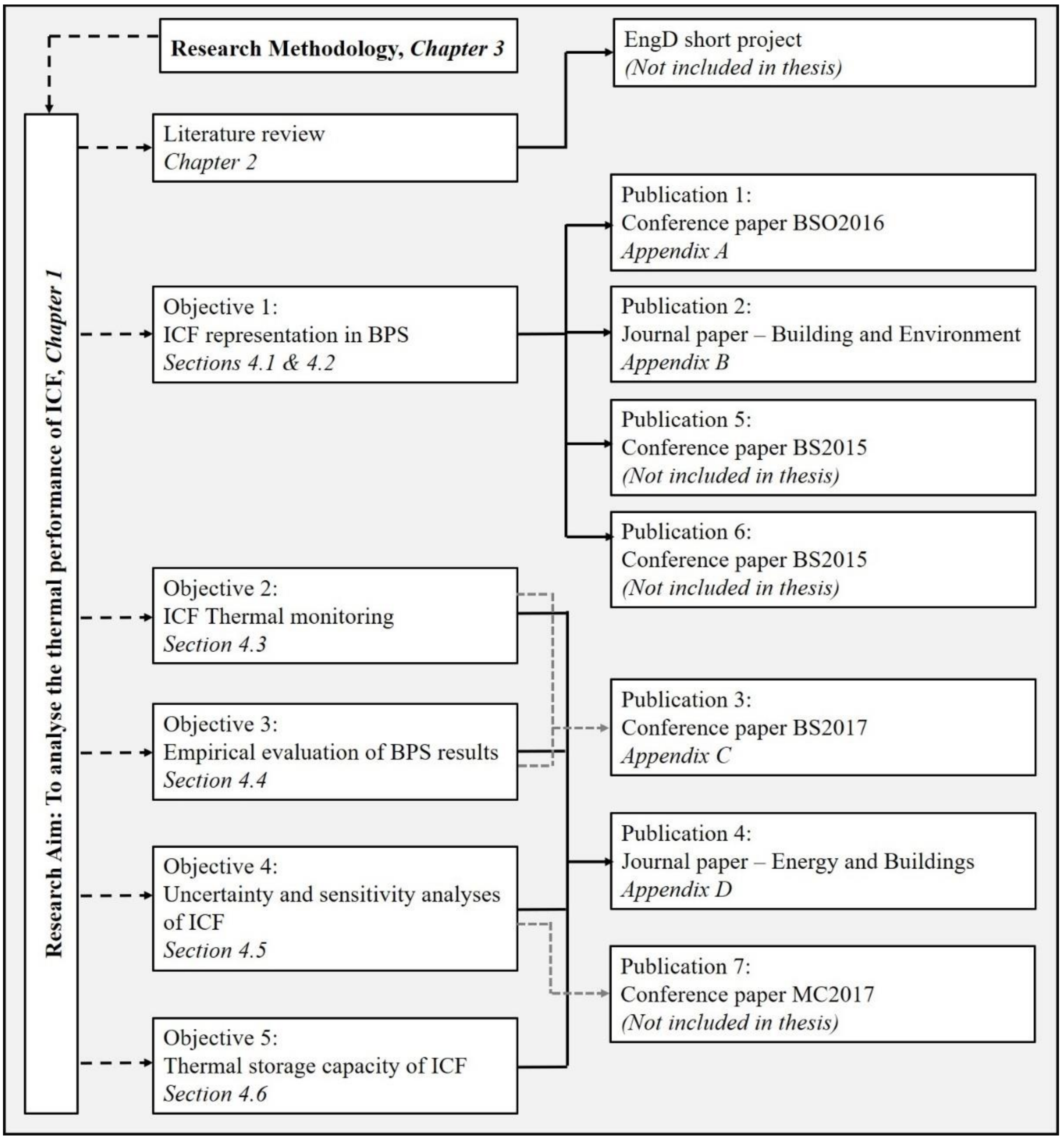


Figure 1.1 *Research map linking the research aim and objectives of the EngD to specific chapters and produced outputs*

2 ENHANCED FABRIC PERFORMANCE AND THE ROLE OF ADVANCED BUILDING MODELLING IN CREATING ENERGY EFFICIENT BUILDINGS

This chapter provides an overview of the existing literature in three relevant subject areas: a) the physical behaviour of thermal mass in buildings (Section 2.1), b) the performance of ICF construction method (Sections 2.2), c) the benefits and challenges associated with the use of computer-aided simulation (Section 2.3).

2.1 THERMAL MASS IN BUILDINGS

There is growing evidence that a number of existing buildings are already vulnerable to overheating (due to climate change, but also under current climatic conditions). Hence, the purpose of this section is to explore the use of thermal mass as a means of buildings' adaptation to climate change and measure against overheating.

The thermal mass of the fabric can be used as a passive design strategy to reduce energy use for space conditioning (Balaras, 1996; Hacker et al., 2008; Navarro et al., 2016; Reilly & Kinnane, 2017). The term thermal mass defines the ability of a material to store sensible thermal energy by changing its temperature. The amount of thermal energy storage is proportional to the difference between the material's final and initial temperatures, its density, and its specific heat capacity (Dincer & Rosen, 2011). The fundamental benefit of thermal mass is its ability to capture the internal, casual and solar heat gains, helping to moderate internal temperature swings and delaying the point at which the peak load occurs (Rodrigues, 2010; Al-Sanea et al., 2012; Slee et al., 2014; Kumar et al., 2017).

2.1.1 QUANTIFICATION OF THERMAL MASS

Thermal mass is dependent on the material of the object and its heat transfer properties; specific heat capacity, thermal conductivity and density. Typically, construction materials that are characterised as having high thermal mass are those that have a high specific heat capacity (to maximise the heat stored per kg), high density (to maximise the overall weight of material used) and a moderate conductivity, which is able to synchronise the heat flow in and out of the building with the diurnal temperature swing. The thermal storage capacity of a material is quantified as the product of its density (ρ) and its specific heat capacity (C_p) and it is known as the **volumetric specific heat capacity (C_p ρ)** (Hopfe & McLeod, 2015).

The term $C_p\rho$ defines how much heat should be added to the material in order to change its temperature by a unit of temperature. Two further parameters can be derived by the material's heat transfer properties, **thermal diffusivity (α)** and **thermal effusivity (ε)** (or thermal inertia). Thermal diffusivity (α) is defined as the ratio between thermal conductivity and the specific heat-density product and it measures the rate of heat removal from the heat source (Jankovic, 2012). The thermal diffusivity of a material is an indicator of the rate of heat transfer through the cross-sectional depth of a material (Hopfe & McLeod, 2015).

$$\boldsymbol{\alpha = \lambda/(Cp * \rho)} \qquad \textbf{(Eq.1)}$$

Thermal effusivity measures the material's ability to exchange heat with its surroundings, hence characterises the transfer of heat through the material's surface (Rodrigues, 2010).

$$\boldsymbol{\varepsilon = \sqrt{\lambda * Cp * \rho}} \qquad \textbf{(Eq.2)}$$

Where:

α is the thermal diffusivity (m^2/s)

λ is the thermal conductivity (W/mK)

C_p is the specific heat capacity (J/kgK)

ρ is the density (kg/m^3)

A material that has a high thermal diffusivity has a high conduction rate relative to its heat storage capacity, so responds quickly to changes in temperature. On the other hand, when the heat storage capacity of a material is higher than its thermal conductivity, it is said to have low thermal diffusivity, hence responding slower to changes in temperature. In practical terms, the thermal effusivity of a material determines its transient thermal behaviour when in contact with another material. The material with greater thermal effusivity will prevail in maintaining its temperature for a certain period of time.

The thermal diffusivity and effusivity can be used to help characterise a material's capacity to act as thermal mass. Nevertheless, when it comes to characterising the thermal storage capacity of multilayer fabric constructions (such as ICF), their use is not as straightforward. There are three other concepts that can help characterise the influence of thermal mass in the context of building fabric: **Thermal Admittance, Time Lag** and **Decrement Factor**.

The **thermal admittance (Y_{mm})** is used to define the exchange of the heat between the thermal mass and the interior space, so it can also be an indication of the construction's thermal mass. The admittance value of a wall may be described as a measure of its thermal conductance when subject to a cyclic variation in temperature (BS EN ISO 13786, 2017). The thermal admittance of a construction is equal to its U-Value in steady-state calculations but differs in transient conditions. It is likely to be high in constructions that have high thermal mass materials in their inner most layers and low if they have insulating materials internally. In multi-layer constructions, the thermal admittance is mainly determined by the properties of the inner-most material layers.

The **decrement factor (D_f)** and the **time lag (ω)** are two important characteristics to determine the heat storage capabilities of any construction (Asan, 2000). The decrement factor (D_f) is the amplitude of internal air temperature fluctuation divided by that of the ambient temperature fluctuation. Hopfe and McLeod (2015, p.65) define D_f *as the ratio by which the amplitude of* *the external temperature sine wave is dampened as a result of the material's specific thermal capacity*.

$$\boldsymbol{D_f = \frac{t_{i,amp}}{t_{e,amp}}} \qquad \textbf{(Eq.3)}$$

Where:

D_f is the decrement factor (unitless)

$t_{e,amp}$ is the amplitude of the external temperature sine wave (K)

$t_{i,amp}$ is the amplitude of the internal temperature sine wave (K)

Decrement delay (ω) (or time lag) is the time span between the time of peak external temperature and the time of peak internal temperature, and is measured in hours (Hopfe & McLeod, 2015).

$$\boldsymbol{\omega = T_{ti,max} - T_{te,max}} \qquad \textbf{(Eq.4)}$$

Where:

ω is the decrement delay (Hours)

$T_{ti,max}$ is the time of the maximum internal temperature

$T_{te,max}$ is the time of the maximum external temperature

An illustration of the decrement factor and the decrement delay as an evaluation mechanism in the context of building physics is given in Fig.2.1. Research has shown that the time lag increases and the decrement factor decreases with increasing thermal mass. These terms are key to this research and feature heavily in the papers included in Appendices A and D.

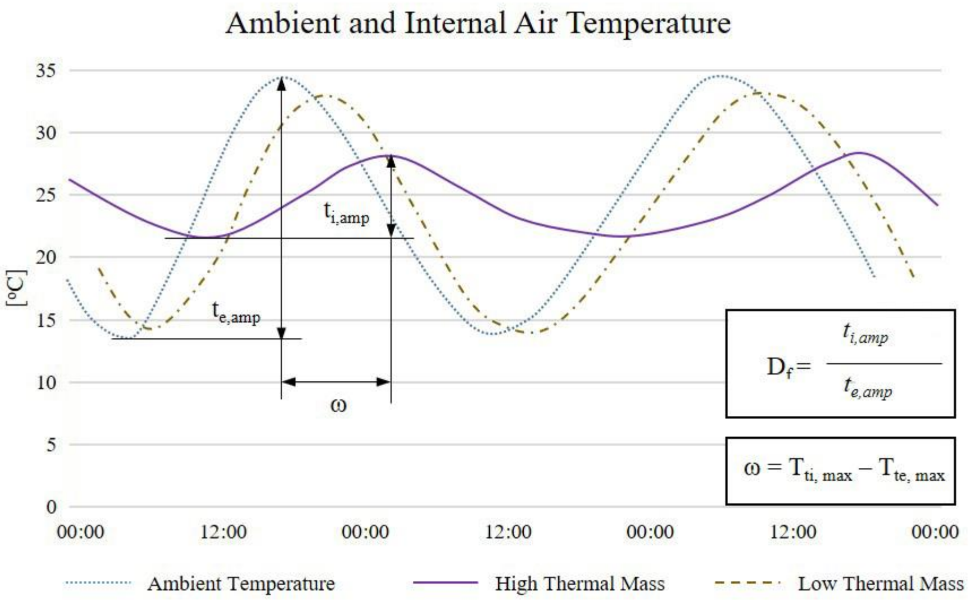


Figure 2.1 *Stabilising effect of thermal mass on internal air temperature; decrement factor and time lag*

2.1.2 BUILDING REGULATIONS, TECHNICAL GUIDES AND THERMAL MASS

In line with the EU Directive 10/31/EU (European Parliament and Council, 2010), the UK Government has introduced Part L of Building Regulations 2010, which is focused on the conservation of fuel and power of new or existing dwelling (Part L1A and Part L1B, respectively), but also for buildings other than dwellings (new or existing – Part L2A/Part L2B) (HM Government, n.d.). The Approved Document (AD) Part L gives practical guidance about how to meet the requirements and comply with Building Regulations. Among other criteria, Part L1A specifies that the CO_2 emissions and the fabric energy efficiency of a new dwelling should be below the Target Emission Rate (TER) and the Target Fabric Energy Efficiency (TFEE), both of which are calculated using the Standard Assessment Procedure (SAP) for energy rating of dwellings (BRE, 2012). SAP is used to calculate the energy performance of dwellings, taking into account a range of factors that contribute to energy efficiency, such as the materiality of the fabric, the air leakage and ventilation regime of the buildings, the efficiency of the heating systems, among others. In terms of the thermal mass, SAP defines the thermal mass parameter (TMP), which is required in both heating and cooling calculations. The TMP is calculated as the sum of the product of area multiplied with the heat capacity for all construction elements in a building zone, divided by the floor area of the zone. To calculate the heat capacity of a building element, starting from the inside surface, one should stop when one of the following conditions occurs: a) half the way through the element, b) when an insulation layer is reached, c) when the total thickness of 100mm is reached (BRE, 2012). SAP is compliant with the Energy Performance of Buildings Directive (EPBD) (European Parliament and Council, 2010) and it is consistent with the standards BS EN ISO 13790 (2008).

BS EN ISO 13790 (2008) provides the means to assess the contribution of building products and services to energy conservation and to the overall energy consumption of buildings. These standards were developed to support the requirements of the EPBD on the energy performance of buildings, by calculating monthly and annual energy use for space heating and cooling. In ISO 13790 the internal heat capacity (in other words the thermal mass) of the building is calculated by summing the heat capacities of all building elements in direct thermal contact with the internal air of the zone. The thermal mass of building elements is calculated in accordance with BS EN ISO 13786 (2017) for a maximum effective thickness of 100mm starting from the internal surface.

BS EN ISO 13786 (2017) is focused on the thermal performance of building components and provides guidance on the calculation of their dynamic characteristics. There are two methods described within these standards for the calculation of the thermal mass of a building component: a) the simplified method, which is used as a rough estimate of the internal thermal inertia of a zone and b) the detailed method, which is used to calculate the heat capacity of building components considering their thermal admittance and the decrement factor.

The thermal admittance method for thermal mass calculation is also described in CIBSE Guide A: Environmental Design (CIBSE, 2015). CIBSE Guide A is a technical reference source for practitioners and designers of low energy buildings. Within Guide A, the thermal mass of a building element is calculated based on its material properties, when subject to sinusoidal temperature variations.

2.1.3 UNDERSTANDING MECHANISMS OF THERMAL MASS IN BUILDINGS

The effects of thermal mass in building performance have been studied since the 1980's, when the first energy analysis methods were developed (Givoni, 1979; Johannesson, 1981). There is a significant number of studies investigating the potential of thermal mass to save energy and act as a passive design strategy (e.g. Balaras, 1996; Kontoleon & Bikas, 2007; Kalema et al., 2008; Aste et al., 2009; Zhu et al., 2009; Kendrick et al., 2012; Csáky & Kalmár, 2015; Navarro et al., 2016; Kumar et al., 2017; Mousa et al., 2017).

Table 2.1 summarises the key findings reported in literature on the performance of thermal mass in buildings.

Table 2.1 *Understanding the performance of thermal mass in buildings: synthesis of previous research.*

Authors	Year	Description	Key Findings
Kontoleon and Bikas	2007	The authors studied the impact of solar absorptivity for representative wall configurations and different insulation locations.	The solar absorptivity of the external wall surface has a profound effect on the time lag, the decrement factor and the internal temperature variations. Increasing solar absorptivity, decreases the time lag, resulting in a shorter time span between external and internal peak temperature. However, it also decreases the decrement factor resulting in a more stable internal environment (with regards to internal temperature swings).
Kalema et al.	2008	The authors studied the same case study building for different frame materials varying from extra lightweight to heavyweight and analysed the effect of thermal mass on	Energy savings of 4-15% were found, due to increased thermal mass.

		space heating and cooling in Nordic climate.	
Aste et al.	2009	The authors investigated the parameters that affect the role of thermal mass in terms of energy savings by comparing several external wall systems with the same U-value but different dynamic characteristics (dynamic thermal transmittance and admittance)	The difference between heating demand for a low thermal mass wall compared to a high thermal mass wall can be up to 10% and the energy savings in cooling demand can be as high as 20% in a high thermal mass wall.
Zhu et al.	2009	The research compared two identical buildings constructed with timber and concrete frames in the context of a hot climate.	The wood frame building showed increased heating demand but slightly reduced cooling loads in comparison to the concrete frame one.
Casky and Kalmar	2015	The authors conducted a lab experiment to investigate the influence of different glazing orientations along with the effect of thermal mass and air change rate on indoor air temperatures.	The energy required for cooling can be significantly reduced if the thermal mass and the air changes per hour (ACH) are properly chosen according to the different glazing orientations.
Kumar et al.	2017	The authors developed mathematical correlations based on monitoring data of high thermal mass buildings located in India to predict indoor air temperatures.	High thermal mass constructions are effective during peak summer or winter seasons and are able to reduce space heating and cooling energy consumption in naturally ventilated buildings.
Mousa et al.	2017	The authors investigated the impact of thermal mass on indoor air temperatures and reduction of cooling loads in summer. The research used monitoring data from a house located in Cairo, Egypt to calibrate a simulation model created in TRNSYS. Subsequently, a comparative analysis was performed between existing building model (as built basecase – traditional stone building) and a new one with alternative wall construction (hollow brick).	The results indicated a relative stability of the indoor air temperatures, where the maximum air temperature of the stone building case was reduced up to 5.5ºC in comparison to the maximum ambient temperature, whereas the brick wall building showed a gradual heat built up, requiring increased cooling demand.
Reilly and Kinnane	2017	The authors presented new parameters to measure the effect of thermal mass on the energy consumption of a building located in both hot and cold climates.	The thermal mass of the fabric can be beneficial for hot climates with large diurnal ambient temperature variations. However, for cold climates, thermal mass can be a drawback (due to the extended periods of preheating required) and insulation is better located inside the high thermal mass structural layer (rather than outside).

The general remark of previous research is that high thermal mass structures can offer substantial energy savings, particularly in terms of cooling demand. When combined with sufficient ventilation, the thermal mass can reduce the energy consumption used for space conditioning and is able to maintain stable and comfortable internal conditions.

All the above studies considered in Table 2.1 were mainly focused on the effects of thermal mass during the operation stage of a building's lifecycle. In addition, there are also comparative studies focusing on the thermal and energy performance over the whole life cycle of a building (Hacker et al., 2008; Monahan & Powell, 2011; Dodoo et al., 2012) including construction and operation. However, these are outside the scope of this study because the primary focus of this EngD was to gain a deeper understanding on the transient thermal behaviour of high thermal mass constructions.

2.1.4 THERMAL MASS AND INSULATION

The thermal response of a heavyweight building construction under dynamic conditions is significantly affected by the distribution of thermal mass and insulation layers. Although the overall thermal transmittance (U-value) of the structure may not be affected by the wall configuration, the arrangement of the material layers and the location of the insulation in respect to the thermal mass influences the dynamic behavior of the wall (Al-Sanea & Zedan, 2011). It is therefore important to study the effects of insulation and mass both independently, and also in conjunction. Several researchers have studied the impact of location and thickness of insulation on the performance of high thermal mass buildings.

Zhang and Cheng (2018) performed a comparative assessment of external and internal thermal insulation for air-conditioned buildings using numerical analysis. The results showed that, in general, different building occupancies, HVAC operation modes (continuous or intermittent use) and indoor heat gains can lead to different suitable thermal insulation configurations. If the building is occupied during the day, external insulation provides better performance. In contrary, if the building is occupied during the night, internal insulation is preferable if the HVAC system runs in continuous mode. When the HVAC runs intermittently, the suitable insulation position depends on the indoor heat gains.

Al-Sanea and Zedan (2011) investigated the thermal characteristics of insulated walls with the same thermal mass, the same thermal transmittance (U-value) and varying thickness and distribution of insulation layers for a hot climate. The best performance among the different configurations for the given climate (in terms of transmission loads, time lag and decrement factor) was achieved by three layers of insulation (each having the same thickness) placed outside, in the middle and on the inside surface of the wall. The worst performance was found on a wall that had a single insulation layer placed on the internal surface of the wall. Asan (2000) investigated the impact of insulation position and thickness on the performance of thermal mass from a maximum time lag and minimum decrement factor point of view. Six wall configurations and two options for thermal mass and insulation materials were analysed. The results showed that placing half of the insulation on the inner surface of the wall and the other half on the outer surface resulted in the smallest decrement factor. Maximum time lag was achieved by placing two layers of insulation at a certain distance apart inside the wall (placed in equal distance between the mid-centre plane of the wall and the inner/outer surface of the wall). Furthermore, the authors concluded that a practical configuration, easy to achieve during construction and very close to optimum performance (in terms of time lag and decrement factor) was to place half of the insulation in the mid-centre plane of the wall and the other half in the outer surface of the wall.

Ozel and Pihtili (2007) investigated the optimum location and distribution of insulation in a high thermal mass wall for twelve configurations, where the total masonry and insulation thicknesses were kept constant. The results were analysed in terms of time lag and decrement factor considerations both for summer and winter periods and showed that the best performance was achieved in the case of three insulation layers placed on the outermost, middle and innermost surface of the wall.

So, for specific climates, the thermal mass of the fabric has been shown to reduce energy consumption for space conditioning. In a temperate climate, such as the UK, where the night temperature is typically around 10^{o}C below the peak daytime temperature (Met Office, n.d), the thermal mass in conjunction with natural night ventilation can effectively reduce the amount of energy required for space cooling. Moreover, during winter time, the ability of thermal mass to capture internal and solar heat gains can help keep the building warm, reducing ultimately the need for supplementary heating.

The quantification of thermal mass in building construction elements is usually associated with the thermal admittance of the inner most layers of the element (Rodrigues, 2010). Despite evidence that the best performance in terms of decrement factor and decrement delay is achieved when dividing the insulation layer into two or three layers distributed across the section of the wall, wall constructions that have an insulating material at their interior surface are usually considered as thermally lightweight structures. One example is the ICF wall assembly, which is described in the next section.

2.2 INSULATING CONCRETE FORMWORK (ICF)

This EngD research is focused on Insulating Concrete Formwork (ICF), so this construction method is described below, and important observations are made about gaps in knowledge regarding its thermal performance.

The ICF wall component is classed among site-based Modern Methods of Construction (MMC) and consists of modular prefabricated Expanded Polystyrene Insulation (EPS) hollow blocks and cast in situ concrete. The blocks are assembled on site and the concrete is poured into the void (Fig.2.2). Once the concrete has cured, the insulating formwork stays in place permanently. As discussed in the previous section (Section 2.1.1), due to the internal layer of insulation (i.e. reduced wall admittance), ICF is often considered a thermally lightweight structure.

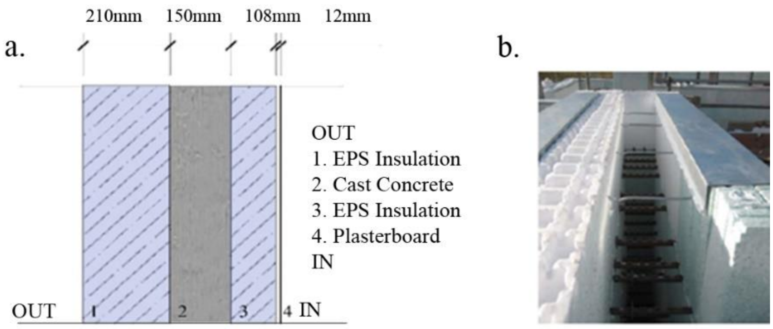


Figure 2.2 *(a) Schematic representation of ICF cross-section, (b) photograph of prefabricated EPS hollow blocks of ICF before the concrete is poured*

2.2.1 KEY LITERATURE ON THE THERMAL PERFORMANCE OF ICF

A number of field and computational studies aimed to investigate the benefits of the thermal mass located at the core of ICF. These were mainly conducted in the USA and Canada. A review of their methods, limitations and main findings is presented in Section 1.1 of the paper in Appendix D. Their key findings are also summarised in Table 2.2 below.

Table 2.2 *Understanding the performance of ICF in buildings: synthesis of previous research*.

Author	Year	Description	Key Findings
NAHB Research Centre	1999	The authors conducted a field study in Maryland, USA to evaluate the energy consumption of three side-by-side houses, two ICF houses and one built with timber-frame walls. The houses were identical (apart from the external wall construction), unoccupied and built for the purposes of the study.	The two ICF houses performed much better than the timber-frame building, requiring on average 20% less energy for space conditioning. However, this difference was mostly attributed to the different thermal resistance (R-value) of the walls and the contribution of the ICF thermal mass was negligible.
Gajda and VanGeem	2000	The authors conducted a computational analysis using DOE2.6 simulation program to compare the energy use in a typical house for five locations across the USA, and for three wall configurations; a conventional timber-frame wall, an ICF wall and a *non-mass* ICF wall (according to the minimum energy code requirements).	In all locations the ICF wall showed higher energy savings compared to the other two walls. ICF savings reached up to 9% compared to timber-frame.
Kosny et al.	2001a	The authors performed a comparative computational analysis (using DOE-2) on the energy performance of lightweight and massive walls (including ICF) and calculated the potential energy savings for ten locations in USA climates.	Among the high thermal mass configurations, the thermal performance of ICF was in between the thermal performance of the externally insulated and the internally insulated concrete wall and performed worse than a sandwich panel (where the insulation would be located at the middle of the wall). In the comparison of ICF to conventional timber-frame wall, the results showed that

			ICF can provide between 6% and 8% energy savings.
Kosny et al.	2001b	The authors performed a field investigation of two side-by-side houses in Tennessee, one having ICF walls and one having timber-framed walls. The houses were unoccupied and built for the purpose of the experiment. Subsequently, computer simulation was used to evaluate the performance of the houses in a number of different US climates.	The results of the field study showed that the ICF building used 7.5% less energy than the timber-framed building. The simulation models predicted that the ICF building would require between 5.5% and 8.5% less energy than the timber-framed building, depending on the climate.
Hill and Monsour	2007	The study was a monitoring project to characterise the thermal performance of ICF and its airtightness in a residential building in Ontario, Canada. By placing temperature sensors and taking heat flux measurements, the aim was to record the transient temperature behaviour of the ICF wall. Subsequently, a computational comparative analysis was performed (using eQUEST) and the as-built scenario was compared to a theoretical model without thermal mass (resembling a timber-frame structure)	There were only insignificant improvements in terms of energy consumption between the as-built ICF scenario and the theoretical *non-mass* ICF.
Rajagopalan et al.	2009	The study was a comparative life cycle assessment (LCA) of wall sections comprised of ICF and timber-frame for the whole life cycle phases of a buildings, from raw materials to manufacturing, construction, use and end of life phases.	ICF has a higher embodied carbon than traditional timber-frame wall during manufacturing phase. Nonetheless, the ICF showed reduced energy consumption during the use phase, meaning that the overall environmental footprint of the ICF building could be outweighed by benefits achieved in terms of energy savings during operation.
Armstrong et al.	2011	The authors conducted a field monitoring study on the dynamic heat transmission through an ICF wall in Ottawa, Canada.	During transient conditions, the concrete core of ICF played a significant role in tempering heat losses to the exterior. The thermal mass of the concrete has been shown to reduce the transmission losses through the assembly during cold weather. The ICF walls have consequently the potential to reduce the peak heating demand.
Saber et al.	2011	The research investigated (using numerical analysis) the contribution of ICF thermal mass due to the concrete layer compared to a theoretical “ICF” wall without concrete and equal R-value for the cold climate of Ottawa, Canada.	The thermal mass of the concrete core can give up to 6% savings in heating loads, compared to the same wall without the concrete layer.
Hart et al.	2014	The authors used simulation (EnergyPlus) to analyse the variation in energy end-use for 607 wall assembly combinations across eighteen climate zones in the USA. The study compared externally and internally insulated concrete walls, ICF and timber-frame walls.	The energy use of ICF falls between the energy consumptions of externally and internally insulated concrete walls, and always performs better than a timber-frame wall (with equal levels of insulation).

The general conclusion of all the above studies is that ICF usually consumes less energy compared to a lightweight, timber-framed building. Moreover, the energy consumption of ICF falls in between that of externally and internally insulated heavyweight structures. However, the various studies summarised above draw contradictory conclusions with regards to the contribution of ICF thermal mass in energy savings, showing that there is still a gap in knowledge, which requires further investigation.

Alongside those studies considered in Table 2.2, there is also a limited number of studies that analysed the accuracy of ICF simulation using BPS (Kośny & Kossecka, 2002; Mantesi et al., 2018). The findings of both projects suggest that there is a greater degree of modelling uncertainty associated with ICF simulation compared to simple low thermal mass wall assemblies. Further details on the methods and key findings of these studies can be found in Section 1.1 of Appendix D.

Among the previous studies conducted on the thermal performance of ICF, some conclude that the concrete core of ICF played a significant role in energy savings (Gajda & VanGeem, 2000; Kosny et al., 2001a; Armstrong et al., 2011; Saber et al., 2011; Hart et al., 2014), whereas other studies draw the opposite conclusion, i.e. that the contribution of ICF thermal mass is insignificant in reducing building energy consumption (NAHB, 1999; Hill & Monsour, 2007). While there is a number of different research methods employed, these were mostly either field studies, measuring the performance of test buildings (NAHB, 1999; Kosny et al., 2001b), or simulation studies without a means to evaluate the accuracy of simulation predictions (Gajda & VanGeem, 2000; Kosny et al., 2001a; Hart et al., 2014). Few studies combine monitoring and simulation results, yet these mostly included information only on surface temperatures and heat flow rates and were performed for the cold climate of Canada (Armstrong et al., 2011; Saber et al., 2011). None of these studies considered the internal thermal conditions and the energy consumption of an existing, occupied, ICF building.

The aforementioned shortcomings of all existing studies on the thermal performance of ICF, were used to inform the focus and methods employed in the present EngD research. As so, this EngD was the first whole building monitoring study which combined theoretical computational analysis with empirical data and advanced calibrated simulation to evaluate the internal thermal conditions and the energy consumption of an actual occupied ICF building located in a temperate climate (such as the UK climate). Particular focus was given on the thermal storage capacity of ICF concrete core with the aim to answer the question which still remains unanswered whether an ICF building should be characterised as a thermally heavyweight or lightweight structure. Furthermore, the combined analysis of monitoring and simulation results allowed the accuracy of simulation predictions to be empirically evaluated and provided original insights into the modelling uncertainties that lead to the performance gap (difference between actual and predicted performance) of ICF.

2.3 BUILDING ENERGY QUANTIFICATION METHODS

The final section of this chapter considers the different methods used to quantify the energy consumption of a building and particularly the use of computer-aided simulation for the design and delivery of energy efficient building. All energy quantification methods fall under three main categories: calculation-based methods (also known as building simulation), measurement-based methods (also known as building monitoring) and hybrid methods (a combination of both) (Wang et al., 2012). Calculation-based methods can be classified as dynamic methods and steady-state methods. Dynamic methods are able to capture and predict the dynamic thermal performance of the building, in terms of transient heat flow in and out of the building as a function of time (Kossecka, 1998), caused by changes in the boundary conditions (Clarke, 2001). In the steady-state methods, the dynamic effects are ignored, there is a constant temperature difference on both sides of the building element over an extended period of time

(Threlkeld, 1970). In steady state heat transfer the heat flux through the building wall approaches a constant value and has an almost linear profile (Rodriques, 2009). There are two approaches to steady-state models for energy calculation (ASHRAE, 2009; Wang et al., 2012):

- Forward (classical) approach
- Data-driven (inverse) approach

In the former, all the equations needed to describe the physical behaviour of a system, along with their inputs are known. The aim is to predict the output (Fumo, 2014). In the latter, all the input and output variables are known (measured) and used to define a mathematical description of the system.

When trying to predict the energy consumption and the thermal performance of new buildings, calculation-based energy quantification methods is the only option. For existing buildings however, measurement-based energy quantification methods are also available. Wang et al. (2012) divide the measurement-based methods into two broad categories: monitoring-based methods and bill-based methods. Bill-based is a quantification method using energy bills to collect information on the energy performance assessment of a building. Although, access to energy bills can be easy and cost-effective, this type of data is usually grouped according to end-uses and disaggregation of results into energy use of main systems and equipment is essential. Monitoring-based building measurement includes more sophisticated metering systems or platforms (such as Building Management Systems – BMS) to provide more accurate and detailed energy use information for building energy consumption assessment.

The hybrid quantification methods combine calculation analysis with building measurements to reduce calculation discrepancies or to identify model parameters (Wang et al., 2012). There are two main types of hybrid quantification methods: calibrated simulation and dynamic inverse modelling. Dynamic inverse modelling involves in-situ measurements for the identification of key performance metrics such as heat loss coefficients and effective capacity of buildings

(Jimenez et al., 2008). This type of hybrid energy quantification is outside the scope of this project. Calibrated simulation however, forms part of the methodology adopted in this EngD and it is further analysed in Section 2.3.5.

2.3.1 BUILDING PERFORMANCE SIMULATION (BPS)

Building Performance Simulation (BPS) was first introduced in the 1960s (Zhu et al., 2012). Initially, BPS focused on loads calculation and energy analysis. Eventually, BPS tools were developed to integrate all aspects of energy use, thermal and visual comfort, simultaneously employing a variety of sub-systems and components as well as Graphical User Interface (GUI) to facilitate their use by a wider group of people, such as researchers and practitioners (Fumo, 2014; Clarke & Hensen, 2015). Hence, BPS is currently used both in academia and in industry (Wang & Zhai, 2016). However, there are several limitations and considerations associated with the accuracy of building modelling and the reliability of simulation predictions. These are thoroughly reviewed in the following section with the purpose of critically discussing the capabilities and limitations of current BPS tools, aiming to ultimately evaluate the modelling uncertainties associated to the simulation of ICF in buildings (Objective No1).

2.3.2 BUILDING MODELLING, SIMULATION AND UNCERTAINTY

It is common to see the words “simulation” and “modelling” used interchangeably. However, they are not synonyms. Becker and Parker (2009) defined simulation as the process that enacts and implements a model. On the other hand, modelling is the representation of a system that contains objects that interact with each other. A model is often mathematical and describes the system that is to be simulated at a certain level of abstraction. Within a BPS program descriptions of the construction, occupancy patterns and HVAC systems are given and a mathematical model is constructed to represent the possible energy flow-path and their interactions (Clarke, 2001; Wang & Zhai, 2016). Many assumptions, approximations and compromises are inevitably made on the mathematical equations describing the physical laws within the model (Irving, 1988). Consequently, an exact replication of reality should not be expected.

A significant number of previous studies analysed the various sources of uncertainty in BPS results and these are thoroughly discussed in Section 1.3 of the paper in Appendix B.

A broader classification of the various sources of uncertainty is given by Der Kiurenghian and Diflevsen (Hopfe & Hensen, 2011; Nikolaidou et al., 2015), who divided uncertainties into two categories, epistemic and aleatory. The epistemic conception of uncertainty involves missing knowledge concerning a fact. The aleatory uncertainty in contrast, involves unknown outcomes that can differ each time an experiment is run under similar conditions, due to the variability and randomness of an event (Brun et al., 2011). Uncertainties characterised as epistemic could be reduced or even resolved by the user with the help of BPS. Aleatory uncertainties are not possible to be reduced by the user solely.

Among others, the reliability of simulation outcomes depends on the accuracy and precision of input data, the simulation models and the skills of the energy modeller (Irving, 1982; Guyon, 1997; Burman et al., 2012; Menezes et al., 2012; Prada et al., 2014; Berkeley et al., 2014; Mantesi et al., 2015).

Sources of uncertainty can be classified as follows (De Wit & Augenbroe, 2002):

- ***Specification uncertainties***, associated to incomplete or inaccurate specification of building input parameters (i.e. geometry, material properties etc.)
- ***Modelling uncertainties***, defined as the simplifications and assumptions of complex physical processes (i.e. zoning, scheduling, algorithms etc.)
- ***Numerical uncertainties***, involving all the errors that are introduced in the discretisation and the simulation model.

Scenario uncertainties, which are in essence all the external conditions imposed on the building (i.e. weather conditions, occupants' behaviour).

These terms are important to this research and feature heavily in Sections 4.2 and 4.5 and in the papers included in Appendices A, B, C and D.

Another term which is frequently used in this EngD is the ***modelling gap***. The modelling gap is used to address the impact of default settings and the implications of the various calculation algorithms on the results divergence when simulating a single building using different BPS tools (Mantesi et al., 2018). Based on the above, two further sources of uncertainty that could potentially lead to inaccurate simulation predictions are:

User-introduced uncertainties, which are all the intentional and unintentional decisions that the BPS tools user can make during the specification of a building model and which can lead to unreliable and erroneous simulation predictions.

Uncertainties related to default settings/ input values of BPS tools, which are the uncertainties that are introduced to the simulation model due to the predefined input values and algorithms selection found in BPS tools.

2.3.3 Uncertainty and Sensitivity Analyses in Building Simulation

As described in the previous section, both uncertainty and sensitivity are associated with BPS methods and tools. The purpose of Uncertainty Analysis (UA) is to investigate uncertainties in the output of a simulation model when the input parameters are also uncertain. Sensitivity Analysis (SA), on the other hand, aims to identify the most influential input parameters that have the most significant impact on the simulation predictions (Lomas & Eppel, 1992; MacDonald, 2002; Hopfe, 2009).

Hopfe (2009) notes that there are also other benefits attributed to the use of UA/SA in BPS. It enables the simplification of the model by identifying the most significant parameters affecting the simulation output. It helps evaluate the robustness of the model. It can be used as a means of quality assurance by highlighting unexpected sensitivity that could lead to errors in the specification of a model. Finally, it can be used to perform "what-if-analysis"; therefore, it can be considered as a decision-support tool.

Almost all input parameters entered into a simulation model to describe the system to be modelled are subject to uncertainty (MacDonald, 2002). Moreover, there are also uncertainties in the mathematical models and the boundary conditions that are employed within a given simulation program (MacDonald, 2002; Sun, 2014).

MacDonald (2002) describes two approaches to uncertainty quantification within BPS:

- External Methods[4]: In this case, arithmetic functions and the mathematics of the simulation remain unaffected. Changes are only made in the input parameters used to describe the model, and the initial conditions and the solution methods employed within the tool.
- Internal Methods: The essence here is to represent the uncertainty information by altering the underlying arithmetic functions to account for ranges in the input parameters, rather than individual numbers.

To continue, external methods tend to fall into two broad categories (MacDonald, 2002; Hopfe, 2009):

- Local methods, which are used to describe the variations in the model's output with respect to changes in individual parameters.

[4] This EngD project is focussed only on this category, i.e. external methods, because it aims to investigate the uncertainty in the representation of ICF using common BPS tools, when the input parameters, regarding its thermal mass, are also uncertain.

- Global methods, which are used to quantify the overall/ total sensitivity of a model when all uncertain parameters are varied simultaneously.

Among the external local methods for uncertainty quantification, differential sensitivity analysis (DSA) is considered the best known (Lomas & Eppel, 1992; Hamby, 1994; MacDonald, 2002). DSA calculates the effect of uncertainties on each parameter independently and is relatively quick and easy to implement. However, to account for the total uncertainty in the model deriving from the combined effect of multiple uncertain parameters, the behaviour of these uncertainties needs to be assumed linear and superposition of their effect is necessary (Hopfe, 2009). MacDonald (2002) described the factorial method as a local method invented to overcome the weaknesses of DSA. In the factorial method, all uncertain input parameters are altered between simulations so that at least one simulation is undertaken for all possible combinations of the parameters' values. The main drawback is the resulting number of simulations, which grows factorially, making it only suitable for small number of uncertain parameters.

Morris developed a screening method derived from DSA and factorial methods (Morris, 1991; Saltelli et al., 2000; Campolongo et al., 2007). This varies one factor at a time (OAT) over the whole range of uncertainty distribution. It allows for the selection of influential input parameters by evaluating the uncertainty of the model output due to different input parameter sets (Hopfe, 2009). The main drawback is that it is only appropriate for identification of critical parameters rather than the quantification of their effect on the output (MacDonald, 2002). Hence, it does not allow for uncertainty analysis (De Wit, 2001; Hopfe, 2009).

The most commonly used external global method is Monte Carlo Analysis (MCA) (MacDonald, 2002; Hopfe, 2009). MCA requires that the model inputs are described by a probability distribution. All parameters are varied at the same time, hence all possible interactions between the variables are fully accounted for. One disadvantage of this method is that only total uncertainties can be considered since the input factors are varied simultaneously. In other words, the model's sensitivity to individual parameters is not evaluated.

2.3.4 BPS RESULTS VALIDATION

In order to rely on BPS predictions with a degree of confidence, it is important to represent the actual performance of a building as accurately as possible (Coakley et al., 2014; Fumo, 2014). Validation is a common practice used to ensure that the results from simulation programs are reliable (Ryan & Sanquist, 2012; Fumo, 2014). A BPS model contains hundreds of input variables and parameters. Current state-of-the-art BPS tools have several limitations related to air flow, lighting, HVAC systems, and occupants, among others (Clarke & Hensen, 2015).

As a means of addressing this, Judkoff & Neymark (1995) described the validation methodology adopted by NREL preceding the BESTEST project, which incorporated three kinds of tests:

- ***Analytical verification***: the output from a program algorithm is compared to the results provided by analytical solutions under simple boundary conditions (Judkoff & Neymark, 1995). This is disadvantageous in validating the coupling of model components and limited in verifying overall predictions (Ryan & Sanquist, 2012).
- ***Comparative testing:*** it is used to compare a simulation program to itself or to other programs. This approach includes sensitivity testing and inter-model comparison (Judkoff & Neymark, 1995). Its main limitation lies on the assumption that the other models are accurate and validated (Ryan & Sanquist, 2012).
- ***Empirical validation:*** this allows calculated results from a program to be compared with monitored, experimental data from a real building, test cell or laboratory experiment (Judkoff & Neymark, 1995). It contains high levels of uncertainty in the experiment, it is considered expensive and time consuming (Ryan & Sanquist, 2012), yet it can test the combined effect of all the internal errors in a program (Lomas et al., 1997). It can

be conducted either in idealised conditions of a building operation (i.e. test cell, laboratory), where only the parameters associated to building structure and HVAC are analysed, or in realistic conditions (i.e. real building), where the impact of occupants is also included in the analysis (Ryan & Sanquist, 2012).

Among the three validation tests described above, the last two (i.e. comparative testing and empirical validation) have been used to validate the output of simulation predictions in this EngD.

2.3.5 BPS MODEL CALIBRATION

Model calibration is a process where the user/analyst has to *tune* some of the input parameters in the simulation program until the model output matches closely the measured data recorded from the actual building operation (Jankovic, 2012; Fumo, 2014; Silva & Ghisi, 2014). Its purpose is to reduce inconsistencies between actual and predicted building performance and to achieve more insightful and reliable BPS predictions (Monari & Strachan, 2014; Fumo, 2014). The calibration of BPS models involves thousands of input parameters, and there is a lack of explicit standards for calibration criteria; hence, it remains a problem that requires further research. (Coakley et al., 2014). In the early years of model calibration, a simple per cent difference calculation was performed between measured and simulated data. More recently, several standardised statistical indices (e.g. Mean Bias Error, Covariance of Root Mean Square Error) are used to assess calibration performance (Coakley et al., 2014).

BPS models are referred to as “calibrated” when they meet the criteria set by the International Performance Measurement and Verification Protocol[5] (IPMVP) (EVO, 2012) and the ASHRAE Guideline 14[6], (ASHRAE, 2014).

The most common calibration techniques can be broadly categorised into the following types (Reddy, 2006; Mustafaraj et al., 2014):

- Manual iterative calibration, in which an adjustment of input parameters is performed by the user on a trial-and-error basis until the model output matches the recorded data.
- Graphical methods, in which the calibration is based on graphical representations and comparative displays of the results.
- Automated calibration methods, in which the calibration is performed based on special tests and analytical procedures involving intrusive tests and measurements.

Table 2.3 summarises the various calibration techniques as specified in literature (Reddy, 2006; Mustafaraj et al., 2014; Coakley et al., 2014).

[5] According to the acceptance criteria, as stated in IPMVP, a model is referred as calibrated when the error between hourly monitoring and simulation results on energy consumption is CV-RMSE<20% and MBE<5% (EVO, 2012).

[6] According to the acceptance criteria, as stated in ASHRAE Guideline 14, a model is referred as calibrated when the error between hourly monitoring and simulation results on energy consumption is CV-RMSE<30% and MBE<10% (ASHRAE, 2014).

Table 2.3 *Current Approaches to BPS calibration (Adopted from Coakley et al., 2014)*

Manual Methods	Graphical Methods	Automated Methods
Characterisation techniques:	*Advanced graphical approaches:*	*Optimisation techniques:*
Building and site audits Short-term end-use monitoring High-resolution data Intrusive testing	3D comparative plots Graphical statistical indices Signature analysis Parameter reduction Data disaggregation	Objective function Penalty function Bayesian calibration
Procedural extensions:		*Alternative modelling techniques:*
Evidence-based development Sensitivity analysis Uncertainty quantification		Artificial Neural Network (ANN) Primary and secondary term analysis and renormalisation Meta-modelling Simplified energy analysis procedure System identification

2.3.6 SECTION SUMMARY

It becomes clear from this section that considerations regarding the input uncertainties and modelling assumptions are two areas that require attention in BPS to enhance the physical correctness of the model and quality of simulation results. In accordance with the observation that "e*ssentially, all models are wrong, but some are useful"* (Box & Draper, 1987), Clarke and Hensen (2015) argue that BPS should be used as a learning support tool, assisting the user in understanding the complex systems that are incorporated in a building model and providing feedback on performance implications of alternative designs and strategic decisions. Once a calibrated simulation is achieved, the BPS model is able to provide more reliable and insightful predictions and what-if analyses may be performed to evaluate the impact of decision making under different scenarios and operation conditions.

2.4 SUMMARY

There is growing evidence that the thermal mass of the building fabric can be used to adopt buildings to climate change and, for specific climates and occupancy patterns, it can also help reduce energy consumed for space conditioning. Thermal mass is the ability of a material to store thermal energy. From a qualitative point of view, the performance of thermal mass in buildings is relatively easy to understand; the fabric stores heat during times of surplus, disseminating the stored heat after a few hours during time of scarcity. Unfortunately, from a quantitative point of view, it is not entirely clear how to calculate and optimise the thermal mass of a building. In simplified calculation methods, the thermal mass of construction elements is usually associated with the heat capacity, thermal diffusivity and thermal admittance of the inner most surface layers. For conventional construction methods (such as brick and block), these simplified approaches have been proven adequate to quantify the thermal mass of building elements. In complex and innovative constructions, however (such as ICF), similar simplifications may be problematic and could potentially lead to misinterpretations. The internal layer of insulation in ICF reduces the thermal admittance of the wall. Hence, based on simplified calculations, this would translate to low thermal mass. Consequently, despite the high thermal capacity of its concrete core, ICF is often considered to be a thermally lightweight structure.

Previous studies on the thermal performance of ICF reached to contradictory conclusions regarding the energy savings potential of ICF. This chapter has investigated research methods, limitations and key findings and identified a significant gap in existing knowledge; previous studies were either theoretical computational analyses or measurements of test rigs built for purpose; none considered the internal thermal conditions and energy consumption of an existing occupied ICF building case study; and the few studies to combine computational and empirical analysis focused mostly on the transient heat transmission of the ICF wall assembly and were conducted for cold climates. Hence this EngD is the first to evaluate the suitability of ICF in a temperate climate (such as the UK climate).

There is also a need for accurate performance prediction when designing new buildings. This is challenging in particular when using advanced or new methods (such as ICF) that are not yet well-researched. Faced with a lack of empirical data, computer simulation can be used to provide quantitative data to support the decision-making process. However, it is widely accepted that there are several constraints and limitations associated with the use of BPS for design support. There is often a discrepancy between expected energy performance during design stage and real energy performance (after project completion). Moreover, there are often inconsistencies in the simulation results when modelling a single building but using different BPS tools. These are referred to as modelling uncertainties and can lead to a lack of confidence in building simulation. To improve the reliability of BPS predictions, it is important to validate the accuracy of simulation results and calibrate the model when new information becomes available. Only then can BPS be used with a degree of confidence to support decision making under various scenarios and alternative designs.

This chapter summarised the existing knowledge of the key subject areas relevant to this EngD project, highlighted limitations in the available evidence and identified key gaps in knowledge. And, as discussed in Section 1.4, despite previous research conducted on ICF, there is still a generally poor level of understanding about its actual thermal performance and of how to quantify the effects of its thermal mass. Moreover, there is a lack of evidence used to verify the accuracy of ICF simulation predictions. The identified research problem frames the basis for the following chapter, which describes the research methodology adopted in the project.

3 ADOPTED METHODOLOGY

The following chapter summarises the development and application of a suitable research methodology for addressing the research objectives outlined in Section 1.5. Moreover, the chapter describes the main research methods employed for data collection and analysis. Prior to analysing the adopted research design, several terms associated to *research* and *research methodology* are defined, and an overview of the research methods is provided. The detailed research methods adopted in each of the work packages (WP) conducted as part of this EngD can be found in Chapter 4 and also in the papers included in Appendices A-D.

3.1 METHODOLOGICAL CONSIDERATIONS

English dictionaries define research as the systematic investigation into a subject and the study of materials, sources etc. in order to establish facts and discover new information (Concise Oxford English Dictionary, 1995; Chambers 21st Century Dictionary, 1999; Cambridge Advanced Learner's Dictionary, 2006). The purpose of research is to expand knowledge by solving problems. Problems follow a simple dichotomous classification (Fellows & Liu, 2008); they are either *closed* - simple problems each having a single correct solution-, or *open* – more complex problems, where a solution is hard to find and might require novel ideas.

The *research methodology* involves all the principles and procedures that are applied in order to investigate a problem (Knight & Ruddock, 2008). It is common to see the terms *research methodology* and *research methods* used interchangeably. However, there is a clear and pronounced distinction between them. Ahmed et al. (2016, p.13) define research methods as instruments that are adopted in a study for data collection, whereas research methodology is "*the study of methods and deals with the philosophical assumptions underlying the research process"*. In other words, research methodology is the theory and philosophy that guides and shapes the researcher's ideas about which research methods to use while seeking solutions towards a research problem (Fellows & Liu, 2008; Creswell, 2009; Ahmed et al., 2016). There are two distinct philosophical bases for the adoption of a research methodology (Woods & Trexler, 2001; Creswell, 2009):

1. *Positivism* – Reflects a deterministic philosophy where the reality is fixed and the researcher can acquire objective knowledge and determine effects and outcomes by examining causes and quantifiable evidence.
2. *Interpretivism (phenomenology)* – The focus of research is based upon the *interpretation* of phenomena, events, occurrences, as one experiences them.

Based on the underlying research philosophy that depicts the adopted research methodology, there are three main approaches to research (Blumberg et al., 2005; Fellows & Liu, 2008; Creswell, 2009; Bryman & Bell, 2011; Naoum, 2013; Ahmed et al., 2016):

1. *Quantitative Approach* – these approaches are more "objective" in nature and tend to relate to positivism. The researchers seek to test hypotheses or answer research questions by collecting hard and reliable data. The objective is to verify or reject a theory, rather than develop it.
2. *Qualitative Approach* – these approaches are more "subjective" and more associated to interpretivism. Qualitative research aims to gain insights on people's perception of a phenomenon or "problem". The primary focus of the researchers is to capture the experience, beliefs, understanding, opinion etc. of participants.
3. *Mixed Methods* – these methods combine elements of qualitative and quantitative research approaches, concurrently or sequentially (Love et al., 2002; Johnson et al., 2007). They allow for a multi-dimensional view of the subject, aiming to draw from the strengths and minimise the weaknesses of both previous research approaches (i.e. quantitative and qualitative), but not to replace either of them.

The five common research methods used for data collection are (e.g. Kagioglou et al., 2000; Fellows & Liu, 2008; Yin, 2009; Bell, 2010; Robson, 2011):

1. *Action research* – The researcher actively participates in the process under study, aiming to identify, promote and evaluate problems and possible solutions.
2. *Ethnographic research* – The researcher becomes part of the group under investigation and observes participants' behaviour to gain insights into their pattern of behaviour.
3. *Surveys* – Surveys vary from highly-structured questionnaires to unstructured interviews. A sample of the population is surveyed, and the researcher's aim is to collect data, information and feedback about a specific "problem".
4. *Case studies* – These allow an empirical and in-depth investigation of a specific phenomenon within its real-life context. The selection of a case can be made on the basis of it being representative either of the specific research "problem" or of a spectrum of alternatives.
5. *Experiments* – These are typically carried out in laboratories. The researcher aims to maintain control over all variables that might affect the results in order to test relationships between dependent and independent variables. When the experiments are conducted outside of laboratories, the ability of the researcher to control the variables might be compromised and usually these studies are called *quasi-experiments*.

3.2 OVERVIEW OF RESEARCH DESIGN

Having introduced some of the main definitions and strategies associated to research methodology and research methods, the following section will summarise the research design adopted for this EngD research.

The research design reflects the decisions made by the researcher on philosophical assumptions, bringing together a research approach and particular research methods to meet the objectives of the study (Creswell, 2009).

In general, the aim of any EngD is to demonstrate innovation in the application of knowledge and provide solutions for one or more significant and challenging engineering problems with an industrial context (CICE, n.d.). In that respect, the project is required to adopt an applied approach to research. The term *applied research* is used to describe research which is directed to end-use and practical applications. In contrast, *pure research* is defined as theoretical, contributing to the development of academic theory, laws of nature etc. (Blumberg et al., 2005; Easterby-Smith, 2018). The expected research outcome of this EngD was to create a new evidence base for buildings that use ICF wall construction and the project aim (as stated in Section 1.5) was specifically, to:

> *Analyse the aspects that affect the thermal performance of ICF construction method, to develop an understanding about the thermal behaviour of ICF and its response to dynamic heat transfer, and to investigate how the latter is affected by the inherent thermal inertia of the material's concrete core.*

Moreover, particular emphasis was on the suitability of ICF for the UK housing industry. Consequently, the research can be classified as being simultaneously *pure* and *applied*; *pure* because it aims to contribute to the wider knowledge around the dynamic thermal performance of ICF and *applied* because it is directed to provide practical recommendations to the sponsoring company about the potential use of ICF in low-energy housing construction.

The research was approached based on positivism, aiming to collect quantifiable evidence that would help meet the research aim and address the research objectives (Section 1.5 of the thesis).

A quantitative research approach was adopted, following the perspective of *deductive reasoning* (Blumberg et al., 2005; Bryman & Bell, 2011). As such, the development of knowledge followed a "top-down" approach, focusing on testing theories from more general to more specific (Fellows & Liu, 2008); from building physics and thermal mass in general, to the performance and simulation of the ICF construction method. The aim and objectives of the research project emerged from studying the existing theories and literature. The collection of numerical and quantitative data was used to produce quantifiable results and reach scientifically-verifiable conclusions.

3.3 RESEARCH METHODS USED

The following section provides an overview of the research methods used in this EngD for the collection and/or analysis of data, which fall broadly in three categories; literature review (Section 3.3.1), computational analysis (Sections 3.3.2 and 3.3.4) and empirical evaluation (Section 3.3.3). Moreover, a research design map is included, summarising the research methods employed in this research, along with a table linking the overarching aim to the research objectives, the various work packages, the research methods employed in each study and the outputs of the EngD (published papers).

Wang et al. (2012) presented a number of approaches to quantify energy use in existing buildings[7]. The authors suggested that all methods fall under three main approaches; Calculation-based approach, measurement-based approach and hybrid approach, as illustrated in Fig.3.1.

[7] For further information of the energy quantification methods included in this Section and summarised in Fig.3.1 please refer to Section 2.3 of Chapter 2.

The research design of this EngD project employed a combination of methods from all three approaches for the energy quantification and thermal performance assessment of ICF construction method:

- Dynamic simulation
- Monitoring-based method
- Calibrated simulation

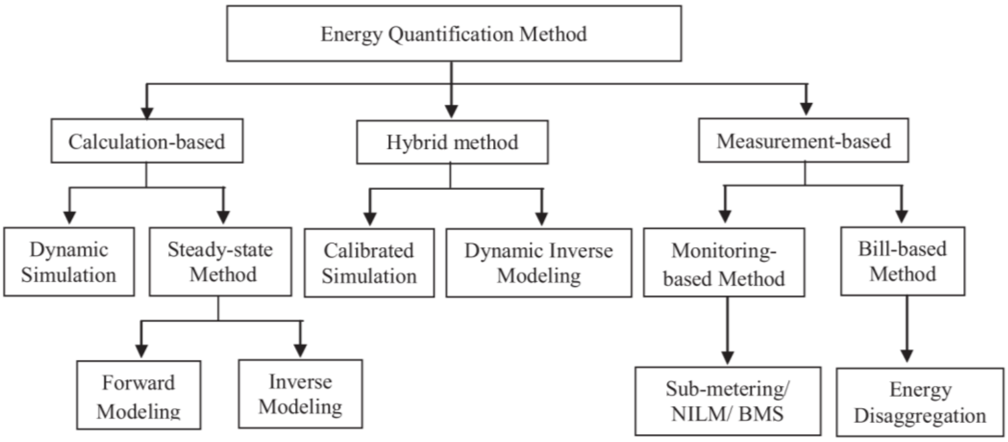


Figure 3.1 *Energy quantification methods for existing buildings* (Wang et al., 2012, p.878).

The research methods employed in this project, the sequence of procedures and their correlation is represented schematically in Figure 3.2, whereas Table 3.1 on the following pages links the overarching aim of the project with the research objectives as stated in Section 1.5, the work packages undertaken (Chapter 4 of thesis), the research methods adopted in each study and the papers that were produced.

The research design comprised three main stages:

1. **Theoretical computational analysis**, employing dynamic simulation, aiming to provide some initial insights into the accuracy of ICF simulation predictions. The aim of this stage was to investigate the modelling uncertainties associated to ICF simulation using a single-zone test building. In other words, using a simplified geometry that would

serve as a preliminary step prior to analysing the energy consumption of a multi-zone real ICF building (conducted in the following stage).

2. **Empirical evaluation of the ICF thermal performance**, using monitoring-based analysis. The aim of this stage was to assess the actual performance of a real occupied ICF building and to provide a robust dataset that could be used to empirically validate the accuracy of simulation results and to calibrate the simulation models for the third and final stage of the analysis.
3. **Advanced calibrated simulation**, using a combination of computational analysis with building monitoring. This stage used the dataset collected during the previous stage of the analysis in order to calibrate the simulation models against real measured data. The aim was to gain a better understanding of the transient thermal performance of the ICF wall and on how it compares to conventional heavyweight and lightweight structures.

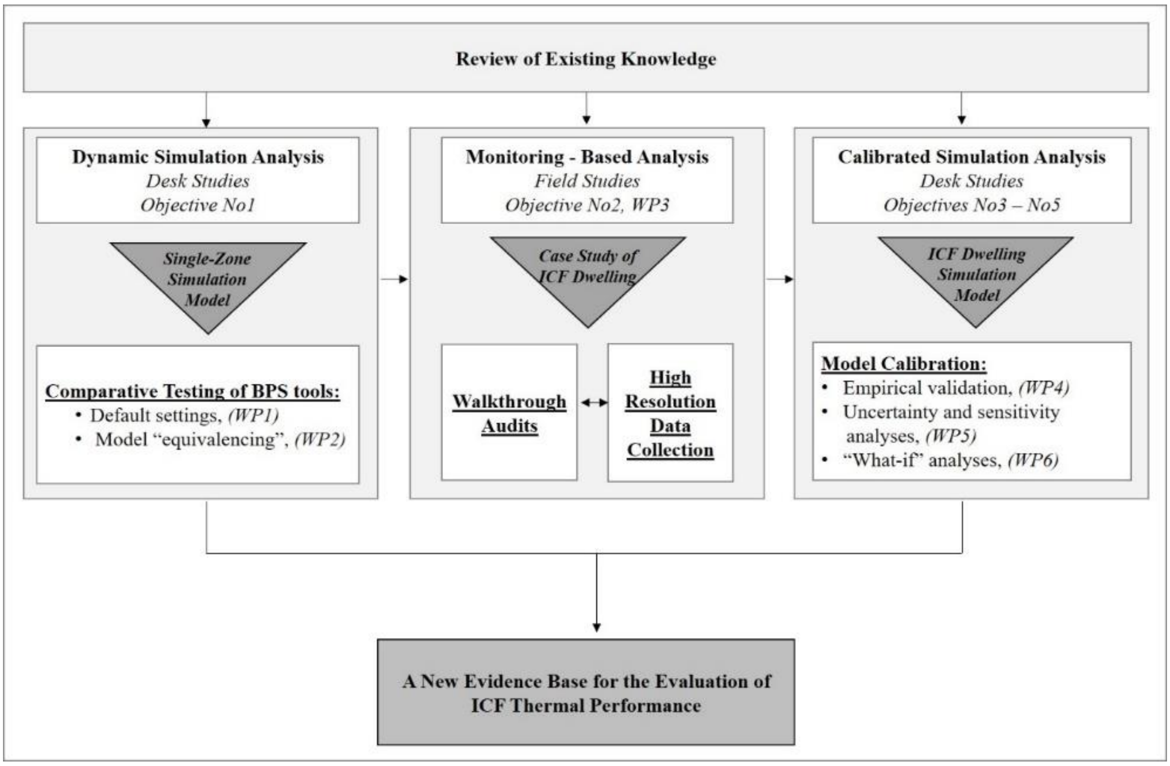


Figure 3.2 *Research design map summarising the methods employed in the research project*

Table 3.1 *Research aim and objectives, work undertaken, methods used and outputs.*

Research Aim			
To analyse the aspects that affect the thermal performance of ICF construction method, to develop an understanding about the thermal behaviour of ICF and its response to dynamic heat transfer, and to investigate how the latter is affected by the inherent thermal inertia of the material's concrete core.			
Work Packages	**Objectives**	**Research Methods**	**Output**
WP0 *Review of Existing Knowledge*	***Literature Review:*** To critically review existing knowledge around ICF, building physics, dynamic heat transfer, thermal mass and dynamic thermal modelling.	Literature Review	**EngD Short Project (Not included in thesis)**
WP1 *Comparative Analysis of ICF simulation results using different BPS tools.* **WP2** *Evaluating the modelling uncertainty in the simulation of ICF in whole BPS.*	***Objective No1:*** To test and evaluate common dynamic Building Performance Simulation (BPS) tools in predicting ICF thermal and energy performance, and to identify the key modelling uncertainties that are associated to ICF simulation.	Dynamic Simulation: Comparative Testing of BPS Tools	**Publication 1 – Conference Paper (Appendix A)** **Publication 2 – Journal Paper (Appendix B)** **Publication 5 – Conference Paper (Not included in thesis)** **Publication 6 – Conference Paper (Not included in thesis)**

<table>
<tr><th>Work Packages</th><th>Objectives</th><th>Research Methods</th><th colspan="2">Output</th></tr>
<tr><td>WP3
ICF building monitoring project: Assessing the thermal performance of a real ICF case study</td><td><u>Objective No2:</u>
To monitor and analyse the actual energy consumption and thermal performance of an ICF building located in the UK and to scrutinise ICF's potential for indoor temperature control.</td><td><u>Monitoring – Based Analysis:</u>
Case Study Analysis
Walkthrough Audits
High Resolution Data Collection</td><td rowspan="2">Publication 3 – Conference Paper (Appendix C)</td><td rowspan="4">Publication 4 – Journal Paper (Appendix D)</td></tr>
<tr><td>WP4
Empirical validation of ICF Simulation output.</td><td><u>Objective No3:</u>
To empirically validate, with the use of real monitoring data, the accuracy of BPS simulation results in calculating the thermal performance of ICF.</td><td><u>Calibrated Simulation:</u>
Model Calibration
Empirical Validation</td></tr>
<tr><td>WP5
Uncertainty and sensitivity analysis on the thermal performance of the ICF wall assembly.</td><td><u>Objective No4:</u>
To evaluate the level of uncertainty and the sensitivity of the model in the representation of ICF in BPS, when considering the physical uncertainties of the wall material properties.</td><td><u>Calibrated Simulation:</u>
Uncertainty Analysis
Sensitivity Analysis</td><td>Publication 7 – Conference Paper (Not included in thesis)</td></tr>
<tr><td>WP6
Investigating the Thermal Mass benefits of ICF Using Calibrated Simulation</td><td><u>Objective No5:</u>
To investigate the thermal storage capacity of ICF concrete core and determine whether ICF can be characterised as a thermally heavyweight or lightweight structure.</td><td><u>Calibrated Simulation:</u>
"What-if" Analysis</td><td></td></tr>
</table>

3.3.1 REVIEW OF LITERATURE

The literature review is an integral part of the research project. It involves reading and critically appraising existing knowledge and previous studies in the subject area. The literature review is both descriptive and analytical (Naoum, 2013). Descriptive because it describes previous work conducted by researchers, and analytical because it reflects on their contribution into the subject area, with a view of identifying similarities, contradictions and gaps in knowledge. Among others, the objective of the literature review is to expose gaps in existing knowledge and define appropriate research methods (Robson, 2011).

An extensive literature review was carried out throughout the EngD project. At the beginning of the project, a critical review of existing literature was used to set the foundations for the study and identify gaps in knowledge with respect to the subject area. Further reviews were conducted throughout the duration of the research to address the specific needs of individual work packages and to ensure that any new findings were considered as new publications became available.

Chapter 2 of the thesis provides an overview of the key outcomes of the literature review. Further accounts of key literature can also be found in each of the published papers included in Appendices A - D.

3.3.2 DYNAMIC SIMULATION

Dynamic simulation of buildings, also called Building Performance Simulation (BPS), is generally accepted as a powerful tool for analysing the thermal and energy performance in buildings (Waltz, 2000; Clarke, 2001; Davies, 2004).

The use of computer-aided design tools was firstly introduced into architectural and engineering practices in early 1960s. The energy crisis of 1970s resulted in the development of several (initially simplified) computer-based building energy performance prediction tools (Raslan, 2010). The area of building energy modelling has developed significantly over the last decades

(Clarke & Hensen, 2015). There are currently two main approaches to building energy modelling:

- Simplified modelling methods
- Complex dynamic simulation methods

The former category includes simplified approaches to building modelling that are either:

i. Steady-state calculation methods, using variables averaged over a longer period of time (monthly, seasonally or annually). These models involve certain assumptions to the underlying model of the building. Several energy flow-paths, usually dynamic in nature, are approximated or neglected completely. They are commonly used for fast and low-cost estimation of building performance, for benchmarking and comparing a building to a "stock average" building of the same type.

ii. Simplified dynamic methods are often used to demonstrate compliance with building regulations (as per CEN standards) (Kokogiannakis et al., 2008). The simplified dynamic models take into account the effect of transient parameters (such as weather) to achieve more accurate predictions of building performance (Kim & Kim, 2007).

The simplified modelling methods, also referred to as "calculation tools" (Raslan, 2010), do not aim to investigate all complex interactions between the building and the surrounding environment, in contrast to the other category of dynamic simulation tools. The tools that fall into the category of dynamic simulation methods account for all possible energy flow-paths and their interactions within a building (Clarke, 2001). They involve complex and iterative predictive analytical procedures and they typically use hourly or sub-hourly time steps (Raslan, 2010). The dynamic tools take fully into account the transient performance of the building and they are considered more realistic and more accurate in predicting the overall energy performance of design proposals. A thorough literature review on the benefits and challenges associated with the use of dynamic BPS can be found in Section 2.3 of this thesis. In the context of this project, only dynamic simulation tools have been used to quantify the energy consumption and the thermal performance of a simple ICF building model and to address the requirements of **Objective No1**.

3.3.2.1 Comparative Testing of BPS Tools

An inter-model comparative testing was employed as the key research method in the first stage of the research (i.e. computational analysis). This step was focused on reviewing and contrasting the main features and capabilities of a list of nine widely-used BPS tools and evaluating their ability to predict the thermal performance of ICF using whole BPS. The building model selected for this step of the analysis was a single-zone test building based on the one specified in the BESTEST methodology (Judkoff & Neymark, 1995).

As discussed in Section 2.3.4, comparative testing is a common validation method used to compare a simulation program to itself or to other programs (Judkoff & Neymark, 1995; Ryan & Sanquist, 2012). Its main limitations involve the lack of an absolute truth and the assumption that the other models are accurate and validated. Hence, prior to proceeding to any comparison, it was essential to verify that the models used for the analysis were "validated" and thus capable of delivering reliable results. International Energy Agency (IEA) Building Simulation Test (BESTEST) and diagnostic method (Judkoff & Neymark, 1995), also adopted in ASHRAE Standard 140 (ANSI/ASHRAE, 2014), was used for model validation. The BESTEST method consists of a number of building energy simulation test (BESTEST) suites and it is used for evaluating the modelling capabilities of whole building performance simulation tools and for diagnosing errors in their source code. The output data from a number of widely-used BPS tools (state-of-the-art) are provided as a basis for comparison and are used to define an "acceptable" range for the annual and peak heating/cooling results (Judkoff & Neymark, 1995). BESTEST case 600 (low thermal mass) and case 900 (high thermal mass) were used to validate all simulation models (from all nine BPS tools) and to ensure that there are no input errors that could lead to significant inaccuracies in the results. Then the construction details were changed in line with the specific study. To ensure consistency, all other input parameters remained identical to the BESTEST methodology. Moreover, all simulations were performed by the author to minimise the influence of user variability on the results (Guyon, 1997; Berkeley et al., 2014).

3.3.2.2 Default Models

The simulation results (for the same single-zone building) provided by the nine BPS tools were compared to each other, relying initially on the default settings and solution algorithms employed by the various tools. The divergence of the nine tools was investigated by looking at the annual heating and cooling energy consumption and the annual peak heating and cooling loads. This variability was analysed by means of percentage difference between minimum and maximum values (to show the range of variation), and by looking at the percentage difference of each individual tool from the median of all tools. This step provided some insight into the level of modelling uncertainty associated with the simulation of ICF in buildings. Further details can be found in the papers in Appendix A and B.

3.3.2.3 Model "Equivalencing"

To identify key parameters and modelling factors that contribute to modelling uncertainty when simulating an ICF building, two of the nine BPS tools (which showed relatively consistent results in the first instance of the analysis) were selected for further investigation (Tools E and I). Monthly and hourly predictions on heating and cooling energy consumption, system loads and surface temperatures were analysed and compared with the use of Normalised Root Mean Square Error (NRMSE). The NRMSE is a metric used to quantify the typical size error between sets of data relative to their mean value (Granderson & Price, 2013). For example, a 10%

NRMSE means 10% difference from the mean value. The NRMSE when normalised to the mean of the observed data is also called CV-RMSE. In the model "equivalencing" process the use of the NRMSE was selected to avoid any confusion with the CV-RMSE as defined in the ASHRAE 14 Guidelines for model calibration (ASHRAE, 2014). In the ASHRAE 14 Guidelines the denominator is the mean of the measured energy data. In the analysis reported here the denominator was the mean value of the simulation predictions provided by the two BPS tools. The equation of the NRMSE is given below.

$$NRMSE\ (\%) = \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_{i,i} - x_{i,e})^2}{n}}}{\bar{x}} * 100 \quad \textbf{(Eq.5)}$$

$$\bar{x_i} = \frac{x_{i,e} + x_{i,i}}{2} \quad \textbf{(Eq.6)}$$

$$\bar{x} = \frac{\sum_{i=1}^{n} \bar{x}_i}{n} \quad \textbf{(Eq.7)}$$

Where,

$x_{i,e}$ and $x_{i,i}$ are the predictions provided by tools E and I respectively at each time step

$\bar{x}_i$ is the mean value of $x_{i,e}$ and $x_{i,i}$ for each time step

$\bar{x}$ is the mean value of the predictions provided by both tools E and I

n is the size of the sample

The aim of this step was to reflect on the impact that the various solution algorithms and calculation methods had on the variability of results. To achieve this, a step-wise method of making the models equivalent for comparison was developed, aiming to minimise the differences between the two tools by changing to identical algorithms and simulation settings, where possible. Details of the model "equivalencing" method can be found in the paper in Appendix B.

3.3.3 MONITORING – BASED ANALYSIS

The second stage of the research was focused on the empirical evaluation of the thermal performance of ICF. Recorded monitoring data from an existing ICF building were gathered, examined and analysed in order to gain a deeper understanding of the specific construction method and the ways ICF affects the building's internal thermal conditions and energy consumption. This addressed the requirements of **Objective No2**.

3.3.3.1 ICF Building Case Study

The case study analysis was considered to be the most appropriate approach for the empirical evaluation of ICF thermal performance. As already discussed, case study research method allows for an empirical and in-depth investigation of a specific phenomenon within its real-life context (Yin, 2009). The case study approach is particularly beneficial when the boundaries between the phenomenon and its context are not clearly specified (Robson, 2011). Accordingly, in order to draw conclusions on the suitability of ICF method for the UK housing construction industry, the project investigated thoroughly (through thermal monitoring) the thermal performance of a real and occupied, ICF dwelling. Details of the ICF case study building can be found in Section 4.3 of the thesis, and in the paper in Appendix D.

3.3.3.2 Walkthrough Audits

Walkthrough surveys are often conducted prior to any energy audit for an existing building in order to gain a better understanding vis-à-vis its physical characteristics and building systems (Thumann & Younger, 2009; Coakley et al., 2014). During the preparation of the thermal monitoring project, two buildings were considered as potential case studies. Initial site visits were performed at both locations to evaluate their suitability for this research. Once concluded, a walk-through survey was conducted to visually inspect the building form and HVAC systems, to update the architectural drawings based on the post-construction details, to define the requirements for the thermal monitoring project and to specify the location for sensors etc.

3.3.3.3 High Resolution Data Collection (Thermal Monitoring)

The use of high-resolution data is among the most common manual methods for BPS model calibration. Monitoring instrumentation is placed in a building to provide hourly (or sub-hourly) averages of ambient and interior conditions and energy consumption of HVAC systems (Clarke et al., 1993; Norford et al., 1994; Haberl & Bou-Saada, 1998; Coakley et al., 2014).

In this context, a thermal monitoring project was conducted on the selected ICF building case study, called Twiga Lodge. The dwelling was a two storey, three-bedroom house of approximately 270m^2, located in the wider area of Guildford, in the rural settlement of Gomshall, at Surrey, UK. A number of monitoring sensors were installed in the building and high resolution (sub-hourly time step) data were collected for a period of 18 months, between April 2016 and February 2018, including information on the building's:

- Internal thermal conditions
- Energy consumption
- Dynamic fabric performance

The results of the thermal monitoring project were used to empirically evaluate the suitability of ICF for the UK housing construction market. Moreover, the measured data were used to calibrate simulation models and empirically validate the accuracy of simulation predictions. Finally, the collected data set provided further insights into modelling uncertainties associated to ICF simulation as addressed in previous stage. Further information about the case study building and the experimental setting of the monitoring project can be found in Section 4.3. Detailed information about the monitoring equipment and time-step resolutions can be found in Appendix F. The results of the thermal monitoring can be found in Section 4.3 and in the papers in Appendices C and D.

3.3.4 CALIBRATED SIMULATION

Reddy (2006, p.1) described calibrated simulation as:

> *"the process of using an existing building simulation computer program and "tuning" or calibrating the various inputs to the program so that observed energy use matches closely with that predicted by the simulation program."*

Once calibrated simulation is achieved, more reliable simulation predictions can be made (ASHRAE, 2009). Calibrated simulation is usually a very useful tool to explore hypothetical, alternative design and operational scenarios and measuring the savings of conservation retrofits to existing buildings (Wang et al., 2012; Aste et al., 2015). However, it is a labour-intensive and time-consuming process that requires a high level of user skill and knowledge in both simulation and practical building operation (ASHRAE, 2009).

In this research, information from the thermal monitoring project regarding on-site recorded weather data, occupancy patterns and the use of MVHR and gas heating systems was used to calibrate the simulation model created using EnergyPlus 8.6 (US Department of Energy, n.d.). EnergyPlus is an open-source, dynamic BPS tool, developed by the Department of Energy (DOE) in the USA. The calibration process was performed using the manual iterative technique (Reddy, 2006; Coakley et al., 2014; Fumo, 2014; Mustafaraj et al., 2014), in which the user of the BPS tool adjusts the input parameters on a trial-and-error basis until the model output matches the recorded data.

3.3.4.1 Empirical Validation of Simulation Results

Measured data from the thermal monitoring project (i.e. zone mean air temperature and heating energy consumption) were plotted against simulation predictions provided from the calibrated model. The aim was to empirically validate the accuracy of simulation predictions and to understand the sources of uncertainty responsible for any observed divergence. The empirical validation of BPS simulation is a common method used to verify the reliability of simulation predictions (Judkoff & Neymark, 1995; Ryan & Sanquist, 2012). Further details of the use of empirical data for model validation can be found in Section 2.3.4. The divergence between measured data and simulation predictions was quantified using the Mean Biased Error (MBE), the Root Mean Squared Error (RMSE) and the Coefficient of Variation of the Root Mean Squared Error (CV-RMSE) (ASHRAE, 2014; Coakley et al., 2014).

The MBE is a non-dimensional measure of the overall bias in the model, reporting the error between measured and simulated data (Coakley et al., 2014). In this study the MBE is used to indicate whether the model over- or under-predicts the actual performance of the building. However, in the MBE the positive bias compensates for negative bias. Hence, further measures of model error are also required.

The RMSE shows the variability of the data between measured and simulated values. Their difference is calculated and squared for each hour, to overcome the issue of the cancelling effect[8]. The squared errors are then added and divided by the number of points. A square root of the result is reported as the root mean squared error (RMSE). The RMSE is expressed in the same unit as the base value, allowing to directly correlate the statistical indicator to the actual analysed value (for example temperature is degrees ^{o}C).

The Coefficient of Variation of the Root Mean Squared Error (CV-RMSE) is another indicator used to quantify how well the model predicts the actual performance of the building (Granderson & Price, 2013), reported as a percentage. The CV-RMSE is calculated from the

[8] The cancelling effect is the condition in which positive and negative values nullify each other.

RMSE normalised by the mean of the measured data. It allows to correlate the errors in values that are typically reported in different units (for example kWh and kW).

$$MBE\ (\%) = \frac{\Sigma_{i=1}^{N}(m_i - s_i)}{\bar{m}} \quad \textbf{(Eq.8)}$$

$$RMSE = \sqrt{\frac{\Sigma_{i=1}^{N}(m_i - s_i)^2}{N}} \quad \textbf{(Eq.9)}$$

$$CV - RMSE\ (\%) = \frac{\sqrt{(\Sigma_{i=1}^{N}(m_i - s_i)^2/N}}{\bar{m}} \quad \textbf{(Eq.10)}$$

Where,

MBE is the mean biased error

$RMSE$ is the root mean squared error

$CV - RMSE$ is the coefficient of variation of the root mean squared error

m_i and s_i are the respective measured and simulated data points for each model instance time step

N is the number of data points

$\bar{m}$ is the average of the measured data points

This method was used to fulfil **Objective No 3**.

3.3.4.2 Uncertainty and Sensitivity Analyses

It is generally accepted that there is a high level of uncertainty and sensitivity associated with current BPS methods and tools, which can lead to a lack of confidence in building simulation (Irving, 1982; Macdonald and Strachan, 2001; Hopfe, 2009; Berkeley, Haves and Kolderup, 2014).

In this project probabilistic simulation was performed using Monte Carlo-based global uncertainty and sensitivity analysis (UA/SA) (see Section 2.4.2). The aim was to investigate the robustness of ICF construction method and to determine the sensitivity of ICF simulation predictions to uncertain input data regarding the material properties of the wall (also known as physical uncertainties). Physical uncertainties refer to the physical properties of the wall materials; thickness (d), thermal conductivity (λ), density (ρ), specific heat capacity (c). Latin Hypercube Sampling (LHS) method was employed as a sampling method to generate sampled variables desirable for the UA (Helton & Davis, 2003; Saltelli et al., 2004; Hopfe, 2009) using SimLab[9] 2.2.1 (SimLab, no date). The LHS is a probabilistic sampling procedure that incorporates features of both random and stratified sampling (Helton & Davis, 2003). A weight is associated with each sampled element for the estimation of integrals. It is easier to implement than stratified sampling, yet achieves a good coverage of the sample space of the selected elements (Saltelli et al., 2004). The use of LHS method was selected because it increases the sampling performance by increasing the sample uniformity in the hyperspace.

Morris's method was employed to generate the sampled variables for the SA (Campolongo et al., 2007). Two sampling files were created. In the first one, a normal distribution was assumed for all physical properties under investigation. Each input parameter was assigned a mean (μ) based on the actual construction details from the building case study and a standard deviation (σ) based on information from literature (MacDonald, 2002; Hopfe, 2009). In the second sampling file, a uniform distribution was assumed. For each input parameter the same mean (μ) value was assigned, as before, with a constant ±20% range of variability. A total of 2430 simulations were performed in JEPlus[10] (JEPlus, n.d.).

[9] SimLab is a free software designed by the EU Science Hub, used for Monte Carlo-based UA and SA. It is composed of three modules: a) Statistical pre-processor (to generate the sample for the UA/SA), b) Model execution module and c) Statistical pro-processor (to perform UA/SA) (SimLab, n.d.).

[10] JEPlus is an EnergyPlus simulation manager used to execute and control multiple simulation (JEPlus, n.d.).

The process was undertaken in three main steps:

1. Pre-processing
2. Simulation
3. Post-processing

The tools and methods used for each of these steps are shown in Figure 3.3.

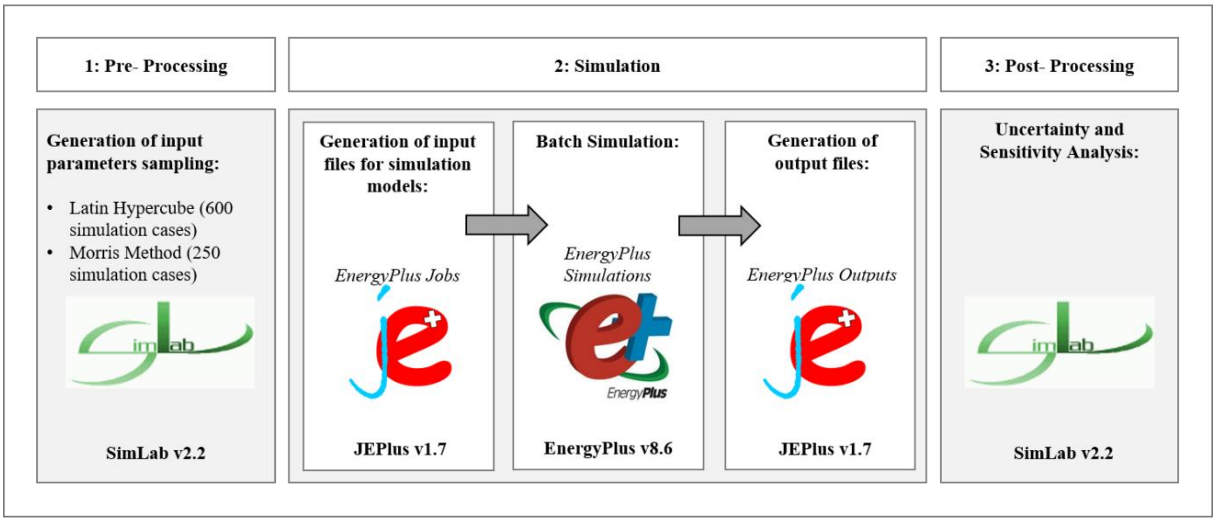


Figure 3.3 *Three steps within the uncertainty and sensitivity analyses.*

UA and SA were employed to fulfil **Objective No4**. Further information about the uncertainty and sensitivity analyses can be found in Section 4.5 and in the paper in Appendix D.

3.3.4.3 “What-if” Analyses

BPS is often associated with the term *virtual laboratory* used to conduct *virtual experiments* to assess the performance of hypothetical, alternative design and operation scenarios and to find quantifiable answers to “what-if” design questions (Attia et al., 2012; Loonen et al., 2014; Clarke & Hensen, 2015). In that respect, calibrated simulation was used to compare the thermal and energy performance of the ICF building case study with that of two hypothetical buildings. The two new building cases were identical to the ICF building (in terms of design, footprint, construction, occupancy, HVAC systems), yet they had different wall constructions representing a high thermal mass and a low thermal mass building. The ICF simulation model was used as a basecase. Two further simulation models were created to investigate *what* the energy consumption, internal thermal conditions and dynamic fabric performance of the building would be *if* the level of thermal mass in the walls was different. The "what-if" comparative method was used to fulfil **Objective No5** of the research.

3.4 SUMMARY

The main priority of the researcher while developing the research design is to maximise the chances of realising the research objectives (Fellows & Liu, 2008). Moreover, the decision on which type of research approach to follow and which research methods to adopt depends on the nature of the problem, the purpose of the study and the type and availability of information required to meet the research aim (Naoum, 2013). A brief review of the main types of methodologies available to the researcher was conducted. The selected research design was justified based on the nature of the research problem, and a number of different methods were presented based on their suitability to meet the research objectives. For this research, the research methodology was designed in such a way as to meet the requirements of the EngD programme and to arrive to conclusions that would contribute to wider knowledge but that would also be applicable within the sponsoring company and the industrial context. The following chapter describes the research undertaken in relation to the chosen methods and is presented as a series of Work Packages (WP).

4 RESEARCH UNDERTAKEN

This chapter presents the research undertaken to meet the aim and objectives of this thesis (Section 1.5). The research was conducted in line with the research methodology presented in Chapter 3 and refers to the specific research methods detailed in Section 3.3. The chapter is divided into six sections relating to the six Work Packages (WPs) undertaken, cross-referencing to the various papers produced throughout the EngD (Appendix A - D). Figure 4.1 is a schematic chart presenting how the WPs are linked to each other and to the research objectives (as specified in Section 1.5) and shows the corresponding section numbers in the chapter.

The first WP (Section 4.1) investigates the divergence in the simulation results provided by different state-of-the-art BPS tools when simulating the same ICF building. The second WP (Section 4.2), building on the findings of the first study, evaluates the modelling uncertainty in the representation of ICF using whole BPS[11]. The third WP (Section 4.3) presents the findings of an ICF monitoring project, aiming to assess the thermal performance of a real ICF building located in the UK. WP four (Section 4.4) is focused on the empirical validation of BPS predictions using real monitoring data, aiming to quantify the divergence between simulation results and monitoring data for the ICF building case study. The fifth WP (Section 4.5) is focused on probabilistic simulation. Uncertainty and sensitivity analyses are performed on the calibrated ICF simulation model aiming to evaluate the robustness or sensitivity of the model in uncertainties related to material properties of the wall. The most significant factors among the physical uncertainties with the most profound effect on the internal air temperature of the space are also discussed. The sixth and final study of the EngD (Section 4.6) is a comparison of ICF to low and high thermal mass wall construction methods using calibrated simulation

[11] The term ‘whole BPS’ is commonly used in the building research community to define the multi-zone building simulation. ‘Zonal model’ is the equivalent term typically used in industry.

aiming to answer the question if ICF should be characterised as a thermally heavyweight or lightweight structure.

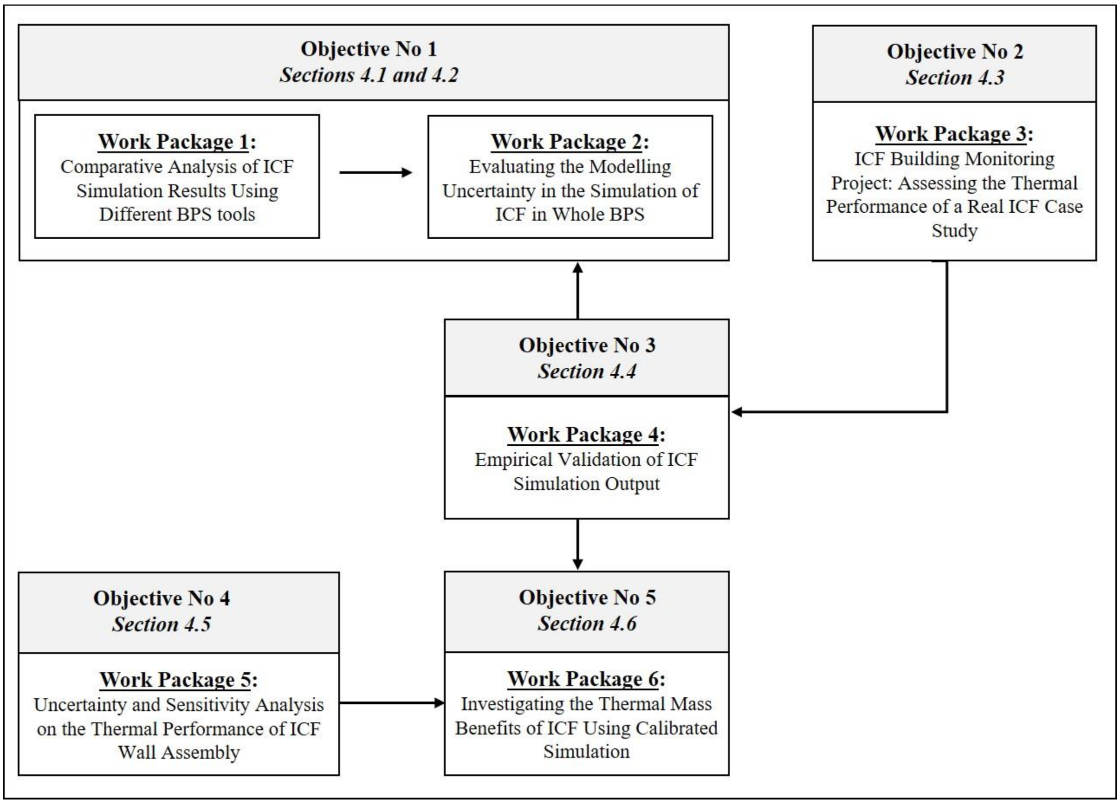


Figure 4.1 *EngD work packages conducted in relation to the research objectives.*

Figure 4.2 is the modelling flowchart adopted in the research undertaken, illustrating the numbered steps of the overall modelling approach, as described in the following sections.

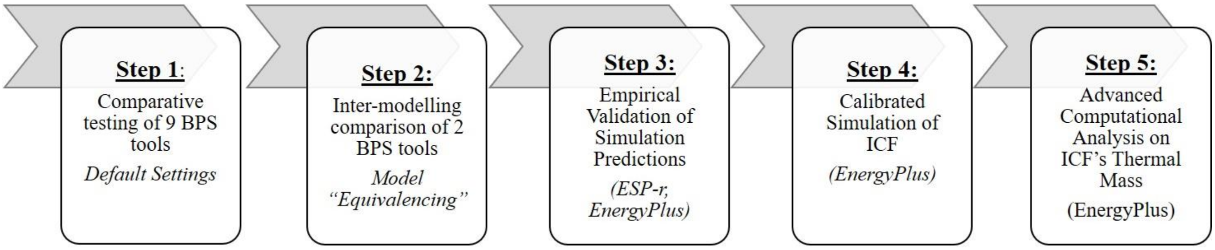


Figure 4.2 *Flowchart of modelling approach adopted in the research undertaken.*

4.1 WORK PACKAGE 1: COMPARATIVE ANALYSIS OF ICF SIMULATION RESULTS USING DIFFERENT BPS TOOLS

4.1.1 SCOPE AND AIMS

The first study undertaken as part of this EngD partly addressed **Objective No1**. The purpose was: "to test and evaluate a list of widely used dynamic BPS tools in predicting ICF thermal and energy performance". The findings of the study were presented in two conferences, Building Simulation (BS) 2015 and Building Simulation and Optimization (BSO) 2016. The papers presented in BS2015 are not included in the thesis. The paper presented in BSO2016 can be found in Appendix A.

The main aims of WP1 were, to:

- Investigate the extent of variation in the simulation predictions provided by a range of BPS tools when simulating ICF using whole BPS.
- Conduct a preliminary analysis of the thermal performance of ICF and see how it compares to low and high thermal mass construction methods by using a simple building case study.

4.1.2 OVERVIEW OF WORK PACKAGE

A single-zone building (as illustrated in Figure 4.3) was selected as a simplified case based on the one specified in the BESTEST methodology (Judkoff & Neymark, 1995). The rationale was to minimise building complexity and thus decrease the number of variables related to geometry and zoning in the input data. At the outset, all simulation models were validated using the BESTEST case 600 for low thermal mass and case 900 for high thermal mass (Judkoff & Neymark, 1995).

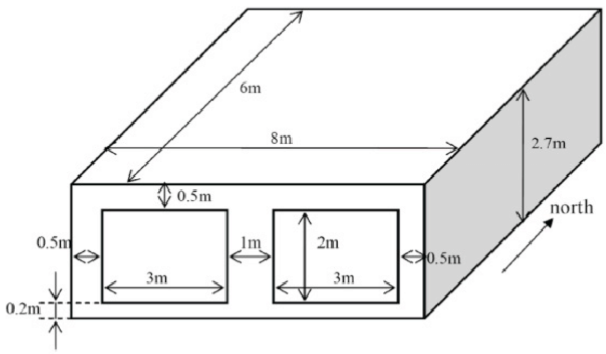


Figure 4.3: *The geometry of the BESTEST building.*

Then, the construction details were changed in line with the objectives of this specific study. Three construction methods were simulated: an ICF, a low thermal mass (LTM) (timber-frame) and a high thermal mass (HTM) (exposed concrete) building. Table A.1 in Appendix B provide more details on the construction of the three building case studies. The cross-section of the three wall constructions are illustrated in Figure 4.4.

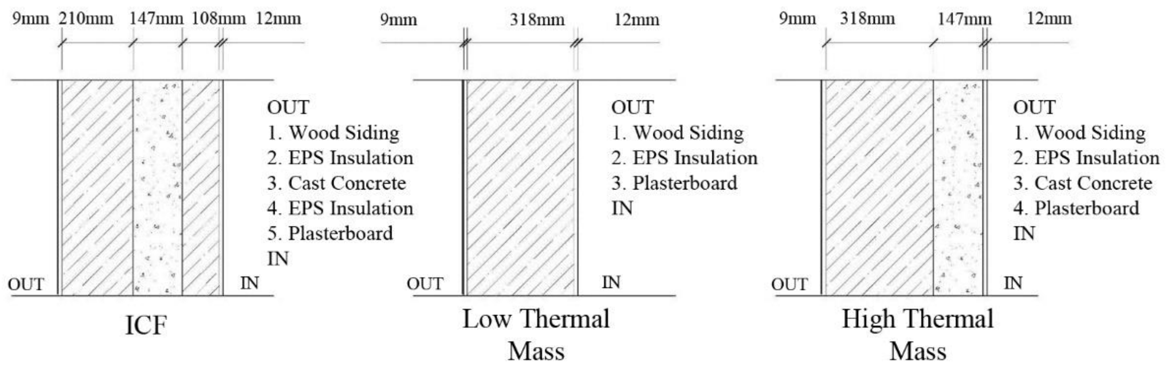


Figure 4.4: *Cross-section of the three wall construction methods (ICF; LTM and HTM).*

The ICF option was based on real building construction details and was used as a reference to specify U-Values for all other construction elements. In this way U-values were consistent for all three building models. Hence, the main difference between the three construction methods was in the amount of thermal mass in the fabric. The simulation settings were identical in all three scenarios; each model had the same building footprint, windows, HVAC system, internal gains and infiltration rates, as summarised in Table 4.1, below.

Table 4.1 *Input data used for the building model*

Building Model Details	
Internal Treated Floor Area	6m x 8m = 48m^2
Orientation	Principal axis running east west direction
Windows	Two double glazed windows, 2m x 3m each, on south façade, U-Value = 3.00 W/m^{2}K, g-Value = 0. 747
U-Values (W/m^{2}K)	Walls = 0.10
	Floor = 0.10
	Ceiling = 0.11
HVAC system	Ideal loads
HVAC Set points	20ºC Heating/ 27ºC Cooling
HVAC Schedule	24h (Continuously on)
Internal Gains	200W (other equipment)
Infiltration	0.5ACH (Constant)

The DRYCOLD weather file, downloaded from NREL[12], was used as a Typical Meteorological Year (TMY), i.e. a climate with cold clear winters and hot dry summers. A list of nine BPS tools commonly used both in academia and industry were selected for the inter-model comparative analysis (more details on the nine BPS tools can be found in Appendix E). Five of the tools (used for the analysis) were proprietary commercial tools. For reasons of sensitivity and fairness, it was decided to anonymise the results. The divergence in simulation predictions provided by the nine tools (when the user relies on the default settings and algorithms of the tools) were analysed for the ICF building and the other two building cases with respect to the annual energy consumption and the system peak loads.

4.1.3 REPRESENTATION OF ICF IN BPS

Figure 4.5 illustrates the relative differences between the maximum and minimum values provided by the nine BPS tools for annual energy consumption and system peak loads when

[12] Available at http://www.nrel.gov/publications/ [Accessed on: 27/04/18].

simulating the same ICF building. The graphs show more substantial divergence for the annual and peak heating demand. More specifically, a 57% difference was observed among the nine tools for the calculation of annual heating energy and a 25% difference was evident in the prediction of peak heating loads. In both cases, tool I estimates the lowest energy consumption, while tools G and H estimate the highest annual heating and peak heating respectively.

In the cooling demand the relative difference among the nine tools was slightly less, yet remained significant. A 22% percent divergence was found in the calculation of annual cooling energy and a 14% difference in the calculation of peak cooling loads. In both cases, tool G estimates the highest values, around 22% increased, compared to tool D, which gives the minimum value for the annual cooling demand and around 14% higher than tool B for the peak cooling loads.

The inter-modelling comparison was also performed for LTM and HTM construction methods. The analysis showed that there were also inconsistencies in the simulation predictions provided by the nine BPS tools for the other two construction methods. The divergence was always higher for the heating energy consumption and the heating peak loads and increased accordingly with the level of thermal mass in the fabric. Table 4.2 summarises the relative differences between the maximum and the minimum estimates energy consumption for all three construction methods.

Table 4.2 *Relative differences between the maximum and minimum estimated energy consumption in [%]*

Energy Use	**ICF**	**Low Mass**	**High Mass**
Annual Heating	57%	30%	70%
Peak Heating	25%	18%	34%
Annual Cooling	22%	15%	29%
Peak Cooling	14%	11%	24%

Further information with regards to the inter-model comparison of the different BPS tools when simulating the same ICF building can be found in the paper in Appendix A.

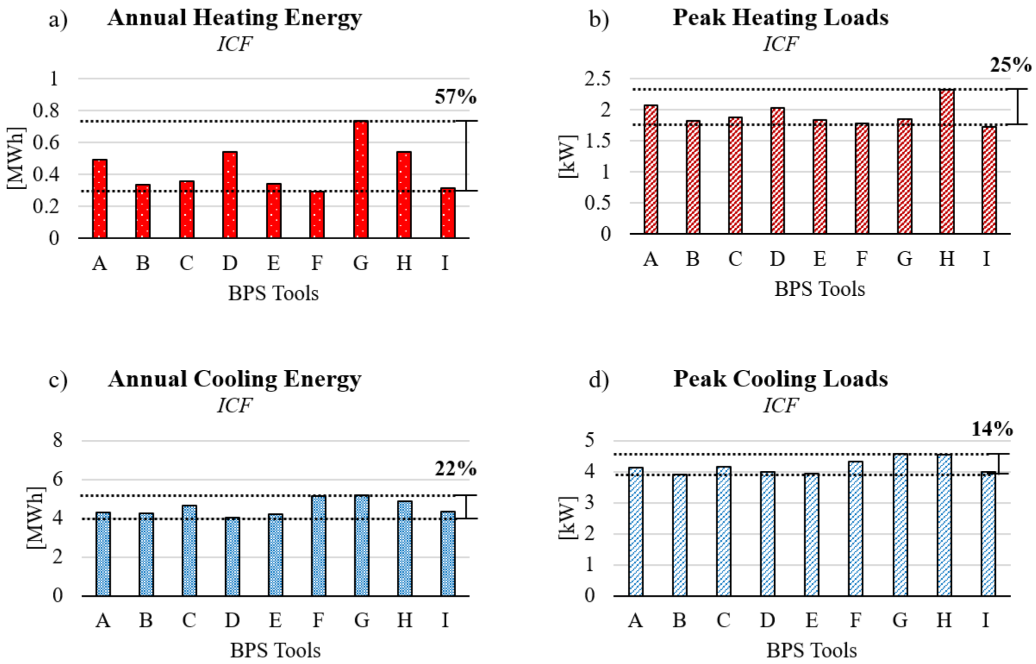


Figure 4.5 *Divergence in the simulation results provided by the nine BPS tools for the same single-zone ICF building for the: a) annual heating energy consumption, b) peak heating loads, c) annual cooling energy consumption, d) peak cooling loads.*

The results from the nine BPS tools showed that there were significant inconsistencies in the simulation of ICF energy consumption and system loads when the user relies on the defaults settings and algorithms employed by the tools.

4.1.4 Evaluating the Ability of Current BPS Tools in Predicting ICF Energy Saving Potentials

A preliminary comparative analysis of the thermal performance of ICF, LTM and HTM construction methods was conducted to investigate how the former behaves in relation to the other two buildings based on simulation predictions. Fig.4.6 shows the simulation results from the nine BPS tools for the annual energy consumption of the ICF building when compared to the LTM and HTM cases. Fig.4.6a shows the decrease in annual heating energy consumption of ICF when compared to LTM, Fig.4.6b shows increase in annual heating energy consumption of ICF when compared to HTM, Fig.4.6c shows the decrease in annual cooling energy consumption of ICF compared to LTM and Fig.4.6d shows the increase in annual cooling energy demand of ICF when compared to HTM.

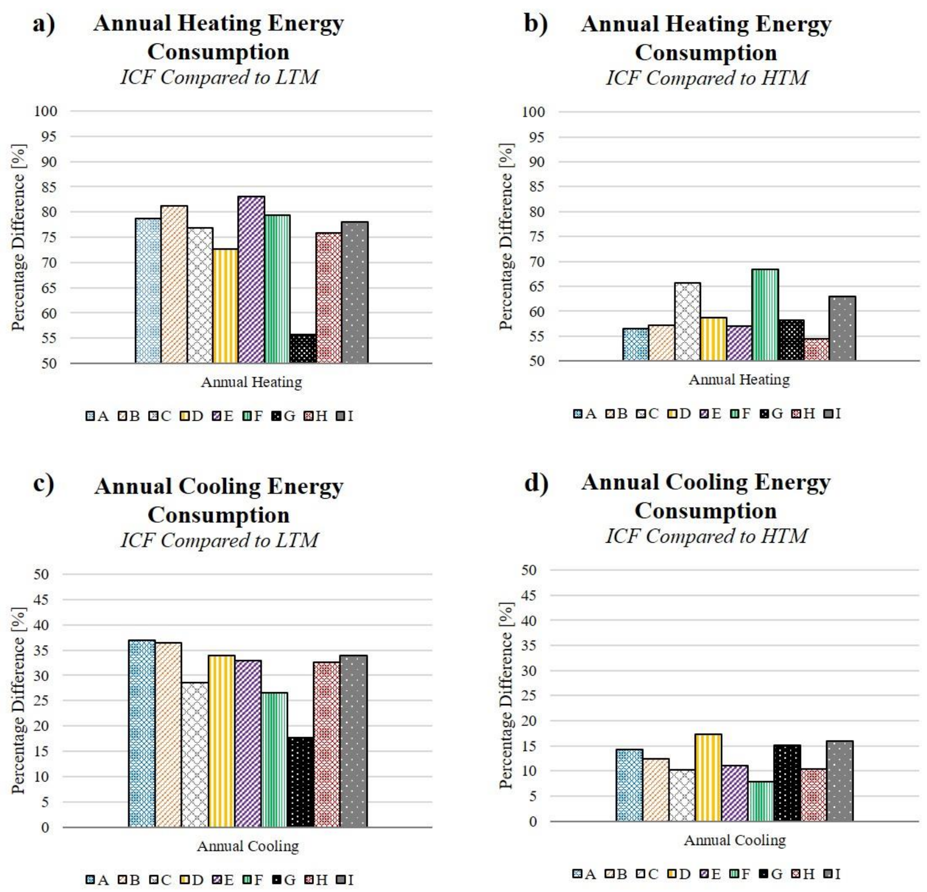


Figure 4.6 *Results of nine BPS tools on the a) annual heating energy consumption reduction of ICF compared to LTM, b) annual heating energy consumption increase of ICF compared to HTM, c) annual cooling energy consumption reduction of ICF compared to LTM and d) annual cooling energy consumption increase of ICF compared to HTM, when the user relies on the tools' default settings.*

The average annual heating energy consumption of all nine BPS tools indicates that the ICF building would require circa 76% less energy than the LTM building and 60% more energy than the HTM building. In regard to the annual cooling energy consumption, the average of all nine tools shows that the ICF building requires around 31% less energy than the LTM building and 13% more than the HTM. The range of variation in the simulation predictions provided by the different tools in the comparison of ICF annual heating demand to LTM lies in a ~25% difference between the maximum and minimum values. In the comparison of ICF to HTM the range of variation is around 14%. In other words, the various BPS tools provide significantly different predictions. Taking Tool G as an example, the energy savings from ICF (when compared to the LTM building) are 56%. On the contrary, Tool E estimates this reduction to be 83%. Similarly, in the comparison of ICF to HTM building, although the range of variation in the results provided by the different tools is significantly lower, the selection of a BPS tool could also affect the conclusions drawn by the modeller. For example, Tool H estimates a 54% increase in the energy consumption of ICF compared to a HTM building, whereas Tool I predicts that the ICF building would require 63% more energy for annual heating.

Similar findings emerge from the comparative performance of ICF to LTM and HTM buildings in terms of annual cooling demand. The range of variation in the energy reduction of ICF when compared to LTM is ~19% between the maximum and minimum values estimated by the tools. A 7% range of variation is evident in the increase of annual cooling demand of the ICF building when compared to the HTM building.

The results show that, depending on which BPS tool is chosen, very different interpretations could be drawn on the comparative thermal performance of ICF to LTM and HTM construction.

4.1.5 SUMMARY

This study highlighted that there are significant variations in the representation of ICF in whole BPS across nine simulation tools. When users rely on the default settings and algorithms, significant divergence was observed in the simulation results provided by the BPS tools - up to 57% relative difference between the minimum and maximum values (i.e. annual heating energy consumption). This discrepancy was particularly evident in the annual and peak heating demand values.

A preliminary comparative analysis was conducted on the thermal performance of ICF, LTM and HTM buildings. The results showed that, for this specific case, the former behaves closer to the HTM building. It is difficult to derive solid conclusions about the actual thermal performance of either of the three construction methods in such a simplified simulation scenario. A more realistic scenario of a representative building case study would improve the reliability of this outcome. Nonetheless, the analysis highlighted how relying on the default settings of the BPS tools would almost certainly result in misinterpretations during the decision-making process. The results provided by the nine BPS tools showed a high range of variation on the energy reduction/increase of ICF when compared to LTM and HTM cases.

This study contributes to Objective No1 of the research by showing that there is a high divergence, reaching up to 57% in the simulation of ICF using different BPS tools. This demonstrates that the selection of a BPS tool could potentially affect the conclusions drawn by the modeller on a building’s thermal performance. This is notably problematic in the case of ICF, which appears to be subject to significant variations in simulation outcomes.

4.2 WORK PACKAGE 2: EVALUATING MODELLING UNCERTAINTY IN THE SIMULATION OF ICF IN WHOLE BPS

4.2.1 SCOPE AND AIMS

The second WP addressed the second part of **Objective No1**. The purpose was: "to identify the key modelling uncertainties that are associated to ICF simulation" using current state-of-the-art BPS tools. The study gave an insight into the implications of default input parameters and the effect of calculation algorithms, both of which contribute to the divergence seen in results from the BPS tools when simulating an ICF building. The findings of this WP were published at Building and Environment journal (see Appendix B).

4.2.2 OVERVIEW OF WORK PACKAGE

The same single-zone building described in the previous Section (WP1) was used for the analysis. Among the nine BPS tools previously tested in the inter-model comparison, Tools E and I showed very similar results. Therefore, they were selected for further investigation. **N.B. In the paper of Appendix B Tool E is referred as Tool A and Tool I as Tool B**. An "equivalencing" process of selecting identical algorithms and consistent input settings was followed to minimise the difference between the simulation models and to determine that any divergence in the results was due to differences in modelling methods and not by other factors. More details of the algorithms and input values used in the equivalent models can be found in Table A.2 of Appendix B.

The results of the "equivalencing" process were analysed sequentially (Fig. 3 in Appendix B) using the Normalised Root Mean Square Error (NRMSE), as described in Section 2 of the paper in Appendix B. The aim was to understand which algorithms had the greatest impact on each discrepancy and to investigate whether any disparity became more obvious in the heating or cooling demand. The analysis investigated the impact of the various solution algorithms and modelling methods on the annual heating and cooling energy consumption, the system peak loads and the surface and intra-fabric wall temperatures for the ICF building, in relation to common LTM and HTM construction types (i.e. timber-frame and exposed concrete, respectively). The purpose was to reflect on the effects of modelling decisions and modelling uncertainty on thermal mass simulation and to investigate if the "modelling gap" would be more significant in the representation of ICF, a relatively new and innovative construction method that is relatively less well-researched.

4.2.3 MODELLING UNCERTAINTIES IN ICF SIMULATION

The analysis started by looking at the annual and hourly simulation results provided by the two BPS tools when the user relies on the default settings. The monthly breakdown of annual and peak heating and cooling results showed a high discrepancy between the two BPS tools, particularly in the simulation of annual heating demand for the ICF building (up to NRMSE = 26.05%) (Step 0 of Fig.4.7). Among the three construction methods, the ICF and HTM cases showed the largest discrepancies, indicating that the amount of thermal mass in the fabric affected significantly disparity of results. The LTM building showed better consistency in comparison to the other two construction types in both annual and peak heating and cooling demand.

The monthly simulation results provided by the two BPS tools for the heating and cooling demand (Fig.4.7 and Fig.4.8, respectively) showed the largest discrepancies over the winter months, when the solar angle is small, for all three construction methods. In contrast, a relatively good agreement was achieved during summer. This suggested that further investigation was required to address the differences in the way the two BPS tools simulate solar gains.

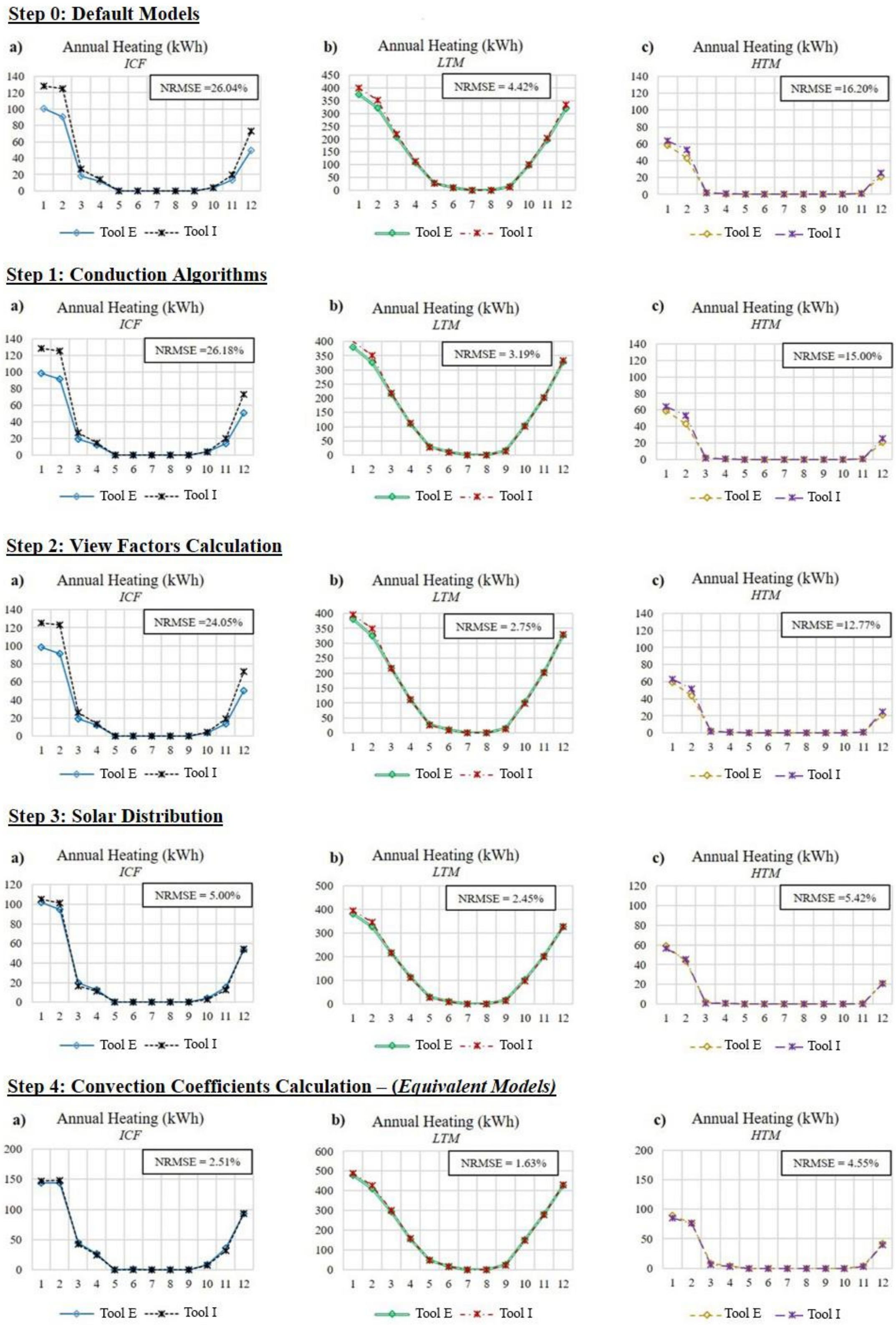


Figure 4.7 *"Equivalencing" the models. Monthly breakdown of annual heating energy predictions provided by tool E and tool I for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM).*

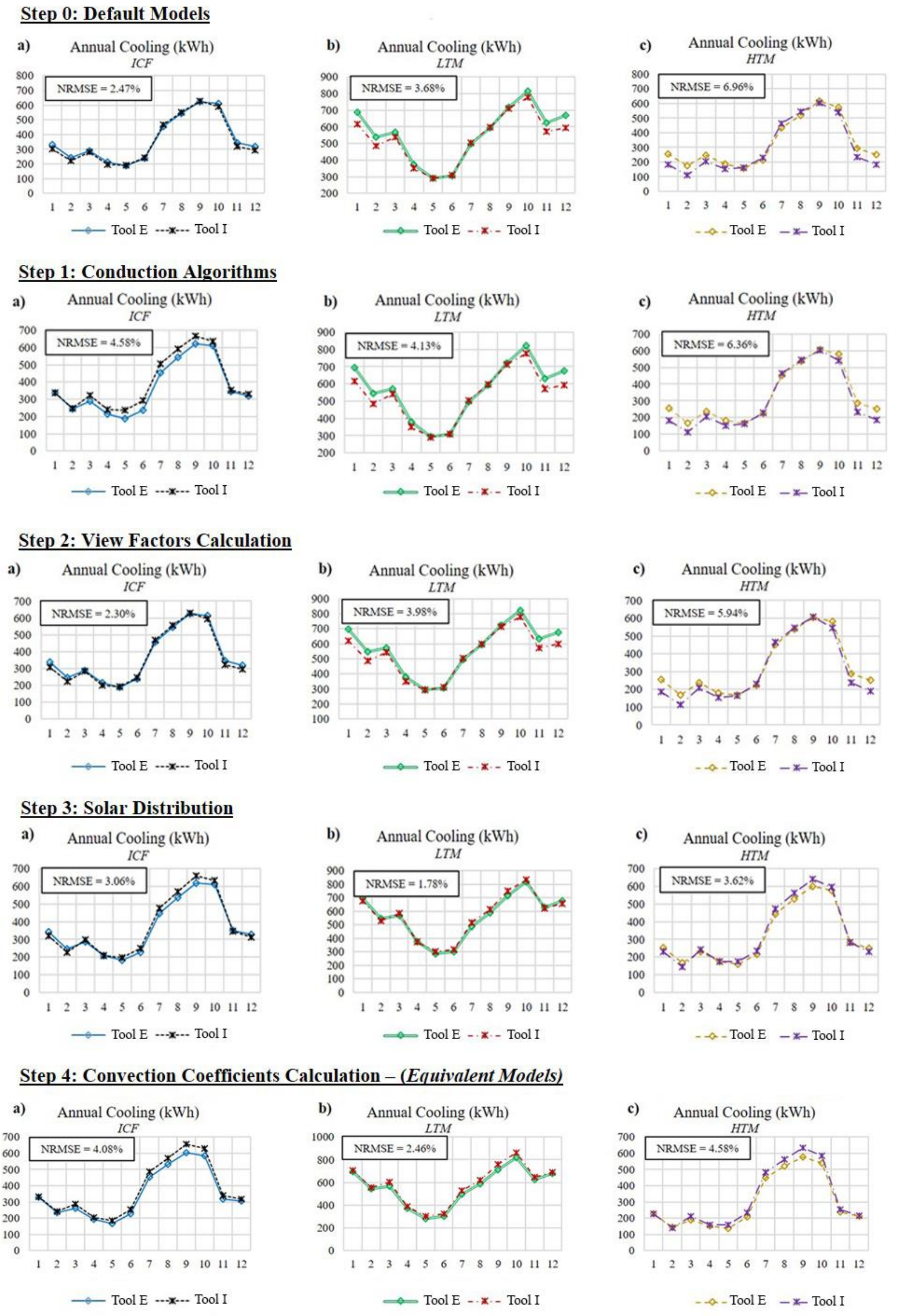


Figure 4.8 *"Equivalencing" the models. Monthly breakdown of annual cooling energy predictions provided by tool E and tool I for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM).*

Furthermore, it was attempted to get a better understanding on the impact of default settings and solution algorithms on the dynamic performance of ICF and thermal mass. For this purpose, hourly simulation results were analysed for the internal, intra-fabric and external wall surface temperatures and for the heating and cooling demand for three consecutive days in the winter and summer periods. Differences in the hourly predictions of cooling demand were negligible (Fig.4.9), whereas the hourly results for heating demand showed that the largest disparity was again observed in the ICF simulation (Fig.4.10).

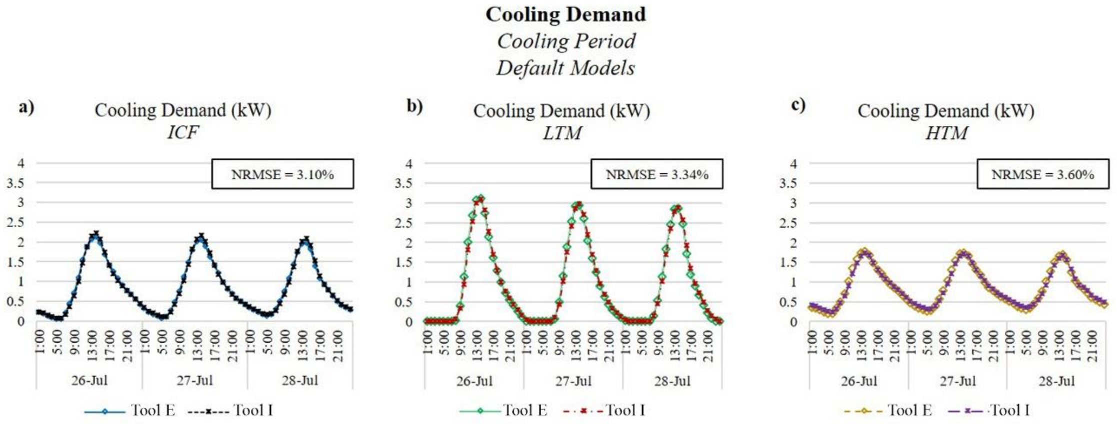


Figure 4.9 *Hourly breakdown of cooling demand. Simulation predictions provided by tool E and I for three consecutive days in the cooling season (26–28 July) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the user relies on the tools' default settings*

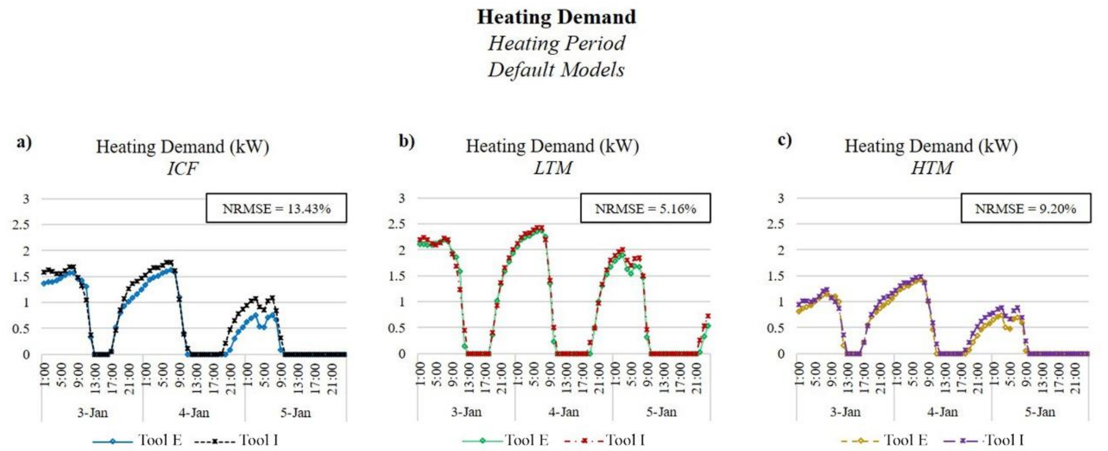


Figure 4.10 *Hourly breakdown of heating demand. Simulation predictions provided by tool E and I for three consecutive days in the heating season (03–05 January) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the user relies on the tools' default settings.*

Simulation predictions from both tools for the hourly wall surface temperatures showed a relatively good agreement (in terms of relative differences) for all three constructions (with the exception of outside surface temperatures). However, the absolute divergence indicated instances of maximum difference as high as 5°C (i.e. internal surface temperature of ICF building - Fig.4.11). This highlighted that the selection of BPS tools could significantly affect the outcome of thermal comfort assessments and could result in different conclusions being drawn about the thermal performance of the building.

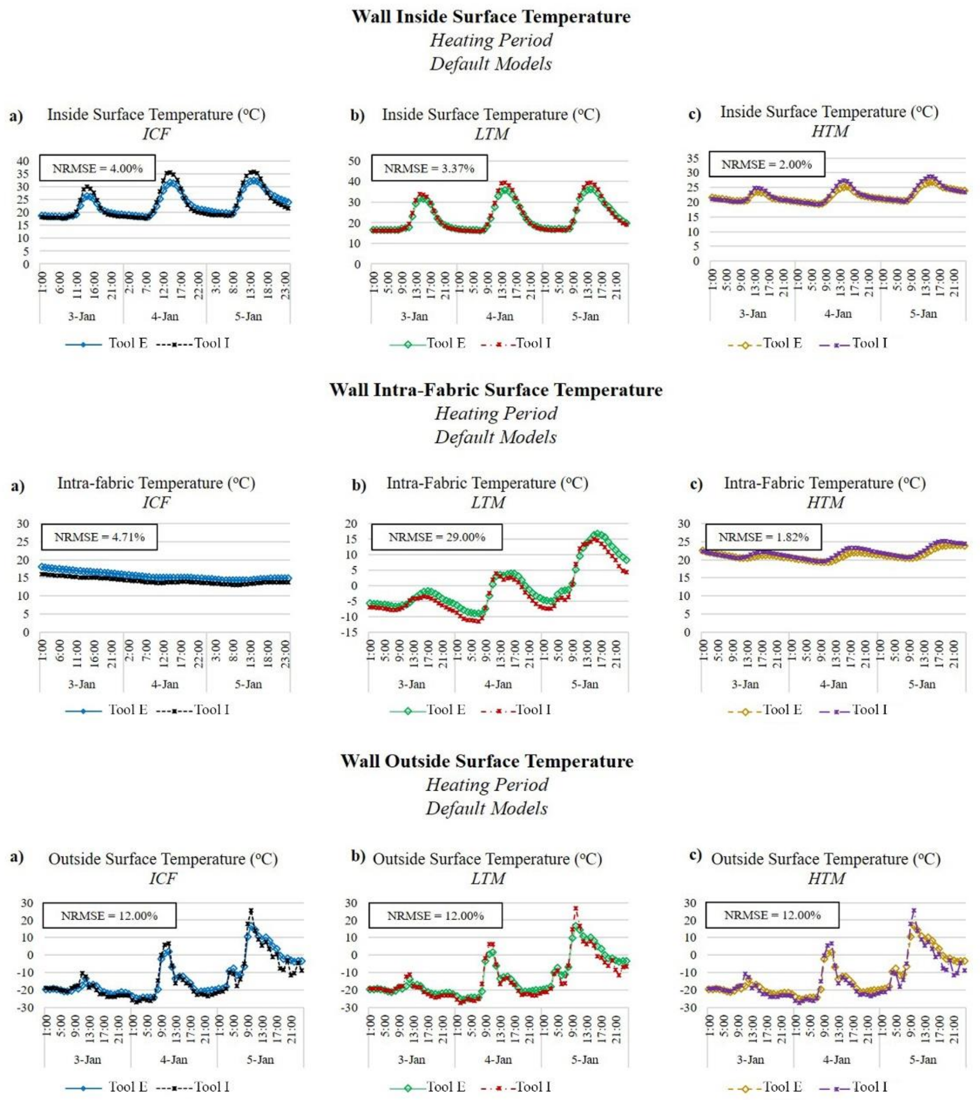


Figure 4.11 *Hourly breakdown of the inside surface, intra-fabric and outside surface temperature of the east wall. Simulation predictions provided by tool E and I for three consecutive days in the heating season (03–05 January) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the user relies on the tools' default settings.*

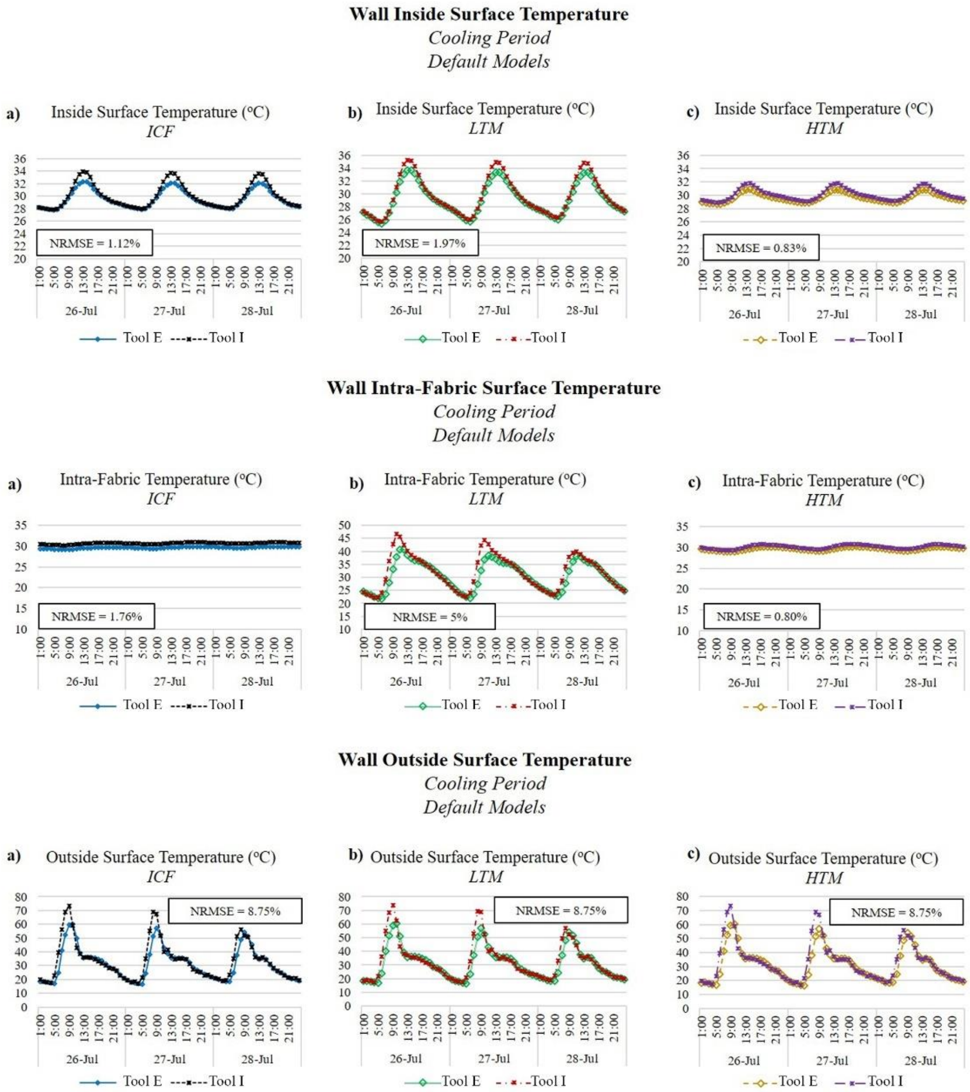


Figure 4.12 *Hourly breakdown of the inside surface, intra-fabric and outside surface temperature of the east wall. Simulation predictions provided by tool E and I for three consecutive days in the cooling season (26–28 July) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the user relies on the tools' default settings.*

In a process of making the models equivalent for comparison, identical algorithms and input values were specified in both BPS tools. The impact of each algorithm that was investigated as part of the "equivalencing" process is analysed in detail in Section 3.2.1 of Appendix B. Moreover, Figs. 4.7 and Fig.4.8 show the results of the two tools for annual heating and cooling demand for each step of the process. The general observation was that the two most influential parameters leading to discrepancies in results were:

- the distribution of direct solar radiation
- the specification of surface convection coefficients.

Following the model "equivalencing" process, the annual simulation predictions provided by the two BPS tools were much more consistent for all three construction methods, with the exception of annual cooling demand for the ICF building (as illustrated in the black bars in Fig.4.13 below). However, the divergence in the prediction of annual cooling demand of ICF increased after the "equivalencing" process. This showed that there is a level of modelling uncertainty allied to ICF simulation that requires further investigation through measurements and empirical validation. The hourly simulation results provided by the two tools for the "equivalenced" models also showed some negligible inconsistencies in terms of both absolute and relative differences, as presented in Section 3.2.3 of Appendix B.

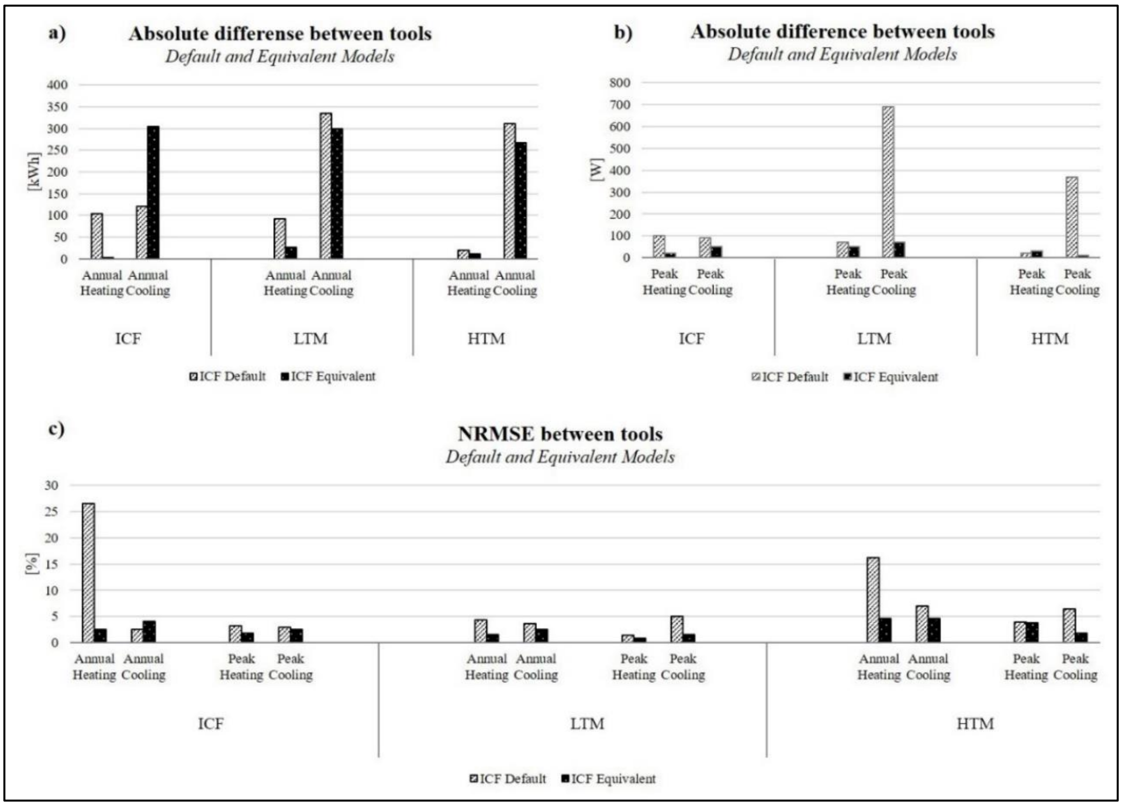


Figure 4.13 *Absolute difference and NRMSE between the simulation predictions provided by tools E and I for the three construction methods ICF, low thermal mass (LTM) and high thermal mass(HTM), when the user relies on the tools' default settings and when the models are equivalent: a) absolute difference in annual heating and cooling energy consumption, b) absolute difference in peak heating and cooling demand and c) relative difference (NRMSE) in annual energy consumption and peak loads.*

During the "equivalencing" process, several observations were made on how the different modelling methods employed by the tools affected the results' discrepancy even when the input values were the same (in this case the climate data). As a result, two modelling factors were analysed:

1. The solar timing (used in the calculation of the solar data).
2. The impact of variations in wind speed (for the calculation of the external surface convection coefficients).

This analysis is presented in Section 3.3 of Appendix B. The general conclusion was that the variation observed in the simulation predictions was higher for heating demand and increased according to the level of thermal mass in the fabric. Consequently, the most profound inconsistencies were observed once again in the simulation of the ICF and HTM buildings.

4.2.4 THE IMPACT OF "MODELLING GAP" ON THE COMPARATIVE SIMULATION OF ICF TO LTM AND HTM CONSTRUCTION TYPES

The results of WP1 indicated that there was a high range of variation in the simulation predictions provided by the nine BPS tools for the comparative performance of ICF to LTM and HTM buildings. To investigate the impact of modelling uncertainty on the calculation of ICF energy savings, the discrepancy in results between Tools E and I was compared before and after the model "equivalencing" process. The aim was to see how close the simulation predictions would be after the differences in the models were minimised. Fig. 4.14 shows the energy reduction arising from ICF when compared to the LTM building, pre- and post-equivalencing.

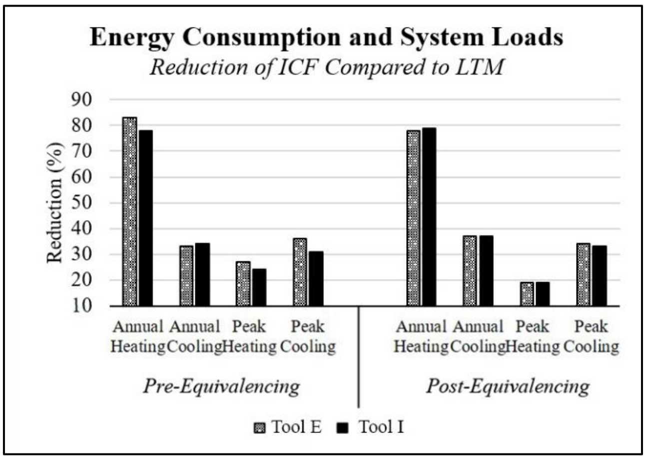


Figure 4.14 *Comparison of ICF building annual energy consumption and peak system loads to LTM building, pre- and post-equivalencing. Results of two BPS tools on the percentage difference of ICF compared to LTM.*

Fig. 4.15 shows the energy increase from ICF when compared to the HTM building, pre- and post-equivalencing.

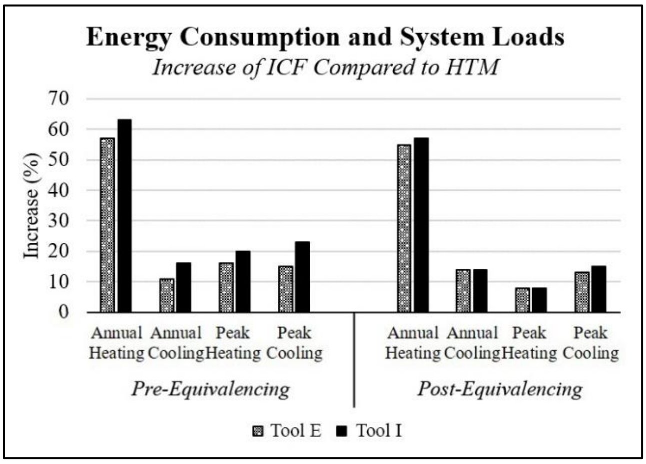


Figure 4.15 *Comparison of ICF building annual energy consumption and peak system loads to HTM building, pre- and post-equivalencing. Results of two BPS tools on the percentage difference of ICF compared to HTM.*

The ICF building was found to perform similarly to the HTM building, both pre- and post-equivalencing. However, predictions of the comparative performance of ICF in relation to the other two construction methods was different based on the selection of the BPS tool pre-equivalencing. Figs.4.14 and 4.15 show that after the models were "equivalenced", the outputs from the BPS tools were much closer, i.e. in closer agreement.

4.2.5 SUMMARY

This study (WP2) investigated the impact of the "modelling gap", namely the impact of default settings and the implications of various calculation algorithms on the representation of ICF and thermal mass in BPS. The results showed that modelling uncertainties accounted for up to 26% variation in the simulation predictions for the monthly breakdown of annual energy consumption provided by two tools when simulating an ICF building. This divergence becomes particularly important considering that these two tools gave relatively similar results in their analysis of the total annual energy consumption.

In Phase 1 of this study, the discrepancy in the simulation results provided by the tools when the model user relies on the default input settings was found to be relatively high, particularly in the annual heating energy consumption. In Phase 2, a model "equivalencing" process was followed, in which identical calculation algorithms and input values were specified in both simulation models. Following the "equivalencing" process, the results of the two BPS tools showed much better agreement.

The general observation was that the thermal mass in the fabric was found to have a considerable impact on divergence of results. The highest variation was observed in the ICF and HTM cases, indicating that there is a level of modelling uncertainty in the representation of thermal mass in BPS, which requires further investigation.

The relative performance of ICF compared to the other two construction methods was analysed before and after the model "equivalencing" process. This research demonstrated that, for the specific case study, ICF behaved in a broadly similar way to HTM, a finding that was further enhanced after the models were equivalenced. This is a potentially very significant finding, indicating that ICF could be a viable alternative for energy efficient construction. Nevertheless, validation through further computational analysis, empirical testing, and building monitoring is required to validate the results.

The findings of this work package contribute to Objective No1 by showing that, among others, the two most significant factors affecting the divergence in results (when simulating an ICF building) were the simulation of solar radiation and the specification of surface convection coefficients.

4.3 WORK PACKAGE 3: ICF BUILDING MONITORING PROJECT: ASSESSING THE THERMAL PERFORMANCE OF A REAL ICF CASE STUDY

4.3.1 SCOPE AND AIMS

The third work package undertaken as part of this EngD addressed **Objective No2** of the research. The purpose was: “to monitor and analyse the actual energy consumption and thermal performance of an ICF building located in the UK, and to scrutinise ICF’s potential for indoor temperature control”. This is the first whole building monitoring study conducted in a real, ICF, occupied, detached building in the UK.

The main aims were to:

- Analyse the actual energy consumption and thermal performance of a real ICF building in the UK climatic context.
- Investigate the potential of ICF for indoor temperature control.
- Provide an evidence-based dataset for the ICF construction method, which would allow a detailed comparison of monitoring data with simulation results, thereby empirically validating the accuracy of ICF simulation.

4.3.2 OVERVIEW OF WORK PACKAGE

Monitoring data were gathered from an ICF low-energy dwelling, called Twiga Lodge. Twiga Lodge is located within the parish of Gomshall, at a small cluster of dwellings, in the wider area of Guildford, at Surrey, UK. The county of Surrey has a temperate maritime climate with typically warm rather than hot summers and cool to cold winters. On average, the hottest month is July in summer and the coldest is January in winter (Met Office, n.d.). The building was designed to achieve near to Passivhaus levels (Passivhaus, n.d.). It is a two-storey, three-bedroom dwelling, with a floor area of approximately 270m^2. The building envelope is ICF walls with an insulated foundation raft and prefabricated EPS roof panels. All windows are triple-glazed to minimize heat losses through glazing. A rendered wall finish is used externally.

The building is orientated due South, with the south side facing an open field area. Fig. 4.16 shows the ground floor and the first-floor plans of the building. Detailed information about the material properties of the construction elements can be found in Table 1 in Appendix C.

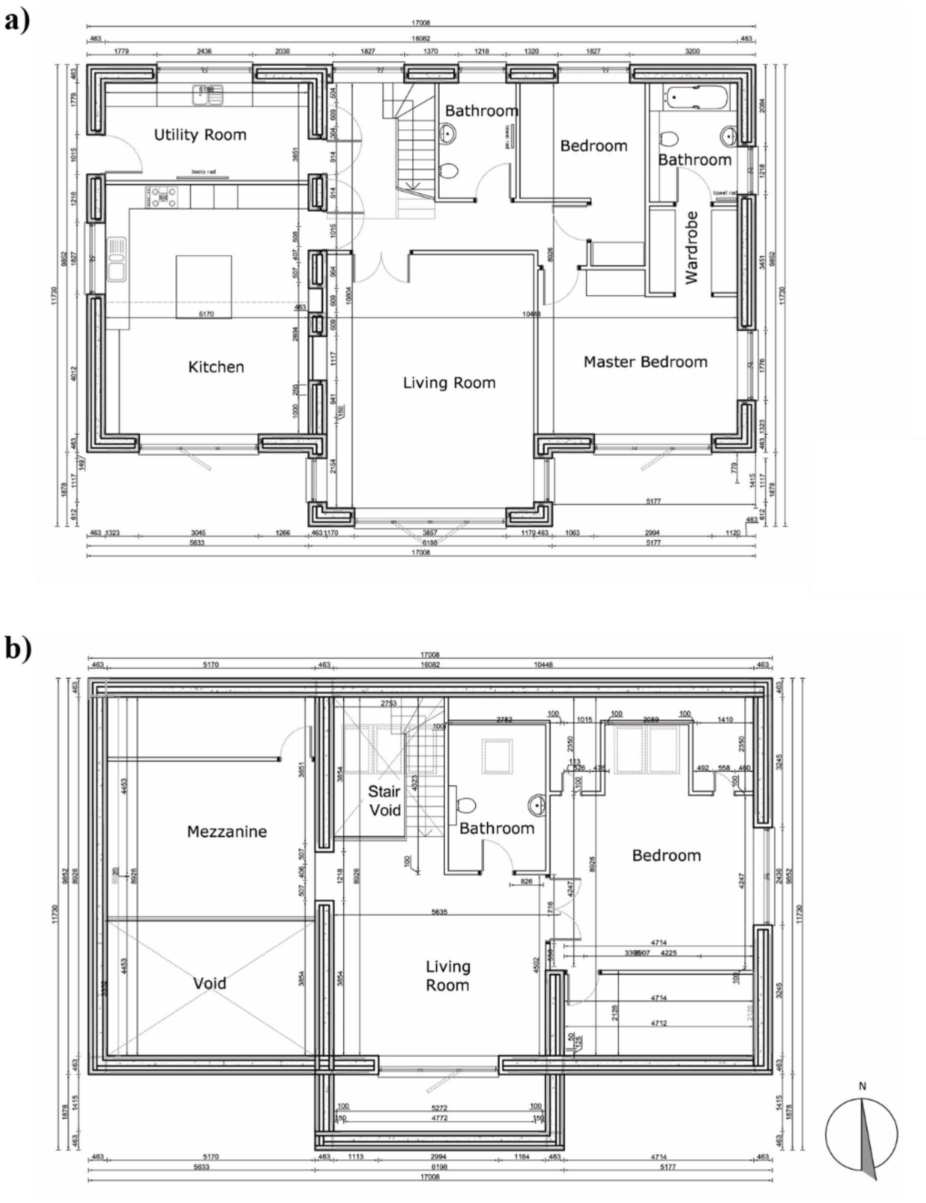


Figure 4.16 *(a) Ground floor and (b) first floor plan of Twiga Lodge*

The house has a Mechanical Ventilation and Heat Recovery System (MVHR) that was designed to provide controlled ventilation and accommodate the occupants' needs for fresh air. Apart from the MVHR system, there are two secondary heating systems (used only when required):

- Gas boiler and radiators
- A wood-burning stove

The gas boiler provides hot water to three towel rail radiators that are installed in the bathrooms and one radiator in the main entrance (i.e. utility room in ground floor). Domestic hot water is provided by a hot water cylinder. The water is heated by:

- the installed gas boiler
- the excess electrical energy produced from the photovoltaic system (PV)

The monitoring study lasted for approximately 20 months, between April 2016 and February 2018. The recorded data included information on:

- On-site weather data
- Surface and intra-fabric temperatures of the external walls
- Heat fluxes of the building fabric
- Internal air temperatures
- Internal relative humidity
- CO_2 levels
- Energy consumption
- Heat input
- Windows opening and closing incidents

More details about the building case study and the monitoring project can be found in Section 2.1 of Appendix D. For more information on the monitoring equipment and time-step resolution please refer to Appendix F.

The thermal performance of the building was analysed by looking at the internal air temperatures for three of the main living areas, the ground floor living room, the master bedroom and the kitchen. The results were plotted first for a whole year. Secondly, further analysis was performed by looking at the monthly results for the warmest month (i.e. July) and the coldest month (i.e. January). The ability of ICF to moderate internal temperature swings was analysed by looking at the dynamic characteristics of the fabric in terms of decrement factor (D_f) and decrement delay (ω) (time lag) as defined in Section 2.1.1, in Eq.3 and Eq.4 and as illustrated in Fig.4.17.

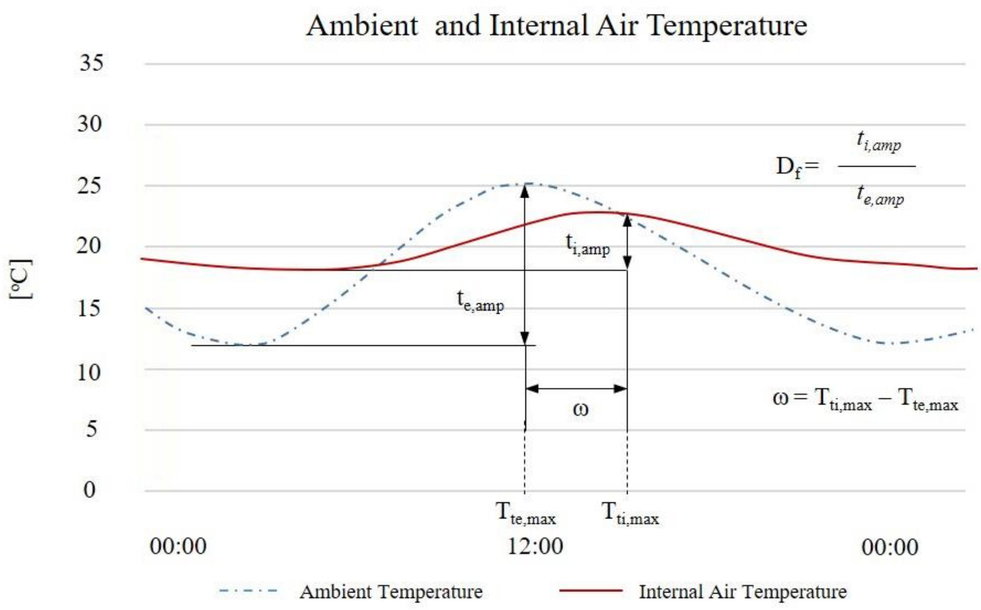


Figure 4.17 *Ambient and internal air temperature. Illustrative example of the calculation of decrement factor* D_f *and decrement delay* ω*.*

The energy performance of the building was evaluated based on the total monthly electricity and gas consumption for a whole year. Further investigation was performed on the daily gas consumption used for space heating and the daily electricity consumption used by the MVHR system.

4.3.3 THERMAL PERFORMANCE

The frequency distribution of ambient and internal air temperatures for three zones were recorded in the field for a whole year, as illustrated in Fig. 4.18. As shown in the graphs, the dry-bulb temperature fluctuates in a range between -7.5°C and 30°C, with an almost normal distribution, and an average temperature around 10°C. However, the zone internal air temperatures show a significantly smaller range of variation, fluctuating between 12.5^{o}C and 30^{o}C during the whole year, while hovering most of the time between 17.5^{o}C and 22.5^{o}C.

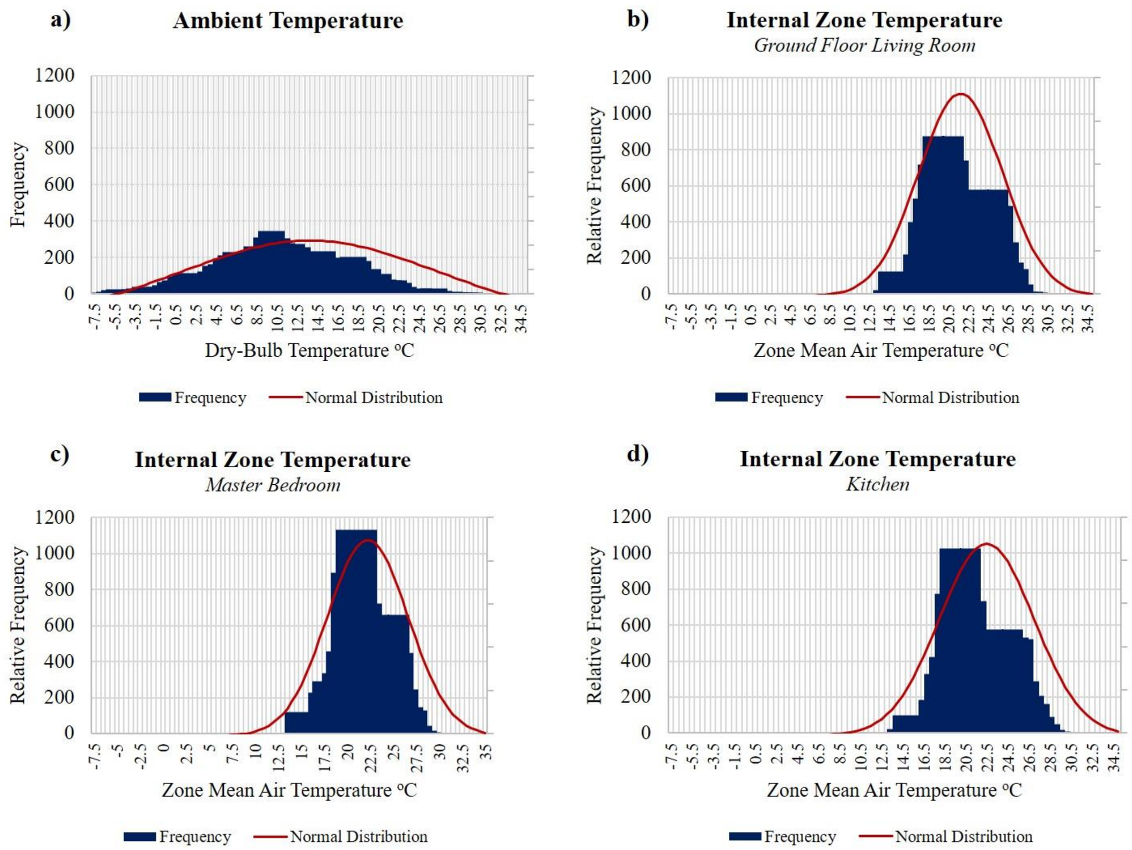


Figure 4.18 *Frequency distribution of: a) ambient dry-bulb temperature, b) internal air temperature in ground floor living room, c) internal air temperature in master bedroom and d) internal air temperature in kitchen (June 2016 to May 2017).*

The diurnal temperature variations for both the internal and external air temperature for the ground floor living room, the master bedroom and the kitchen are shown in Fig. 4.19, again for a year-long period (June 2016 to May 2017). The results indicate that although there was a high range of diurnal variation in the dry-bulb temperature (around 15^{o}C during summer and around 12^{o}C during winter), the internal air temperatures were relatively stable throughout the year. There was an average diurnal variation of internal air temperature between 1.5^{o}C and 4^{o}C during the whole year, even during periods when the house was unoccupied and running in free-floating mode (i.e. March-April 2017). The average temperature of the internal space fluctuated between 22°C and 25°C during summer, with some peaks of 27°C (during periods of increased ambient air temperature) and around 21°C during winter for all three zones. The lowest temperatures were between 15°C and 17°C and were recorded when the house was unoccupied (i.e. November 2016 and March 2017). There was some evidence of overheating during summer, particularly during periods when the ambient temperatures were high, or the house was unoccupied. This is partly attributed to the lack of natural ventilation (windows were kept shut throughout the unoccupied periods) and partly to the design of the building. The building is oriented due South and has large glazing areas on the Southern façade without a shading device to block the direct solar radiation from penetrating the space.

To investigate differences among the three spaces and differences between summer and winter performance, diurnal temperature variations in internal and external air temperatures were plotted for warmest and coldest months (i.e. July and January). All three spaces have large openings in the South wall. The master bedroom is the only room that has an overhang above the window acting as a shading device. The other two rooms have no shading. Fig.4.20 shows that during summer despite the presence or not of a shading device, the diurnal variations in the internal air temperature were almost the same in all three spaces under investigation and around 2°C, with a maximum of 4°C, during a heat wave (16 - 21 July 2016). On average, the internal air temperature was around 23°C during the whole month, increased to 25°C when the house was unoccupied, and further increased to 26°C during the heat wave. In general, the kitchen was found to have increased internal air temperatures and the highest diurnal variation of all three rooms during July.

During winter, the diurnal internal temperature variation between the three rooms was significant. The zones without shading (i.e. living room and kitchen) showed the highest range of variation throughout January, particularly during days with increased solar radiation availability (i.e. 17-23 January 2017). There were instances when the daily internal temperature variation was up to 5^{o}C (i.e. kitchen on 20th of January 2017). The average internal air temperature was also found to vary among the three spaces during winter. The living room and master bedroom showed an average temperature of 20^{o}C throughout the month. The kitchen temperature was lower and around 19^{o}C. During winter, the kitchen, similarly to summer, showed the highest diurnal internal air temperature range of all three spaces. This is partly related to the increased internal gains of the room.

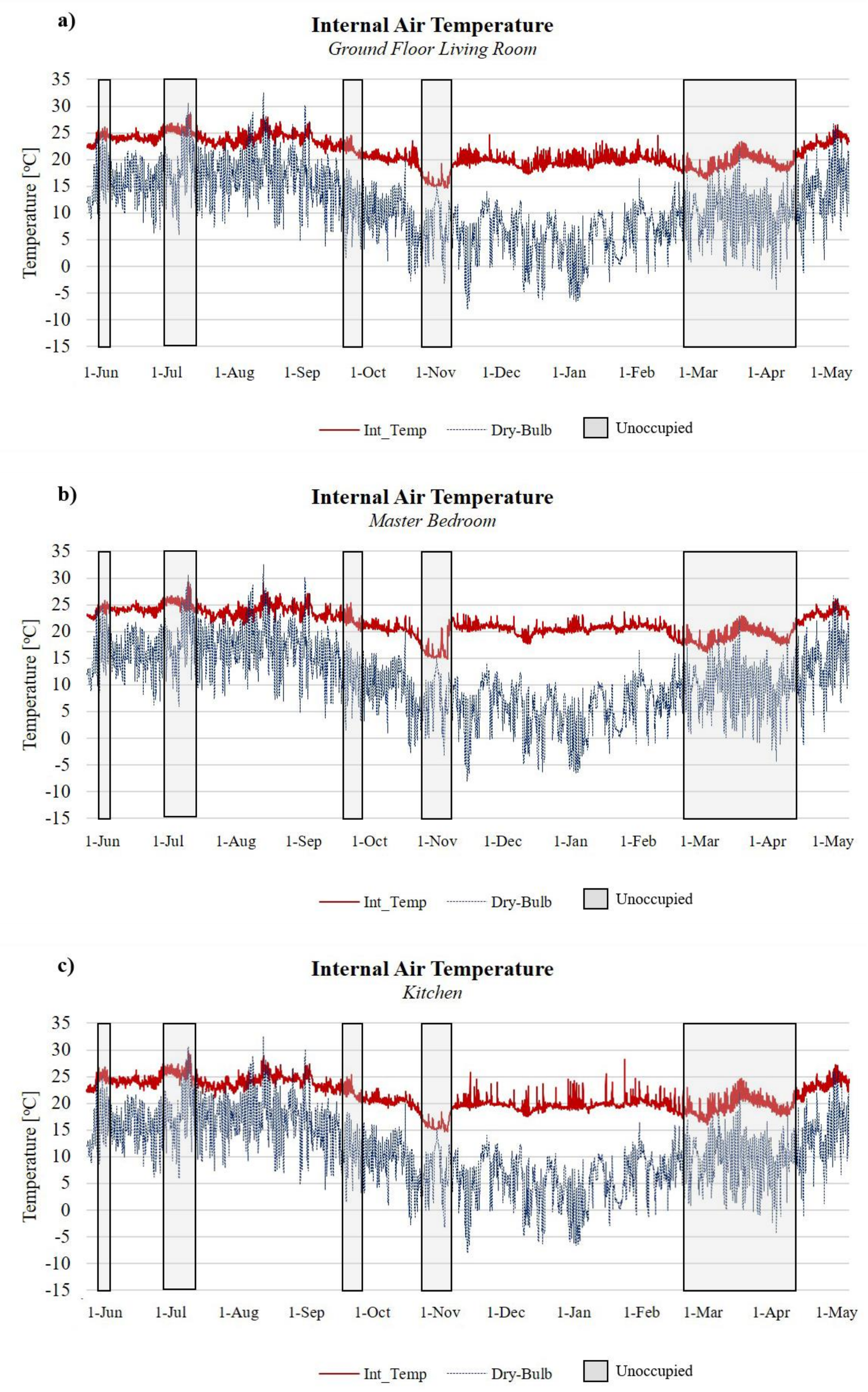


Figure 4.19 *Internal air temperature and outside dry-bulb temperatures: a) ground floor living room, b) master bedroom and c) kitchen (June 2016 to May 2017).*

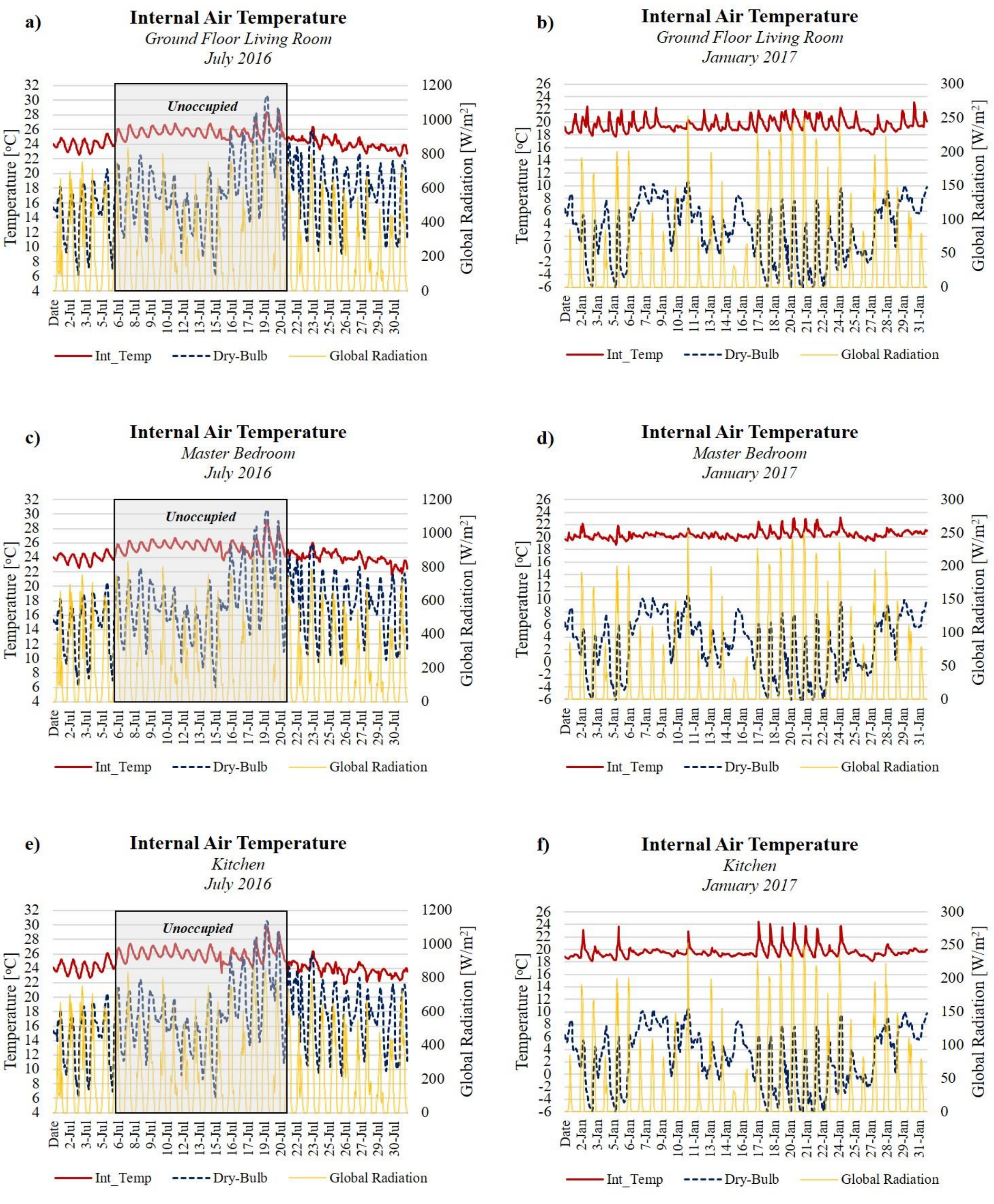


Figure 4.20 *Diurnal internal air temperature variations, outside dry-bulb temperatures and global radiation: a) ground floor living room, July 2016, b) ground floor living room, January 2017, c) master bedroom, July 2016, d) master bedroom, January 2017, e) kitchen, July 2016 and f) kitchen, January 2017.*

4.3.4 EFFECT OF FABRIC PERFORMANCE ON DECREMENT FACTOR AND DECREMENT DELAY

To investigate the ICF fabric performance and its ability to provide a stable internal environment, two dynamic characteristics were analysed, the decrement factor (D_f) and the decrement delay (ω) (as stated in Section 2.2.1). The higher the thermal inertia of the fabric, the smaller the decrement factor. Moreover, the higher the thermal inertia of the fabric, the higher the decrement delay. Fig.4.21 shows the daily value of the D_f and ω, as calculated based on the monitoring results, for the ground floor living room. Fig.4.21a shows that the average D_f was around 0.2 during the whole year, particularly during warm and moderate weather. During cold months the D_f was higher, with a higher spread among the daily values.

The decrement delay of the fabric, as shown in Fig.4.21b, showed a high range of variation throughout the whole year, with an average value of one-hour delay between the time of the maximum external and internal air temperatures occur. The decrement delay is calculated based on the time of the peak internal and external temperatures within the day (as stated in Section 2.1.1). Apart from the thermal storage capacity of the fabric, it is very much influenced by changes that occur in the boundary conditions (i.e. solar radiation, internal gains, mechanical and natural ventilation, infiltration etc.). The high range of variation in the calculation of the daily decrement delay in Twiga Lodge indicates that no solid conclusions can be drawn on the slow (or quick) response of the fabric to changes in surrounding environment.

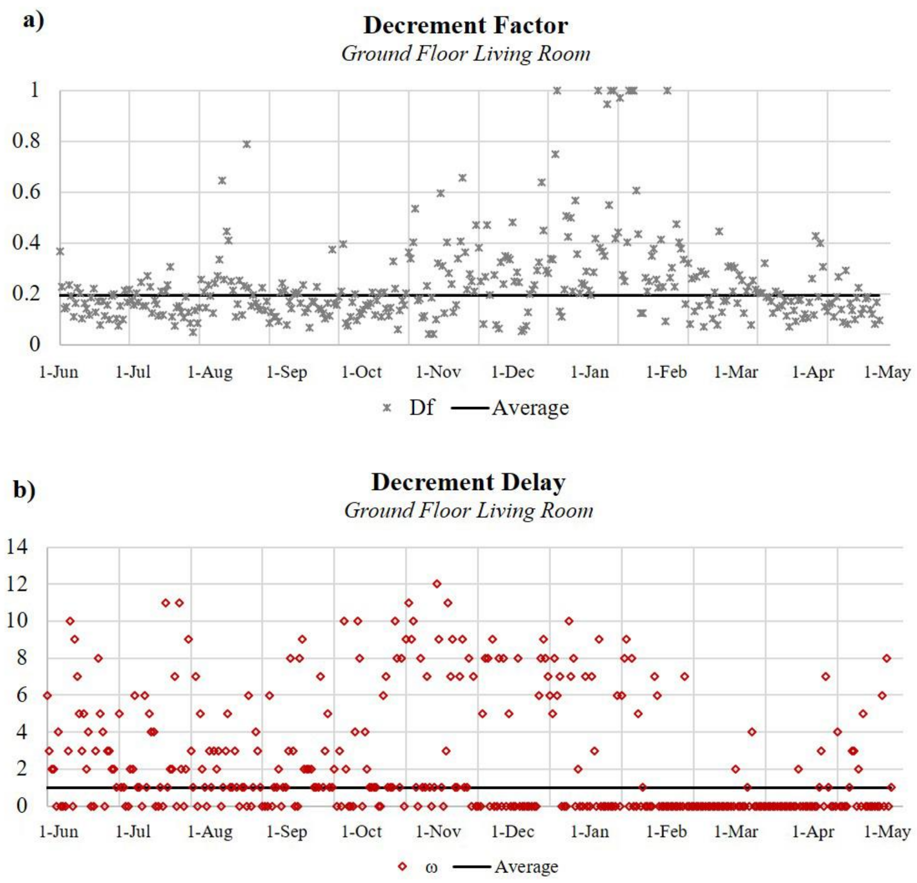
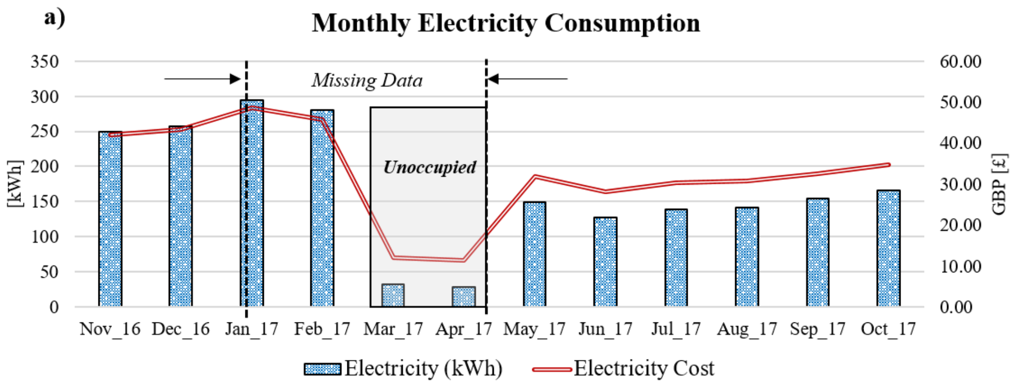


Figure 4.21 *Dynamic characteristics of the building fabric. Daily values and yearly average for: a) decrement factor (D_f) and b) decrement delay (ω) as calculated based on monitoring results for dry-bulb temperature and internal air temperature of ground floor living room, (June 2016 to May 2017).*

4.3.5 ENERGY CONSUMPTION

Fig.4.22 shows the total energy consumption of the building for a whole year (November 2016 - October 2017) in terms of electricity and gas usage. There were some missing data from the monitoring study on electric consumption between January 2017 and April 2017. For that period, information was provided by the occupants based on meter readings. Moreover, the house was unoccupied during March and April 2017. The results of the electricity consumption (Fig.4.22a) showed that, during cold weather, the monthly electricity usage was between 250kWh and 300kWh and during warm weather between 125kWh and 150kWh. Based on the electricity provider's charges, this translates to a cost of £45 - £55 (including standard charges) during winter and an average of £25 per month during warm and moderate months. The total annual electricity consumption of the house was calculated to be 2015kWh (£391). The average annual electricity consumption in a typical UK household is calculated to around 3,828 kWh (BEIS, 2018).

With regard to the gas usage (Fig.4.22b), the monthly consumption was between 1000kWh and 1500kWh during winter, with a maximum of 2000kWh in January, the coldest month. During warm and moderate weather there was no heating demand and gas was only used for DHW; the average consumption was around 450kWh. The gas consumption translates to a cost of £50 - £80 during winter and an average monthly cost of £20 for the rest of the year. The total annual gas consumption of the building was 8425kWh (£430). The average annual gas consumption in the UK domestic sector is calculated to around 12,609 kWh (BEIS, 2018).



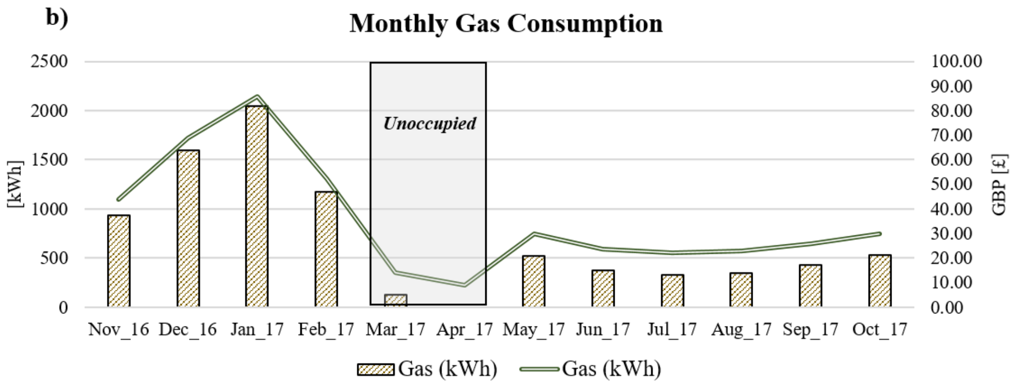


Figure 4.22 *Monthly breakdown of building's energy consumption for a year (November 2016 to October 2017). The primary vertical axis on the left illustrates the usage in kWh and the secondary vertical axis on the right the cost in GBP: a) electricity consumption, b) gas consumption.*

Fig.4.23 shows the daily gas consumption for the building for space heating and DHW. During winter, the daily gas consumption varied between 30kWh and 60kWh, with an average of 35kWh. During moderate and warm weather there was no heating demand and all gas usage was attributed to DHW, which was calculated to an average of 20kWh per day throughout the whole year. Fig. 4.24 shows the daily electricity consumption of the MVHR system. During winter, the electricity consumed by the MVHR unit varied between 0.1kWh and 0.9kWh per day (with an average of 0.45kWh). During moderate and warm weather, the electricity consumption of the MVHR system was somewhat more stable, at around 0.45kWh per day. The daily energy consumption of the building for space heating (including the electricity consumption of the MVHR unit) was an average of 35.45kWh per day during the cold period. This translates to a specific heating demand of 0.13kWh/m^2.day. Assuming the heating period lasts between November and February, the annual specific heating demand of the building is around 15.6kWh/m^2.yr, which is indeed very close to Passivhaus standard (i.e. Specific Heating Demand ≤ 15kWh/m^2.yr (Passivhaus, n.d.).

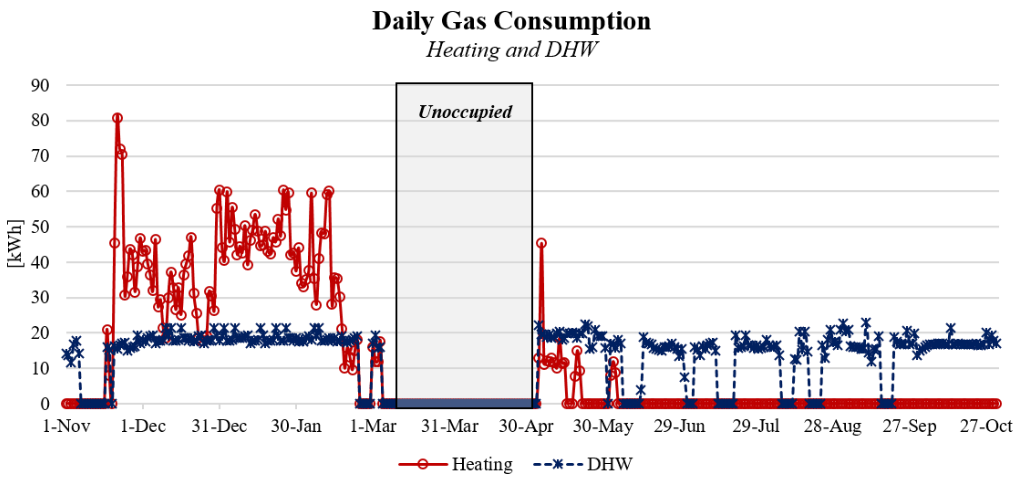


Figure 4.23 *Daily breakdown of gas consumption for a year (November 2016 to October 2017). Energy used for heating and DHW.*

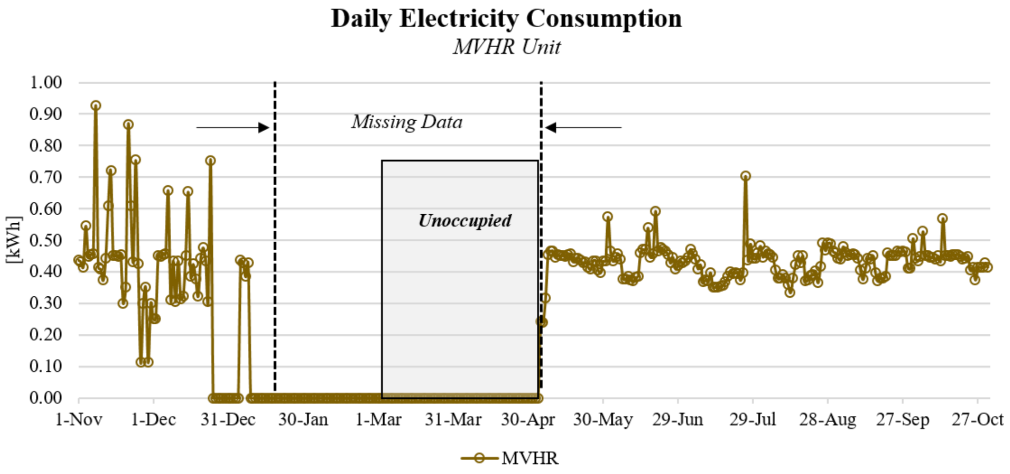


Figure 4.24 *Daily breakdown of MVHR electricity consumption for a year (November 2016 to October 2017).*

4.3.6 Summary

The monitoring study showed that the ICF building fabric of Twiga Lodge was able to moderate significantly the internal air temperature swings, providing a stable internal environment. The average internal air temperature was calculated between 22^{o}C and 25^{o}C during summer and around 21^{o}C during winter. The diurnal external temperature was found to fluctuate significantly during the whole year; however, the daily internal air temperature variations were significantly reduced during the whole of the year.

During summer, there were small differences in the daily internal air temperature of the three spaces included in the analysis. In winter, however, the shading devices were found to affect significantly the performance of the rooms. The zones without shading showed increased diurnal internal air temperature fluctuations during days with increased solar availability. Furthermore, the internal gains in the space had a significant impact on the daily diurnal temperature variation of the internal air temperature. More specifically, in the kitchen, where the internal gains are high, the daily fluctuation of the zone air temperature was higher during both summer and winter, compared to the other rooms.

The ICF fabric showed a decrement factor of 0.2 during the whole year that was found to be higher during winter months. Moreover, the fabric was found to delay the time of maximum internal air temperature by an average of 1 hour from the time of the maximum external air temperature during the whole year. Usually, high thermal mass structures delay the time that the peak internal temperature occurs by several hours compared to the time of the peak external temperature. One-hour delay indicates a relatively quick response of the fabric, usually representative of low thermal storage capacity. However, when looking at the spread between the different daily values of the time span, it becomes apparent that the decrement delay of the ICF fabric is very much influenced by changes in boundary conditions. Hence, no solid conclusions can be drawn on the slow (or quick) response of the fabric to changes in surrounding environment.

The findings of this WP addressed Objective No2 and showed that the ICF fabric dampened significantly the high external temperature swings, providing a stable internal environment. However, it should be acknowledged that there are several factors that could affect the thermal performance of a building, such as the magnitude of internal heat gains, the levels of ventilation, the design of the building and so on. For the specific case study and for the specific building operation, the results of this work package indicated a relatively steady internal air environment pointing towards the positive impact of the ICF fabric in moderating internal temperature swings. Moreover, the analysis of the building’s energy consumption confirmed that Twiga Lodge is indeed a low-energy building operating near to Passivhaus standards.

4.4 WORK PACKAGE 4: EMPRIRICAL VALIDATION OF ICF SIMULATION OUTPUT

4.4.1 SCOPE AND AIMS

The fourth work package of this EngD addressed **Objective No3** of the research. The purpose was: "To empirically validate, with the use of real monitoring data, the accuracy of BPS simulation results in calculating the thermal performance of ICF". The findings of the study were presented in a conference paper at Building Simulation (BS) 2017 (Appendix C) and are included in an article submitted to Energy and Building journal (Appendix D). The aim of this WP was to compare the predicted and actual thermal performance of an ICF dwelling (Twiga Lodge, as used in WP3) and to quantify the divergence between simulation results and monitoring data (if any).

4.4.2 OVERVIEW OF WORK PACKAGE

The analysis presented in this study was focused initially on internal air temperatures and subsequently on heating energy consumption. As a first step, the house (Twiga Lodge) was analysed under a transient state in an unoccupied (07/07 to 13/07) and an occupied (24/07 to 30/07) period. Two simulation models were created using EnergyPlus[13] and ESP-r[14] BPS tools. Both tools are open-source, freeware commonly used in industry and academia. They both offer significant flexibility to the user though changing from default to advanced settings and they showed an overall good consistency in their simulation predictions for the single-zone test case ICF building during the initial inter-modelling comparison. Since there are no proprietary issues associated with these tools, there was no need to anonymise their results. Monitored internal air temperature data were plotted against simulation predictions. The aim of this first step was to

[13] EnergyPlus™ is a whole building energy simulation program developed in the Department of Energy (DOE) in USA. Available at: https://energyplus.net/ [accessed on: 27/04/18].

[14] ESP-r is a whole building energy simulation program developed at Department of Mechanical Engineering at the University of Strathclyde in UK. Available at: http://www.esru.strath.ac.uk/Programs/ESP-r.htm [accessed on: 27/04/18].

investigate the inconsistencies in the simulation results provided by the two BPS tools and the divergence between simulation and reality. At first, benchmarks regarding the building's operation and occupancy schedules were used from the National Calculation Method (NCM)[15], along with the Typical Meteorological Year (TMY) climate file from the nearest weather station (Gatwick Airport). The aim was to identify any issues a modeller would face in the lack of real input data (i.e. assuming they were at an early stage of design). Then, information from the monitoring study was used as input values in the models to represent the actual operation of the building as accurately as possible. The purpose was to reflect on the importance of using accurate and appropriate input values when simulating a building.

Following this step, the analysis focused on two periods when the house was unoccupied, one week in the summer of 2016 (07 – 13 July 2016) and one week during spring of 2017 (14 – 20 April 2017[16]). The rationale was to investigate how the fabric would perform (with regard to internal air temperatures) under a free-floating mode, without the influence of other parameters (such as HVAC operation, mechanical ventilation, occupancy etc.). Information from the monitoring project was used as input values for the simulation model of the building case study, which was created using EnergyPlus v8.6 (US DOE, n.d.). The ground floor living room was selected for the analysis. The room is oriented to the South and has a large opening on the South wall (without shading) and two more windows on its East and West walls (see Fig.1 in Appendix D). The analysis of heating gas energy consumption was performed for the whole heating period between November 2016 and February 2017. Between March and beginning of May 2017 the house was unoccupied.

[15] NCM is a procedure for demonstrating compliance with Building Regulations. Available at http://www.uk-ncm.org.uk/ [accessed on: 27/04/18].

[16] The ambient temperatures during the month of April 2017 were low enough to consider this period as a representative winter period.

The Coefficient of Variation of the Root Mean Square Error (CV-RMSE) and the Mean Biased Error (MBE), as defined in Section 3.3.4.1, was used to investigate the divergence between monitoring and simulation results. To date, there is no standard methodology available to calibrate a model in terms of indoor air temperatures (Coakley et al., 2014). As discussed in Section 2.3.5 of Chapter 2, the International Performance Measurement and Verification Protocol (IPMVP) and ASHRAE Guideline 14 provide some criteria for determining whether a model is calibrated, yet these are applicable only in the case that energy use is assessed.

4.4.3 Comparison of Actual and Predicted Performance

The analysis conducted as part of the paper in Appendix C used information from the monitoring study (see Section 4.3) to empirically investigate the ICF fabric performance, and to validate the accuracy of two BPS tools predictions when modelling ICF. The results indicated that there was very good consistency in the predictions provided by the two BPS tools for all investigated scenarios (i.e. occupied/unoccupied periods, different spaces, benchmarks/real input data). However, looking at the divergence between simulation and reality, it became apparent that there was a significant gap when the modeller uses benchmark values in the specification of the building (i.e. occupancy patterns, climate data, ventilation rates etc.), thus highlighting the significance of calibration and showing the importance of updating post occupancy simulation models with real input data.

At this point it is imperative to acknowledge that the purpose of benchmark values and compliance modelling tools is not to develop an accurate prediction of reality or an accurate calculation of buildings' energy consumption. Instead, the aim is to ensure that buildings are assessed in a fair and consistent way, using a common framework for the evaluation of alternative design options (Raslan, 2010). The use of compliance modelling is limited to determine the performance of the building in a given set of predefined conditions of use, restricted to the approved calculation methodology. In other words, benchmark values and compliance models are used for comparison, rather than absolute predictions (CIBSE AM11, 2015; DCLG, 2015; DCLG, 2016).

The comparison between occupied and unoccupied periods showed that the uncertainty introduced by the occupants in this case study had an insignificant influence on the simulation results. However, no wider conclusions should be drawn from this finding, given that the results come from a single case study.

When the house was running in free floating mode (unoccupied periods) there was very good consistency between monitoring results and simulation predictions. The analysis is thoroughly presented in Section 3.1 of the paper in Appendix D. The general observation was that the simulation model was able to predict accurately the amplitude of daily temperature swings during both summer (Fig.4.25) and spring (Fig.4.26) (RMSE = 0.25^{o}C and RMSE = 0.45^{o}C, respectively).

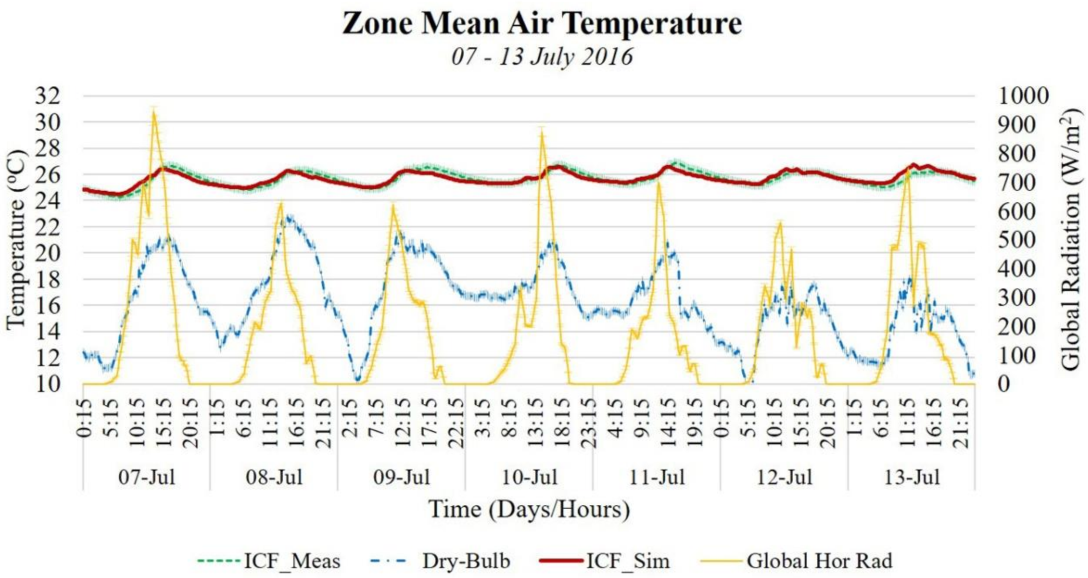


Figure 4.25 *Empirical Validation of ICF simulation results. Monitoring results on zone mean air temperature, dry-bulb temperature and global radiation. Warm period analysis for the unoccupied week 07 – 13/07/16.*

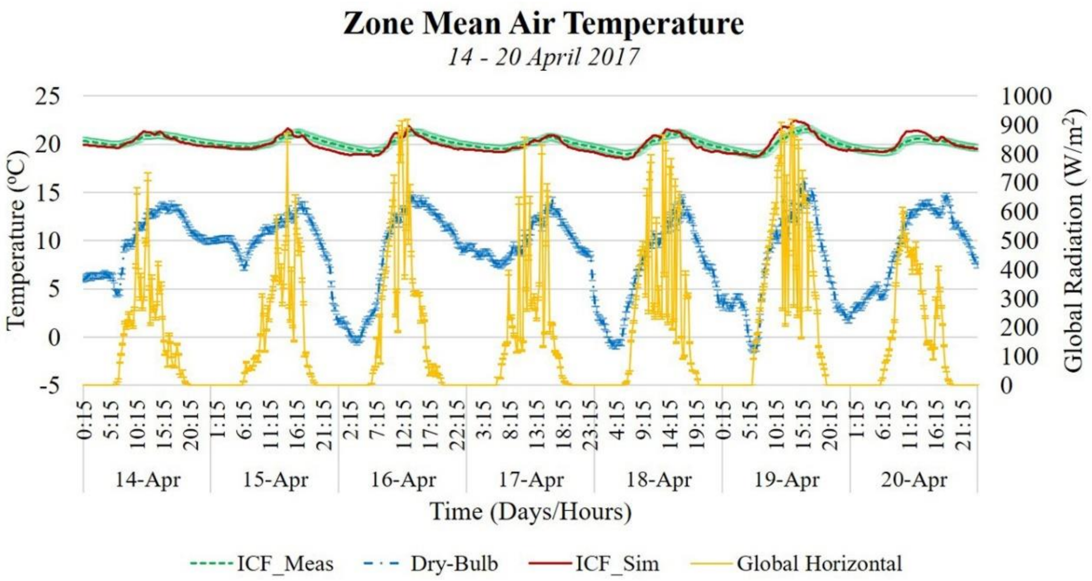


Figure 4.26 *Empirical Validation of ICF simulation results. a) Monitoring results on zone mean air temperature, dry-bulb temperature and global radiation. Cold period analysis for the unoccupied week 14 –20/04/17*

However, in cold spring period the peaks of the maximum internal air temperature were slightly over-estimated by the model compared to the monitoring results, resulting in a higher decrement factor (c.40% higher average D_f provided by the simulation model in comparison to reality). Moreover, the simulation results under-estimated the decrement delay during both warm and cold periods under investigation (62% lower ω is estimated by the model compared to reality in summer and c.33% lower ω is predicted during spring).

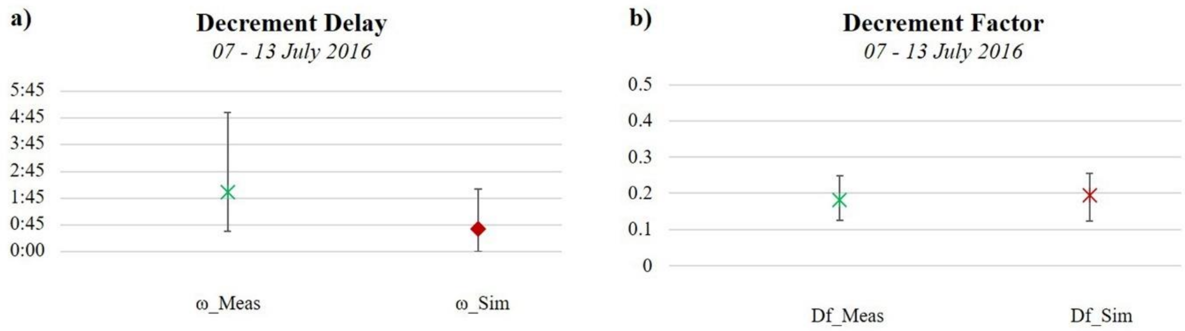


Figure 4.27 *Dynamic characteristics of the ICF fabric, as calculated based on monitoring results and simulation predictions for the summer unoccupied week 07 –13/07/16; a) Decrement Delay, b) Decrement Factor.*

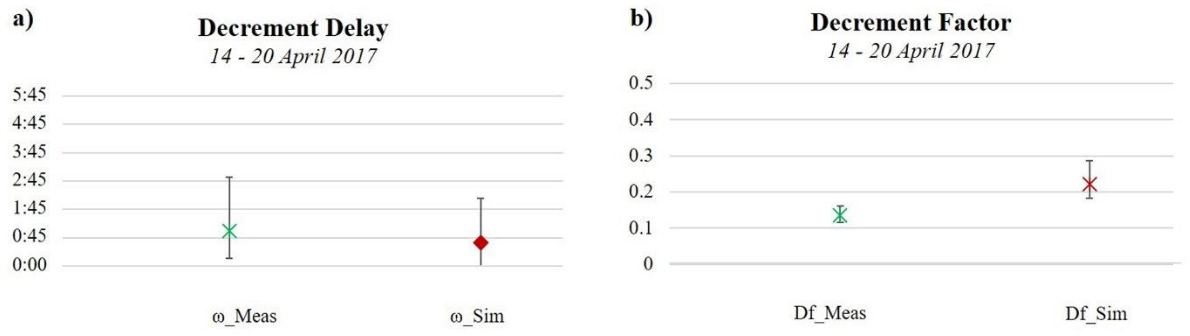


Figure 4.28 *Dynamic characteristics of the ICF fabric, as calculated based on monitoring results and simulation predictions for the spring unoccupied week 14 –20/04/17; a) Decrement Delay, b) Decrement Factor.*

Fig.4.29 illustrates the daily heating energy consumption of the building between November 2016 and early March 2017, as measured on site and as predicted by the simulation model. The daily heating demand is plotted for the whole heating season (as recorded by the monitoring campaign and as predicted by simulation), representing, when adding the daily values, the whole annual heating energy consumption. The error between simulation and reality was found to be very low and equal to RMSE = 0.6kWh (with a CV-RMSE = 1.93%), indicating that the model was able to predict the energy consumption of the building accurately. The results showed that the simulation model tends to over-estimate the energy consumption of the building by MBE = 3.44% in comparison to reality.

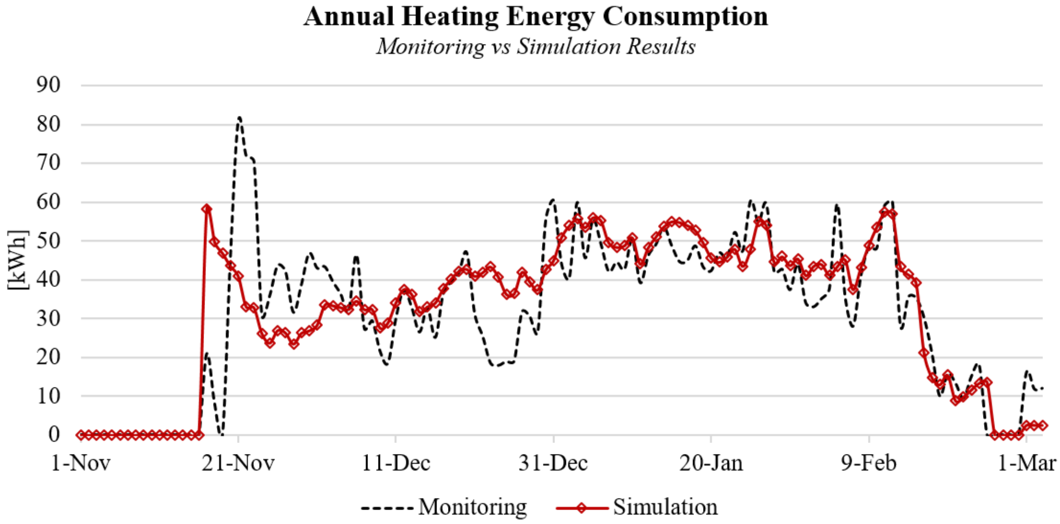


Figure 4.29 *Empirical evaluation of ICF thermal performance. Monitoring results on annual heating gas energy consumption. Heating period analysis between November and March 2017.*

4.4.4 SUMMARY

The empirical validation of the simulation results for the ICF building case study showed that once the model was calibrated with information from the monitoring study, there was good consistency between predictions and reality for both the internal air temperatures and the heating energy consumption. Similarly to findings of previous studies (De Wilde, 2014; Coakley et al., 2014; Fumo, 2014), the analysis of indoor air temperatures, when utilising typical weather data and inputs from the NCM, showed that the selection of appropriate input data has a significant impact on the accuracy of the simulations. The NCM activity profiles are used to define the occupancy schedules, temperature setpoints, ventilation rates and internal heat gains from equipment and lighting for each space type in a consistent basis, allowing that way to compare the difference in buildings' energy performance based on their geometry, construction, building services, regardless of how they may actually be used in practice (DCLG, 2015). Nevertheless, there are several recognised issues associated with the use of NCM activity schedules. In some cases, these profiles are unrealistic. For example, the NCM profile for UK school occupancy assumes a building which is occupied throughout the year, even during mid-terms and summer period (Blight, 2015). Another known issue of the NCM activity database is the steep change in internal heat gains between periods of different occupation densities. In this research, the comparison of NCM activity schedules and the actual recorded occupancy patterns indicated that the internal gains predicted by the NCM database were higher than the actual recorded internal heat gains (with the exception of occupant gains where the NCM underestimated them). In addition, it was observed that the differences between the two datasets regarding ventilation rates had a profound impact on the results. The actual ventilation rates during the monitoring period were found to be much higher than those calculated from NCM, the latter being specified according to the space activity and solely for the occupied periods.

The level of uncertainty introduced in the model due to occupancy resulted in a slightly increased divergence between simulation results and measured data, however it was minimal (RMSE<1°C difference between simulation predictions and recorded temperatures). When the house was running in free-floating mode (unoccupied periods), an even better consistency was achieved in the simulation and monitoring results. An RMSE = 0.25°C was observed between simulated predictions and recorded values during the summer unoccupied period, which was slightly increased to RMSE=0.45°C during cold unoccupied period. Moreover, there was a very good consistency between measured results and simulation predictions for the decrement factor D_f of the fabric during the summer unoccupied period (the percentage difference between average measured Df and the average simulated Df was c.2%). However, in spring a c.40% higher decrement factor was estimated by the model in comparison to reality. The simulation results under-estimated the decrement delay during both warm and cold periods under investigation, indicating a shortcoming of the models.

This study contributed to Objective No3 of this research and showed that when an ICF building is correctly represented in BPS, then the BPS models are able to predict the thermal performance of the building with a good accuracy. While there was a discrepancy in the calculation of the fabric's dynamic characteristics (decrement factor D_f and decrement delay ω), the simulation models showed an overall good representation of reality with regards to diurnal temperature variations. Considering both internal air temperatures and annual heating gas energy consumption, the results indicated that the model can be regarded as calibrated according to the acceptance criteria, as stated in ASHRAE Guidelines 14 (ASHRAE, 2014).

4.5 WORK PACKAGE 5: UNCERTAINTY AND SENSITIVITY ANALYSIS ON THE THERMAL PERFORMANCE OF THE ICF WALL ASSEMBLY

4.5.1 SCOPE AND AIMS

The following work package was conducted to address **Objective No4**: "to evaluate the level of uncertainty and the sensitivity of the model in the representation of ICF in BPS, when considering the physical uncertainties of the wall material properties". Uncertainties in material properties are inevitable in BPS simulation (Hopfe, 2009). Published values on material properties are usually provided by manufacturers, yet these properties are rarely an accurate representation of reality; they can change over time, due to moisture content, time degradation etc. Hence, it is of great importance to account for physical uncertainties in BPS and their use can eventually increase the quality assurance of the simulation predictions. The findings of this study were submitted to *Energy and Buildings* journal (Section 3.3 of the paper in Appendix D).

4.5.2 OVERVIEW OF WORK PACKAGE

Information from the monitoring project was used to calibrate the simulation model of the building case study, which was created using EnergyPlus v8.6 (US DOE, n.d.). Probabilistic simulation was performed on the calibrated model for the two unoccupied weeks, in 07-13 July 2016 and 14-20 April 2017. Monte Carlo-based global uncertainty analysis (i.e. Latin Hypecude Sampling- LHS) and the method of Morris[17] for sensitivity analysis (UA/SA) were adopted to determine the sensitivity of ICF to physical uncertainties (including the thermal mass of the wall). Further details of the methods employed for the UA/SA can be found in Section 3.3.4.2 (and in Section 3.3 of the paper in Appendix D).

[17] A uniform distribution with a constant range of variability ±20% of the mean value was assumed for each input parameter included in the Morris SA, as shown in this section.

4.5.3 UNCERTAINTY AND SENSITIVITY ANALYSIS IN PHYSICAL PARAMETERS

The results of the uncertainty analysis for the summer unoccupied week (Fig. 4.30a) indicate that the uncertainty in the prediction of zone mean air temperature, when accounting for the uncertain material properties of the exterior ICF walls, was small and equal to 0.5ºC. Similar findings emerge from the uncertainty analysis for the unoccupied week in April (Fig. 4.30b). The results indicate that the simulation models were able to predict the internal air temperature of the space with a relatively small deviation, despite any physical uncertainties present in the simulation. Moreover, the ICF construction has shown a good robustness in terms of internal air temperatures, regardless of any changes that might occur to its material properties due to time degradation, moisture penetration etc.

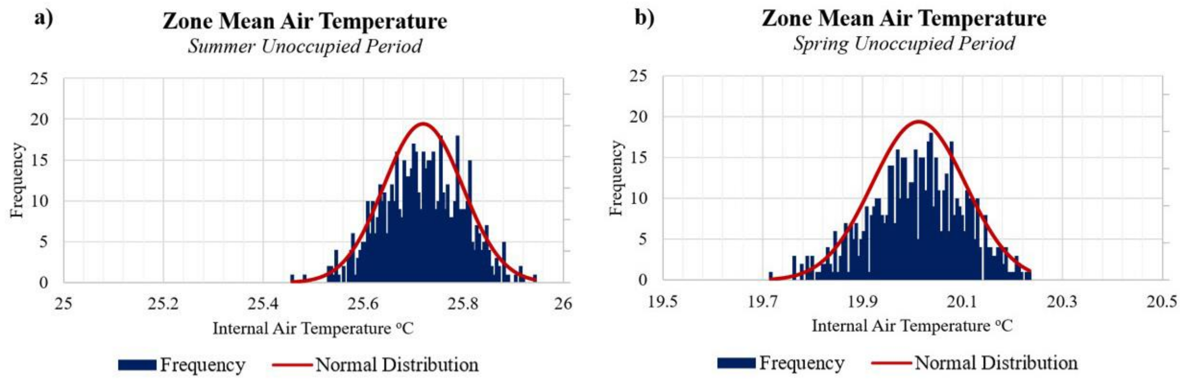


Figure 4.30 *Frequency and normal distribution of zone mean air temperature for: a) the summer unoccupied period, 07 – 13 July 2016, b) the spring unoccupied period, 24 – 20 April 2017.*

The results of the sensitivity analysis showed that, during the summer period (Fig. 4.31), the most significant parameters influencing the zone mean air temperature for the ICF building were the density, the specific heat capacity, the thickness of the concrete core, followed closely by the conductivity and the thickness of the internal insulation layer. In other words, the most important parameters affecting the internal air temperature of an ICF building during summer were the thermal mass of the concrete core and the thickness and conductivity of the internal insulation.

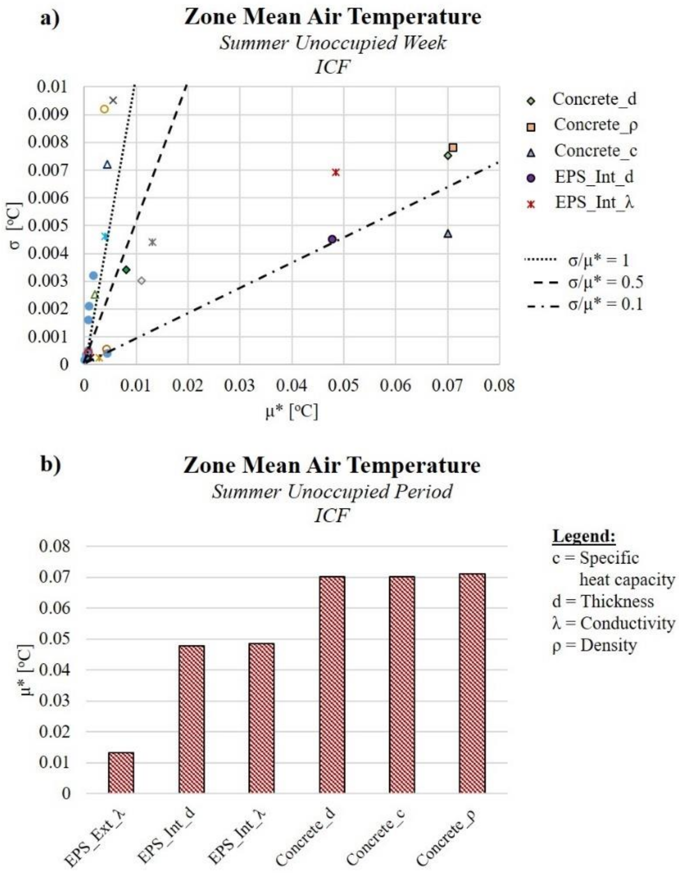


Figure 4.31 *Morris analysis of absolute mean (μ*) and standard deviation (σ) for mean zone air temperature, when considering uncertainty in external wall material properties during summer unoccupied week: a) ICF Morris plot, b) ICF sensitivity ranking.*

During the unoccupied week in April, the results of the sensitivity analysis (Fig. 4.32) showed that, for the ICF building, similarly to summer (Fig. 4.31), the zone mean air temperature was mostly affected by the properties of the concrete core (i.e. the density, the thickness and the specific heat capacity). Moreover, other influential parameters were found to be the conductivity of the insulation layers both internally and externally. The external insulation layer (which was found to have an insignificant effect on the zone mean air temperature during summer) was found to be among the most sensitive parameters affecting the internal environment during cold weather.

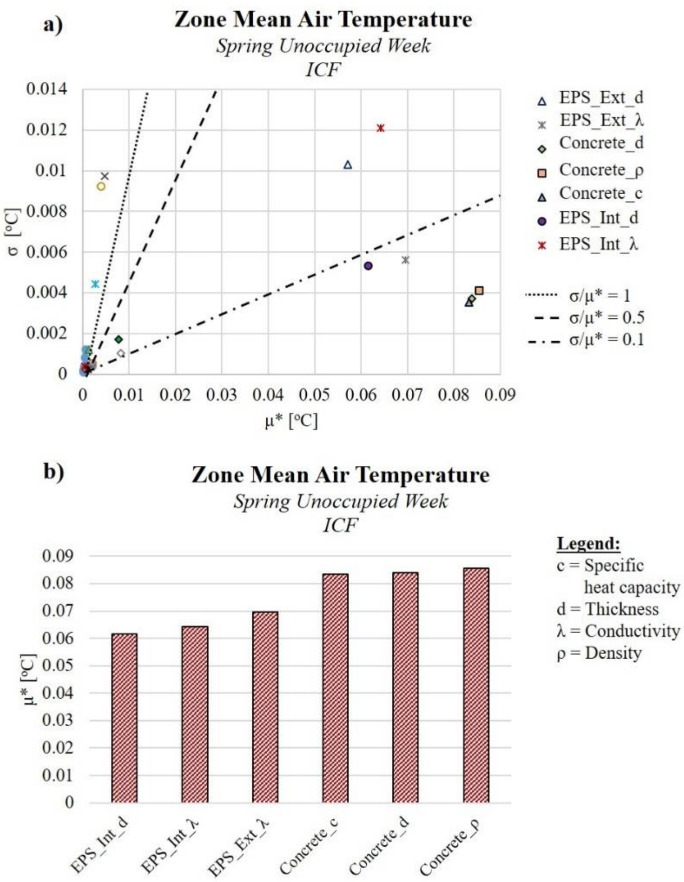


Figure 4.32 *Morris analysis of absolute mean (μ*) and standard deviation (σ) for mean zone air temperature, when considering uncertainty in external wall material properties during spring unoccupied week: a) ICF Morris plot, b) ICF sensitivity ranking.*

To verify the robustness of the SA results, the investigation was also performed based on Monte-Carlo regression analysis. A second sampling file was created for all the physical uncertain parameters of the wall construction using Latin Hypercube Sampling[18] (LHS). A total number of 1200 simulations were performed (i.e. 600 for summer and 600 for spring), and the results were interpreted for the SRRC[19] coefficient and plotted to examine if there are any significant differences between the LHS and the method of Morris. Fig. 4.33 shows that there

[18] For further information on LHS, please refer to Section 3.3.4.2.

[19] The Standardised Rank Regression Coefficient (SRRC) was used in the SA based on LHS, indicating the sensitivity of each parameter investigated. The higher the SRRC value the more sensitive the parameter (Hopfe, 2009).

was indeed good consistency between the two methods for the most sensitive parameters on internal air temperatures during both summer and spring. The specific heat and the thickness of the concrete core were again found to be the most significant parameters affecting the internal air temperatures. An advantage of the SRRC (Fig. 4.33) in comparison to Morris plots (Fig.4.31 and Fig.4.32) is that it also reflects on the impact of each uncertain parameter on the simulation output (i.e. zone mean air temperature). The negative values in the graph of Fig.4.33a indicate that as the specific heat and the thickness of the concrete and the conductivity of the internal insulation increase, the internal air temperatures are reduced. In contrary, when the thickness of the internal insulation increases, the air temperatures in the room also increase during summer. Similarly, during spring (Fig.4.33b), the thickness and the specific heat of the concrete show a negative effect on the zone mean air temperature (i.e. as the values of each parameter increase, the internal air temperature decreases), whereas the thickness of both the internal and external insulation layer are found to affect positively the output of the simulation on internal air temperatures (i.e. increasing the values of the parameters, increases the zone mean air temperature).

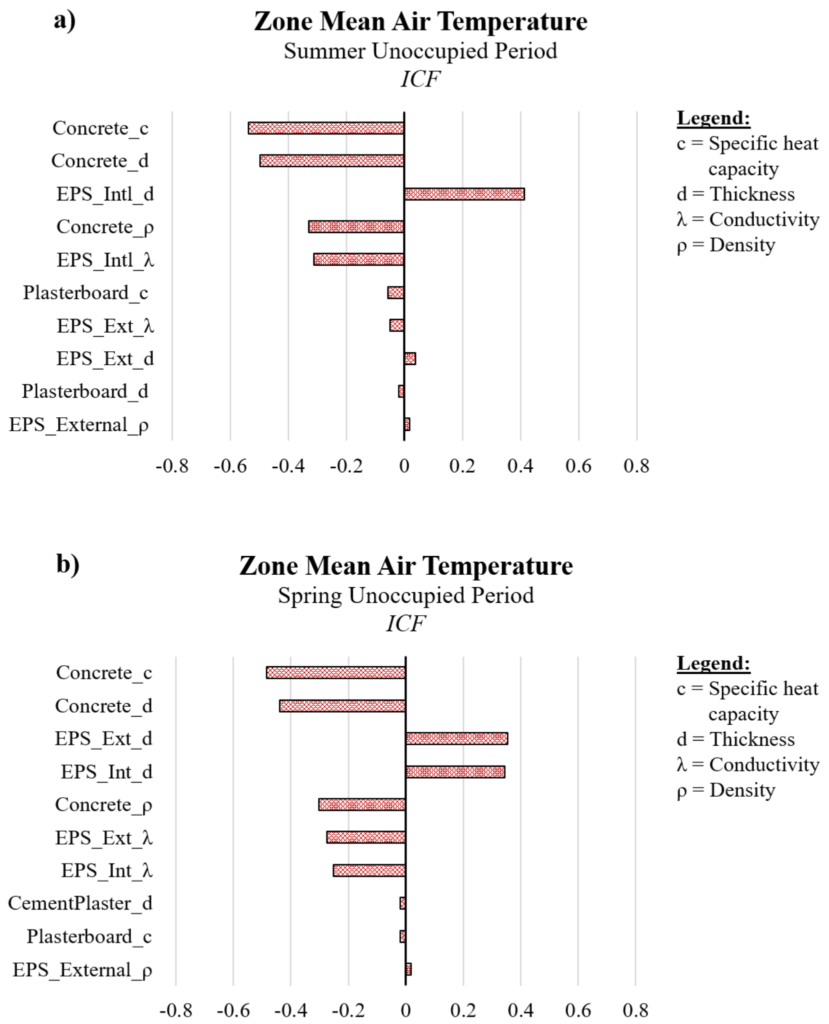


Figure 4.33 *Sensitivity plot showing the 10 most sensitive parameters based on zone mean air temperature when considering uncertainty in material properties of the wall*

4.5.4 SUMMARY

Addressing Objective No 4, the uncertainty analysis conducted as part of this research showed that the ICF building had very little variation in the simulation of internal air temperature, when subject to physical uncertainties (uncertain wall material properties) during both warm and cold weather. The range of uncertainty in the prediction of the zone mean air temperature was small (0.5^{o}C). The sensitivity analysis showcased the most effective wall layers and the most sensitive material properties to be modified for optimizing indoor temperatures. The SA was performed three times; the first two times using the method of Morris, but different distributions for the random variables, the third time using a Monte-Carlo-based regression analysis. The rationale of this decision was to enhance the robustness of the SA findings (i.e. comparing and cross-validating the results of two methods of analysis and of two different distributions and parameter ranges).

In the first Morris analysis, a normal distribution was used for the sampling of random variables, specifying the mean (μ) and standard deviation (σ) based on information from literature and existing knowledge (See Section 3.3.4.2). The second time a fixed ±20% uniform distribution was used for all unknown input values, to avoid introducing bias in the sensitivity ranking, due to the different magnitude of parameter ranges. The outcome of both Morris analyses was very consistent in terms of influential input parameters, regardless the distribution selected (i.e. normal distribution vs uniform) and regardless the magnitude of parameter ranges (variable ranges vs fixed relative range). The results of both tests indicated that among the wall material properties, the density, the specific heat capacity and the thickness of the concrete core were the most influential parameters with regards to the zone mean air temperature during both warm and cold weather. Other parameters that were found to have an impact on the zone mean air temperatures were the thickness and the conductivity of the internal insulation layer during summer, and the conductivity of both insulation layers during spring.

Furthermore, the Monte-Carlo-based regression analysis showed very consistent results with the method of Morris. There were only insignificant differences in the sensitivity rankings, showing that the thermal storage capacity of the ICF concrete core is not as thermally decoupled from the internal space as one would expect, and this does affect the internal air temperatures in the building. It is important to emphasise that both UA and SA are case-specific, so these results are highly dependent on the particular building and climate. Nevertheless, the cross-validated analysis performed in this project, using two methods of SA and two different distributions built up further confidence on the reliability of the results.

4.6 WORK PACKAGE 6: INVESTIGATING THE THERMAL MASS BENEFITS OF ICF USING CALIBRATED SIMULATION

4.6.1 SCOPE AND AIMS

The sixth and final work package of the research aimed to address **Objective No5**: "to investigate the thermal storage capacity of ICF concrete core and answer the question if ICF could be characterised as a thermally heavyweight or lightweight structure." More specifically, the purpose was to investigate how the thermal performance of an ICF building compares to that of a low and high thermal mass building. Consequently, the main aims of the sixth study were, to:

- Investigate the transient thermal performance of the ICF wall assembly.
- Assess how ICF compares to the other two construction methods (LTM and HTM) with regard to its thermal mass.

Moreover, the study aimed to build on the findings of the preliminary comparison conducted for a single-zone simple case study (see Sections 4.1 and 4.2). The purpose was to investigate if similar conclusions would derive regarding the comparative performance of ICF to LTM and HTM buildings in a more representative scenario. The findings of this study were submitted to *Energy and Buildings* journal and the article can be found in Appendix D.

4.6.2 OVERVIEW OF WORK PACKAGE

Three different wall constructions were compared among each other, ICF, high thermal mass (HTM) and low thermal mass (LTM). For ease of reference, these will be referred to as ICF, HTM and LTM from this point forward. The ICF calibrated simulation model was used as a basecase, and two more models were created, the HTM case and the LTM case. The only difference between the three models involved the construction of the external walls. The thermal transmittance of all construction elements (U-value) was kept constant across all three models to allow direct comparison of fabric thermal mass. Details of the material properties of all three wall constructions are included in Table A.1 in Appendix D.

A comparative analysis was performed on three building cases, focusing on internal air temperatures, on the decrement factor (D_f) of the fabric, the annual heating energy consumption and the internal surface temperatures and heat fluxes. The analysis of the internal air temperature and fabric performance (decrement factor) was conducted for two unoccupied weeks, in 07-13 July 2016 and 14-20 April 2017. More details can be found in Section 3.2 of the paper in Appendix D. The analysis of the heating energy consumption included the whole heating period between November 2016 and early March 2017. The heat flux analysis was done for two different three-day periods when the house was unoccupied, one in warm weather (15 – 17 July 2016) and one in cold weather (21 – 23 April 2017). Further information on the transient performance of the ICF wall can be found in Section 3.4 of Appendix D.

4.6.3 INTERNAL AIR TEMPERATURES

The comparative analysis of ICF, HTM and LTM buildings in terms of zone mean air temperature showed that the ICF building sits in between the other two construction methods and behaves closer to the HTM building during summer warm weather. As shown in Fig.4.34, the diurnal temperature variation in the ICF case was slightly greater than in the HTM building, with higher peaks of maximum air temperature. The diurnal temperature profile of the LTM building was similar to the other two construction methods, yet the internal air temperature in the LTM building increased by an average of 2°C. One would expect the diurnal temperature fluctuation of the LTM building to be higher than the other two construction methods and closer to the ambient temperature profile. However, based on the simulation results provided by the three models (Fig.4.34 below and Fig. 7 of Appendix D), the LTM building showed a similar dampening effect on the internal air temperature to the other two buildings. This finding can be partly attributed to the heavyweight ground floor, which was the same in all three buildings.

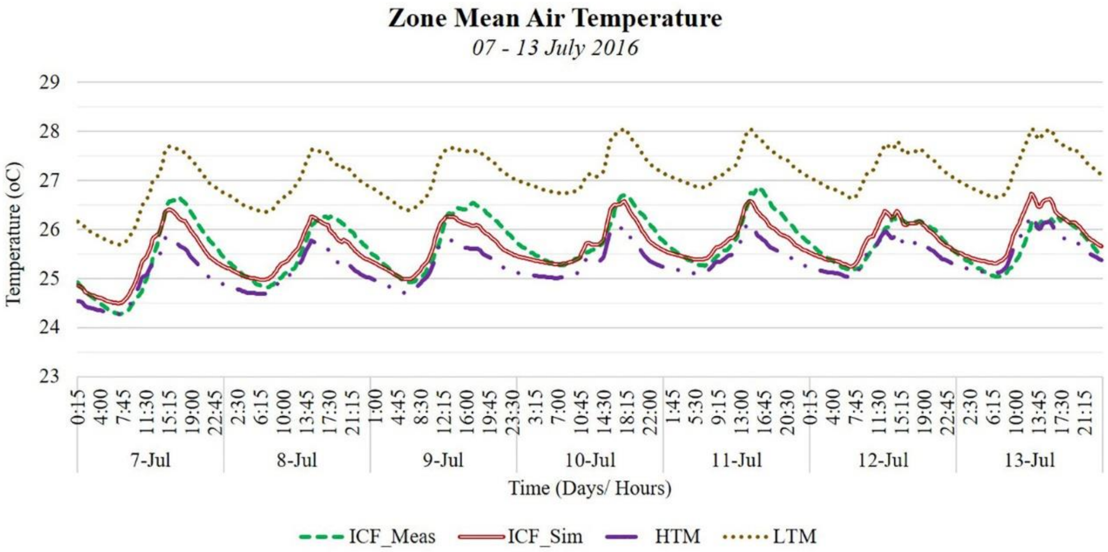


Figure 4.34 *Comparison of zone mean air temperatures between the three different construction methods for the summer unoccupied week 7 –13 July 2016. Simulation results for the ICF, HTM and LTM buildings plotted against measured data for the ICF building.*

The results of the analysis for the spring week (Fig. 4.35) showed that, during cold weather, the differences in the daily internal temperature profiles were insignificant for all three buildings. The LTM building showed a slightly increased internal air temperature compared to the other two buildings, yet the differences were negligible.

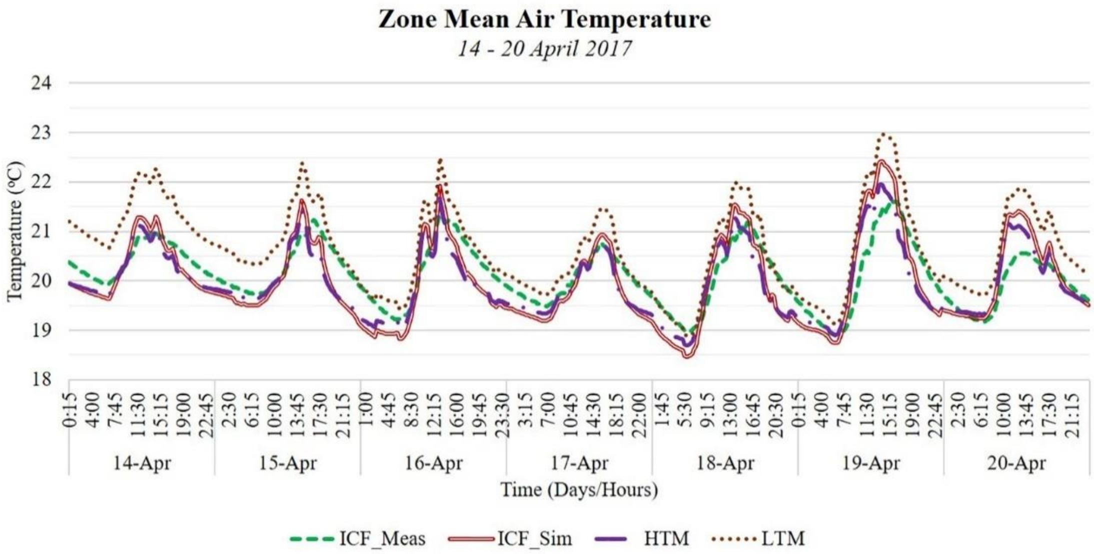


Figure 4.35 *Comparison of zone mean air temperatures between the three different construction methods for the spring unoccupied week, 14 –20 April 2017. Simulation results for the ICF, HTM and LTM buildings plotted against measured data for the ICF building.*

4.6.4 FABRIC PERFORMANCE

The comparative fabric performance of ICF to HTM and LTM cases was analysed based on the decrement factor of the three buildings for both periods under investigation (i.e. summer and spring unoccupied weeks). Based on the simulation predictions, Fig.4.36 shows that the ICF and the LTM building had almost the same decrement factor D_f during the summer week, ranging between D_f = 0.15 and D_f = 0.25. The HTM building showed a lower decrement factor, com- pared to the other two buildings, fluctuating between D_f = 0.10 and D_f = 0.21.

The decrement factor as calculated for the three different buildings cases, based on the simulation predictions, for the cold week in April (Fig.4.37), shows that the ICF and the LTM building had again almost the same decrement factor and the same range of variation throughout the week (i.e. between D_f = 0.18 and D_f = 0.3). The HTM building showed a lower average D_f compared to the other two construction methods, and a smaller range of variation (between D_f = 0.15 and D_f = 0.23).

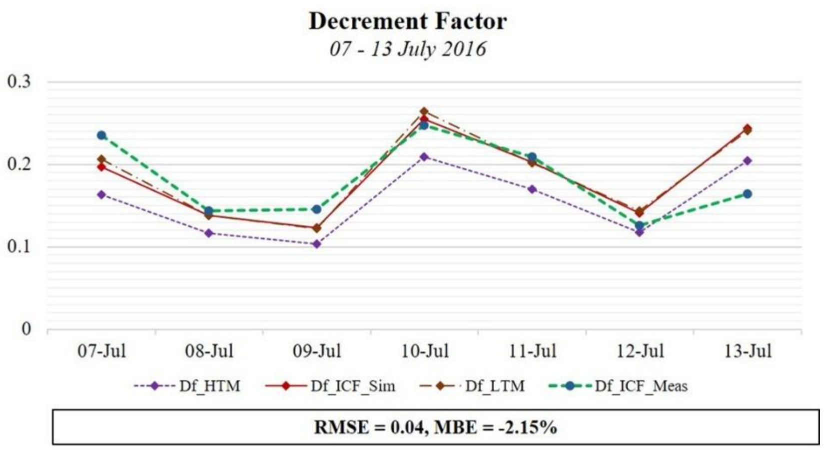


Figure 4.36 *Comparison of decrement factor for the three construction methods, ICF, HTM and LTM as calculated based on the monitoring results and simulation predictions for the summer unoccupied week 07 –13 July 2016.*

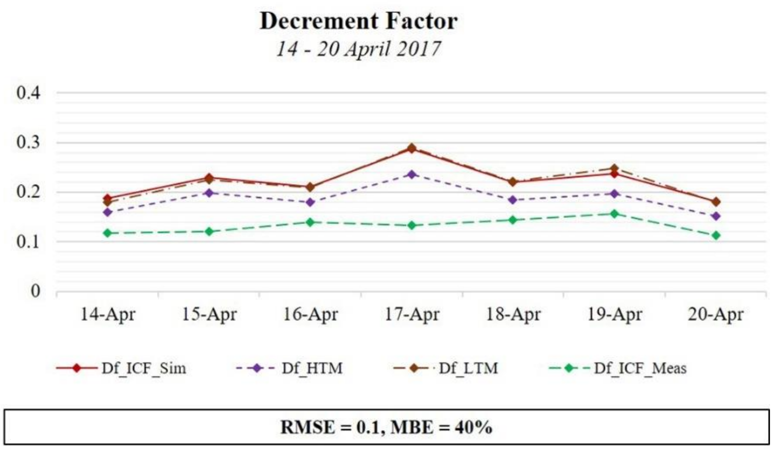


Figure 4.37 *Comparison of decrement factor for the three construction methods, ICF, HTM and LTM as calculated based on the monitoring results and simulation predictions for the spring unoccupied week 14 –20 April 2017.*

4.6.5 ENERGY CONSUMPTION

Fig.4.38 shows the annual heating energy consumption for the three building cases under investigation, ICF, LTM and HTM. The results indicated that similarly to the findings of the preliminary investigation (Section 4.1 - WP1), the energy consumption of the ICF building was in between that of the other two construction methods for most of the analysed period. The LTM building showed a slightly increased heating demand compared to the other two building cases. However, any differences between the three building cases were insignificant, in contrast to what was found for the single-zone building case study. This was expected, considering that the only difference among the three models was the construction of the external walls. In line with the aims of the study and in order to investigate the contribution of the ICF walls in energy savings, all other input parameters were kept consistent across the three models.

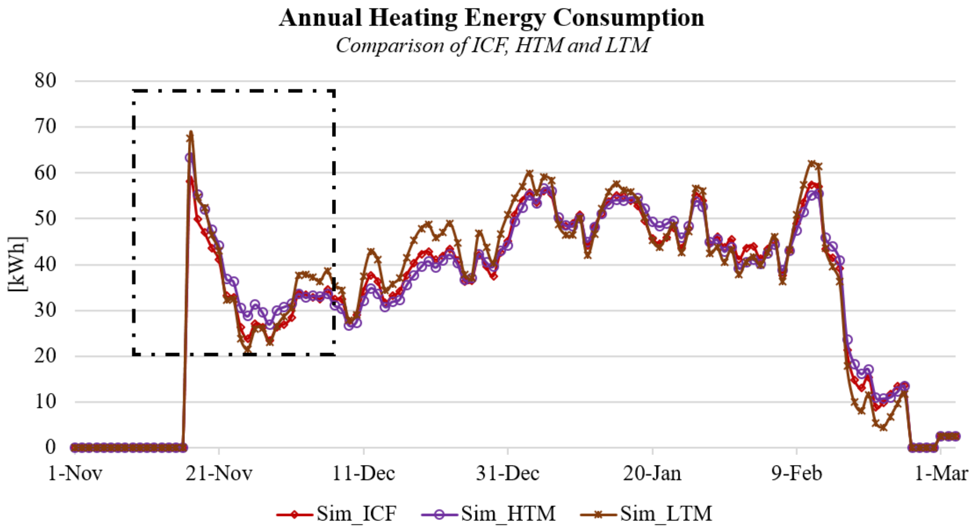


Figure 4.38 *Comparison of annual heating gas energy consumption between the three different construction methods. Simulation results for the ICF, HTM and LTM buildings for the whole heating period between November 2016 and early March 2017.*

The energy consumption of the ICF and the HTM buildings were generally similar throughout the heating period, apart from a two-week period in the beginning of the heating season, after the house was unoccupied (indicated in the dotted-line square in Fig.4.38). In these two weeks, the HTM showed an increased heating demand compared to the other two construction methods, showing the slow response and the extended heating up period of exposed thermal mass (a closer view of this period is illustrated in Fig.4.39). The ICF and the LTM buildings showed an equivalent quick response to indoor conditioning after the unoccupied period, which implies that the ICF (being internally insulated) could also exhibit some of the cited benefits of lightweight structures (Kendrick et al., 2012; Reilly & Kinnane, 2017).

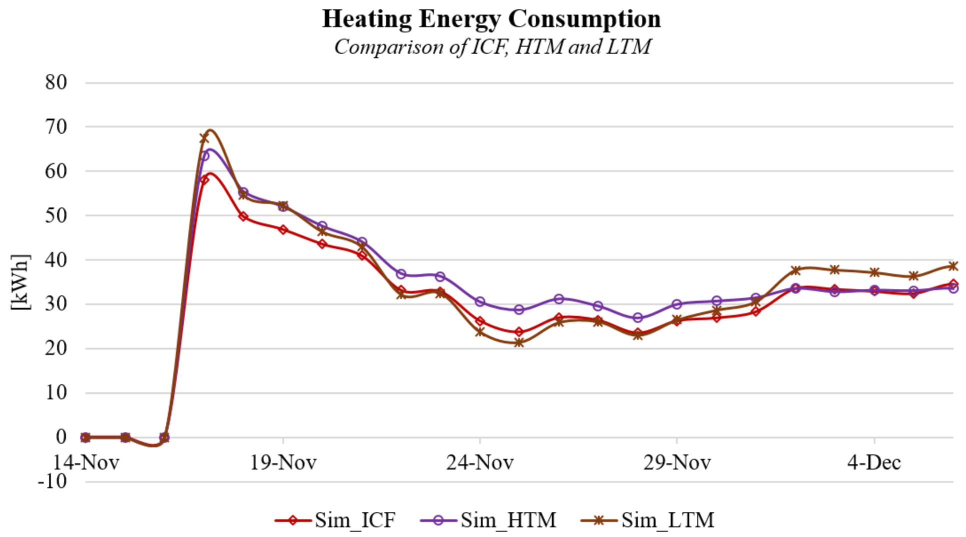


Figure 4.39 *Comparison of annual heating gas energy consumption between the three different construction methods. Simulation results for the ICF, HTM and LTM buildings for the heating up period in November 2016, after the house was unoccupied for two weeks.*

4.6.6 TRANSIENT HEAT CONDUCTION OF THE WALL

Section 3.4 of the paper in Appendix D investigated the transient performance of the three wall construction methods by analysing the internal surface and intra-fabric temperature and the internal surface conduction heat flow rate and energy.

Based on simulation predictions, Fig. 4.40 shows that the ICF building exhibited the lowest heat flux of all three cases with a consistent heat flow from the interior of the space towards the inside of the fabric. The HTM and the LTM buildings showed evidence of heat being disseminated from the wall to the internal space. In the HTM building (Fig.4.40b), the wall surface and intra-fabric temperature were almost the same with very little variation during the three days analysed. The zone mean air temperature fluctuated in a smaller range compared to the other two buildings. The heat flow was mostly from the internal space towards the fabric from midday until midnight. Some of this heat was released back into the space from midnight until the middle of the following day (evidence of the ability of the thermal mass to capture and store internal heat gains). The ICF and the HTM buildings showed a relatively stable intra-fabric temperature, around 16^{o}C and 18^{o}C respectively. In the LTM wall, the intra-fabric temperature (in the middle point of the wall's section) fluctuated by 12K, between 13°C and 25°C.

The LTM building showed increased heat flow rates compared to the ICF building. That was mainly a consequence of the increased fluctuations in the intra-fabric temperature of the LTM wall. The ICF concrete core showed a relatively constant temperature throughout the analysed periods due to its thermal inertia, acting as a buffer to heat flow both in and out of the space.

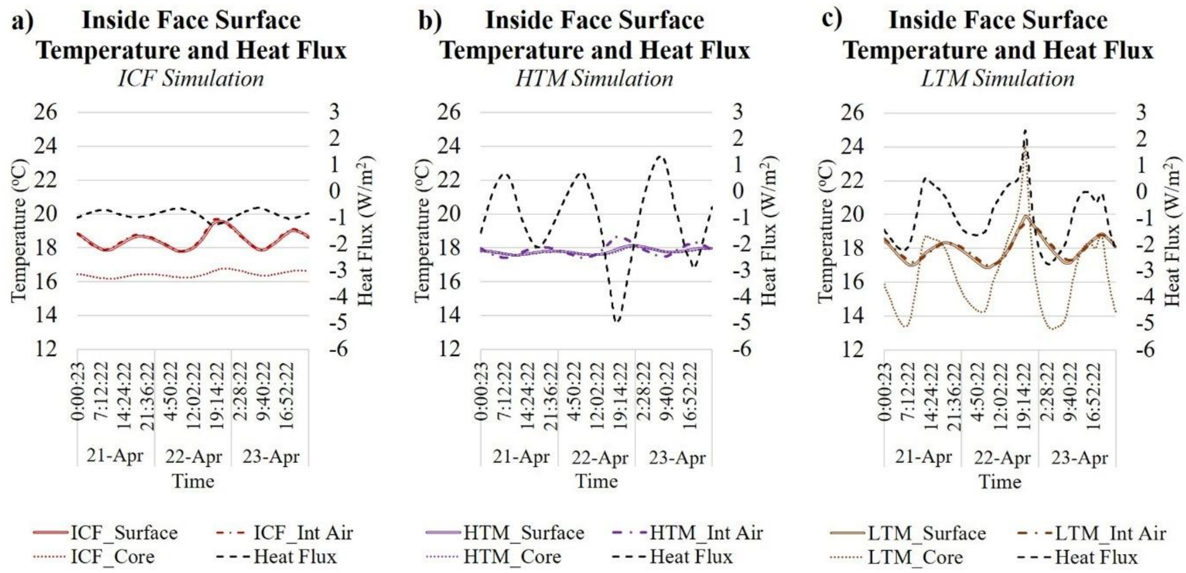


Figure 4.40 *Simulated inside surface, intra-fabric and internal air temperature plotted in comparison to inside face heat flux for three representative days of the cold unoccupied week, 21 –23 April 2017: a) ICF wall, b) HTM wall, c) LTM wall.*

Considering that the only difference among the two wall construction methods was the level of thermal mass (same U-value, same internal and external surface materials), any difference in the heat loss of the two walls can be attributed solely to the thermal storage capacity of the concrete core in the ICF wall assembly. This is clearly illustrated in Fig.4.41. The cumulative conduction heat losses from the inside surface of the LTM wall to the exterior for the whole analysed period were around 280Wh. For the same period, the ICF wall reduced the heat losses by 100Wh. Moreover, the LTM wall showed 30Wh of heat gains from the outside to the interior of the space, whereas the ICF wall showed no evidence of heat gains.

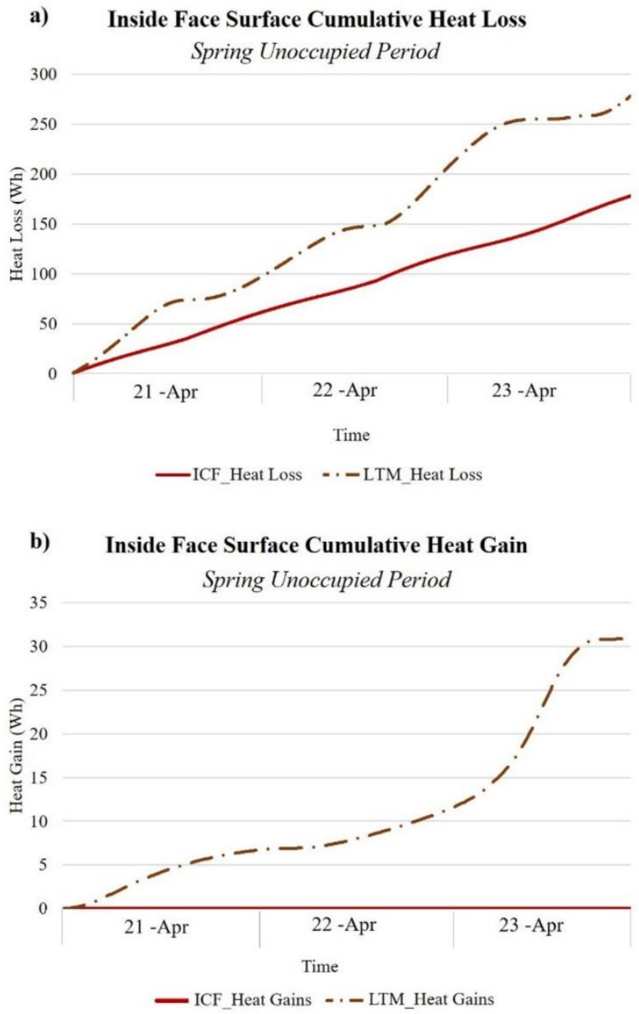


Figure 4.41 *Inside face surface cumulative conductive heat energy flow. Comparison of ICF and LTM walls for three representative days of the winter unoccupied period, 21 – 23 April 2017: a) Conduction heat loss from zone to the exterior, b) Conduction heat gain for the exterior to zone.*

4.6.7 SUMMARY

The comparison of ICF, HTM and LTM buildings confirmed the findings of previous studies (Kosny et al., 2001a; Hart et al., 2014; Mantesi et al., 2018) that the thermal performance of ICF sits in between the other two construction methods. The diurnal temperature variation of the ICF building showed slightly increased peaks of maximum in comparison to the HTM building but, overall, the two buildings performed very similarly. Surprisingly, the LTM building was found to have a diurnal temperature profile broadly similar to the other two construction methods, although one would expect it to reflect the daily variations of ambient air temperature. The decrement factor of the HTM building was the smallest of the three cases during both warm and cold weather. In the comparison of ICF to LTM building, ICF showed a decreased decrement factor during summer and almost the same value during spring.

The analysis of the heating energy consumption showed that the LTM had the highest demand among the three buildings whereas ICF and HTM showed a similar energy consumption. Overall, the differences in the heating demand of the three building cases were insignificant (contrary to what was found in the preliminary investigation conducted for a single-zone building). This could be explained since the only difference among the three models was the construction of the exterior walls. Everything else was identical, whereas in the single-zone case study the whole building construction was different. Moreover, the preliminary comparison was performed for a different climate (DRYCOLD), while the present comparison was performed for the UK climate as recorded on site.

In general, in both studies conducted in this project (i.e. single-zone test building and multizone ICF case study) the space was conditioned following a continuous heating profile. Implementing an intermittent heating profile might have affected the thermal performance of both buildings under investigation. The effectiveness of thermal mass is increased when connected to a continuous heating regime (Zhang & Cheng, 2018). In intermittent heating patterns, thermal mass could be disadvantageous compared to lighter construction methods. According to Mithrarante & Vale (2006) this is because during periods of no heating, the mass will lose all the stored heat to the surroundings and when heating is back on, apart from the air temperature that needs to be raised again, further heating will be required to raise the temperature of the mass surface itself. In fact, during a two-week period at the beginning of the heating season and following a period when that the house had been unoccupied, the HTM building showed an increased heating demand compared to the other two structures due to the slow response of the exposed thermal mass to changes in boundary conditions. The analysis showed that although the ICF building was found to act similarly to the HTM building (in terms of internal air temperatures and heating energy consumption over a long period), it also exhibited characteristics similar to the LTM building in terms of quick response to indoor conditioning.

The analysis of the transient thermal performance of the ICF wall showed low heat flow from the interior of the space to the exterior. The temperature difference between the ICF wall surface and the concrete core was always higher than the temperature difference of the wall surface and the internal air of the zone, triggering a consistent heat flow from the interior of the space towards the core of the fabric, which was found to act as a heat sink.

The analysis showed that the concrete core of the ICF wall was kept at a relatively constant temperature, acting as a buffer to heat flowing in and out of the building. In the comparison of ICF and LTM buildings, the concrete core of ICF resulted in reduced heat losses from the internal space towards the exterior environment. The comparison of ICF to the HTM building indicated that the internal insulation layer of the ICF reduced the admittance of the wall considerably and moderated its ability to capture and store internal heat gains during times of surplus. Consequently, depending on the use, the design and the location of the building, ICF could be more vulnerable to overheating compared to a HTM building.

Contributing directly to Objective No5, the results of this work package showed that ICF behaves in a broadly similar way to the HTM building. Although it is often thought of as an insulated panel acting thermally as a lightweight structure, the thermal mass of its concrete core affects the dynamic heat transmission of the wall and plays a significant role in tempering heat losses and gains to and from the exterior, moderating simultaneously the internal temperature swings.

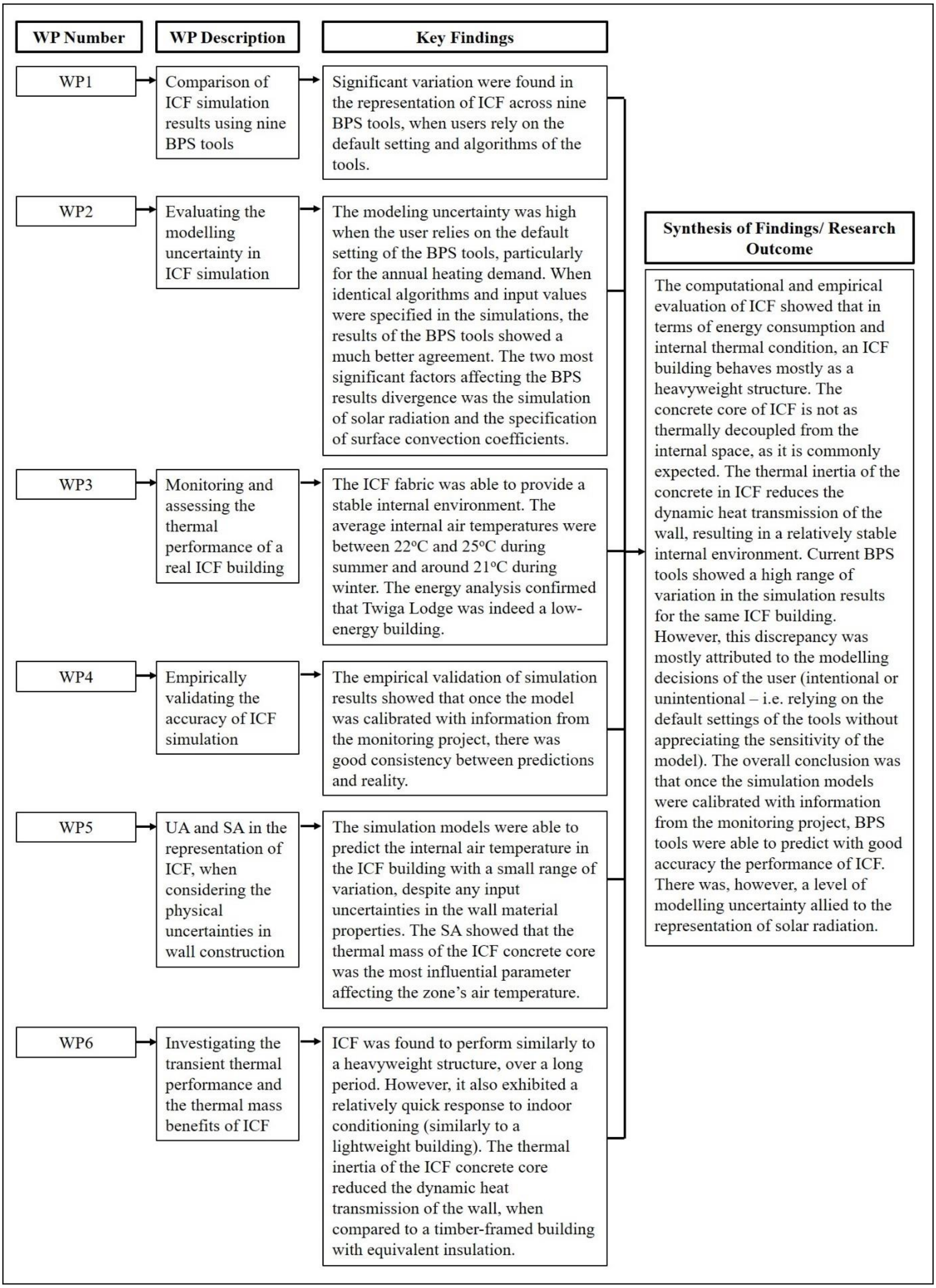


Figure 4.42 *Synthesis of research findings.*

5 FINDINGS & IMPLICATIONS

This chapter presents the main findings of this research project and summarises how the research aim and objectives were addressed and achieved. Moreover, the chapter discusses the academic implications of this research and makes clear the contribution to knowledge, to the industrial sponsor and the wider industry. Finally, it closes with a critical evaluation of the limitations and constraints of this work along with recommendations for future research.

5.1 THE KEY FINDINGS OF THE RESEARCH

The overarching aim of this EngD project was to analyse the aspects that affect the thermal performance of ICF construction method, to develop an understanding about the thermal behaviour of ICF and its response to dynamic heat transfer, and to investigate how the latter is affected by the inherent thermal inertia of the material's concrete core. This aim was achieved by undertaking six distinct work packages and addressing five specific research objectives. The key findings relating to each of these objectives are summarised below.

Review of existing knowledge and published literature around ICF.

The ICF wall construction method has several recognised advantages (i.e. strength, durability, speed of construction, among others). However, its thermal and energy performance is not yet well-researched and understood. A literature review was conducted to investigate the existing knowledge around the thermal performance of ICF and the energy saving benefits attributed to its inherent thermal mass due to the element's concrete core (see Chapter 2). This revealed that previous studies conducted on the thermal performance of ICF reached contradictory conclusions. Some projects showed that the contribution of ICF's thermal mass in energy savings was negligible (NAHB, 1999; Hill & Monsour, 2007), others showed that the existence of the concrete layer affected significantly the dynamic performance of the wall element (Gajda & VanGeem, 2000; Armstrong et al., 2011). Moreover, the literature review highlighted a significant limitation in existing knowledge; from a quantitative point of view, it was not so obvious, how to calculate the thermal mass of ICF. All previous studies were either theoretical computational analyses or measurements of test rigs built for purpose. The few studies that combined monitoring results to simulation predictions included information mostly on the transient heat transmission of the walls. None of these reflected on the internal thermal conditions and energy consumption of an existing occupied ICF building case study. This EngD research has adopted a holistic approach to investigate the performance of ICF by using both empirically validated simulation results as well as measured data from a real ICF building case study. Moreover, it is one of the few studies to evaluate the ability of current BPS in ICF simulation and the accuracy of ICF simulation predictions (Kośny & Kossecka, 2002; Mantesi et al., 2018). It is also the first study to reflect on the uncertainty and sensitivity of ICF simulation due to uncertainties in the material properties (and the thermal mass) of the wall assembly.

Objective No1: To test and evaluate common dynamic Building Performance Simulation (BPS) tools in predicting ICF thermal and energy performance, and to identify the key modelling uncertainties that are associated to ICF simulation.

An inter-model comparative analysis was performed to investigate the modelling uncertainty in the simulation of ICF for buildings. Various previous inter-model comparative studies have pointed towards the issues associated to predictive variability found between BPS tools (Neymark et al., 2002; Brun et al., 2009; Raslan & Davies, 2010; Zhu et al., 2012). Neymark et al. (2002) compared seven BPS tools using simplified test cases and showed 4% - 40% inconsistencies in the energy consumption predictions. Brun et al. (2009) compared five tools in their ability to predict the energy performance of the same low-carbon building and found up to 60% variability in the results when several input parameters were modified. Raslan and

Davies (2010) investigated the issues of predictive inconsistencies between accredited tools used to demonstrate compliance with energy performance criteria in the UK. The results showed a large degree of variability and a lack of consistency in granting approval (pass/fail result) for the same building. The variability was evident both between different tools categories (i.e. quasi-steady state vs complex dynamic calculation methods) but also between the various accredited dynamic BPS tools included in the analysis. The latter was mainly attributed to differences in the calculation algorithms employed by each tool. Zhu et al. (2012) investigated the variability in the building loads calculation by using three BPS tools for the same simple test cases. They found that any variability was mainly caused by the different default values and algorithms used in each program. This EngD research was the first inter-modelling analysis to reflect on the level of modelling uncertainty associated to ICF simulation. The results have shown that when users rely on the default settings and algorithms of the tools, a significant divergence can be observed in the simulation results provided by nine BPS tools, reaching up to 57% relative difference between the minimum and maximum value. This discrepancy was particularly evident in the annual and peak heating demand. Practically this means that when evaluating simulation predictions for decision-making or regulatory compliance, the impact of choosing a particular BPS tool or method could lead to significantly different interpretations.

Two tools that gave relatively consistent results among the nine were selected for further analysis. A step-wise process of "equivalencing" the models (i.e. changing from default into more advanced modelling settings) showed that, among others, the two most significant factors affecting the results' divergence when simulating an ICF building was the simulation of solar radiation and the specification of surface convection coefficients (see Section 3 in Appendix B). When identical algorithms were selected in the BPS tools, their differences were minimised and their results showed a high level of agreement. This highlighted that the evident discrepancy across the nine BPS tools was mostly attributed to the modelling decisions/errors of the user (i.e. intentionally or unintentionally relying on the default settings of the tools without appreciating the sensitivity of the model). This research has therefore showed that, in general, BPS tools were able to predict with good accuracy the performance of ICF. However, there is a need for them to be transparent about their methods of calculation and for modellers to make informed decisions during the specification of a model. Only then the quantification of energy savings through simulation can be determined by researchers, designers and practitioners.

Objective No2: To monitor and analyse the actual energy consumption and thermal performance of an ICF building located in the UK and to scrutinise ICF's potential for indoor temperature control.

A thermal monitoring project was conducted to assess the thermal performance and the energy consumption of a real ICF dwelling located in the temperate UK climate (see Section 4.3 and Appendices C and D). The results showed that the measured internal temperatures of the ICF building were significantly more stable than the external dry-bulb temperature throughout the year and confirmed that the ICF building fabric was able to provide a stable internal environment. The average internal air temperature was between 22^{o}C and 25^{o}C during summer and around 21^{o}C during winter. The ICF fabric showed a decrement factor of 0.2 during the whole year, which was found to be higher during winter months. Moreover, the ICF fabric was found to delay the time of maximum internal air temperature by an average of 1 hour from the time of the maximum external air temperature during the whole year. The analysis of the building's energy consumption confirmed that Twiga Lodge is indeed a low-energy building. The total electricity and gas consumption was calculated to 2015kWh and 8425kWh respectively, which translates to an annual total cost of £821 (based on the charges of the electricity and gas provider).

This EngD research was the first to collect and analyse measured data from a whole building monitoring project conducted on a real, occupied, ICF dwelling located in the UK. The results of the monitoring project were used to investigate the thermal mass benefits of ICF, served as a means of validation for the accuracy of ICF simulation predictions, and were published in two papers (i.e. Appendices C and D), which are both available to the wider industrial and academic community.

<u>Objective No3:</u> To empirically validate, with the use of real monitoring data, the accuracy of BPS simulation results in calculating the thermal performance of ICF.

The simulation results of the ICF building model were compared against measured data from the thermal monitoring project to evaluate the accuracy of BPS predictions and to investigate the sources of uncertainty (see Section 4.4 and Appendix D). Previous parts of this research showed that the divergence in the simulation predictions provided by different BPS tools for the same ICF building could be as high as 57%, when users rely on default settings and input values (Section 4.1). A large part of this divergence has been proven to be a result of the modelling decisions made by the user (regarding the input value and calculation algorithms - Section 4.2). The results of WP4 confirmed this finding and showed that once the model was calibrated with information from the monitoring study, there was good consistency between predictions and reality for both internal air temperatures and heating energy consumption. The role of model calibration in enhancing the reliability of simulation predictions has been also discussed by other researchers (Reddy, 2006; Fumo, 2014; Monari & Strachan, 2014).

Scenario uncertainties imposed on the building due to occupants' behaviour could contribute up to 170% increase in the simulation of annual heating energy consumption (Gaetani et al., 2015). In this research, the level of uncertainty introduced in the model due to occupancy resulted in a slightly increased divergence between simulation results and measured data, although it was minimal for the specific case study. During the unoccupied periods, the results showed that the simulation model of the ICF building was able to predict with a relatively good accuracy the amplitude of the internal air temperature daily swings. However, the peaks of the maximum internal air temperature were slightly over-estimated by the model compared to the monitoring results, which led to a higher decrement factor.

To conclude, this research has shown that current BPS tools are able to predict the performance of ICF with a good accuracy if the ICF simulation model is a reasonable representation of reality. There is still a level of uncertainty allied to the simulation of solar radiation. This EngD has shown that the modelling uncertainties arising from the calculation of irradiated solar energy on buildings were more significant for ICF (and high thermal mass structures) compared to other conventional lightweight structures (e.g. timber-framed construction) (see Appendix B).

Objective No4: **To evaluate the level of uncertainty and the sensitivity of the model in the representation of ICF in BPS, when considering the physical uncertainties of the wall material properties.**

Uncertainty and Sensitivity Analyses were performed on the calibrated ICF model to assess the impact of physical uncertainties on simulation predictions and to investigate the wall material properties that have the most significant impact on the internal air temperatures. In the study of Hopfe and Hensen (2011), the specification uncertainties associated with incomplete or inaccurate specification of physical properties of the materials were found to contribute to an up to 36% increase in the annual heating demand and an up to 90% increase in the annual cooling demand. The results of the present analysis, however, showed that the ICF building was found to be robust to uncertain wall material properties during both warm and cold weather. The range of uncertainty in the prediction of the zone mean air temperature was small and equal to 0.5°C. The results of the sensitivity analysis for the ICF building indicated that the thermal mass of the concrete core (i.e. density, thickness and specific heat capacity of the concrete) was the most influential parameter with regards to the zone mean air temperature in both warm and cold analysed periods. This is a finding that contradicts the common belief about ICF, that it behaves thermally as a lightweight structure and that its internal layer of insulation isolates the thermal interaction of its thermal mass with the internal space. This research has therefore shown that there are certain benefits attributed to the thermal inertia of the ICF concrete core, which requires further investigation.

Objective No5: To investigate the thermal storage capacity of ICF concrete core and to determine whether ICF can be characterised as a thermally heavyweight or lightweight structure.

A comparison of the thermal performance of ICF against the thermal performance of high thermal mass and low thermal mass wall constructions was performed for the ICF building case study model by using calibrated simulation. The results of WP6 showed that, in general, ICF sits in between the other two construction methods and behaves closer to the high thermal mass building. In terms of internal air temperatures, ICF was found to perform similarly to the high thermal mass building with slightly increased peaks of maximum. The analysis of the heating energy consumption showed that the low thermal mass building had the highest demand among the three buildings. ICF and high thermal mass case showed a similar energy consumption. During a two-week period in the beginning of the heating season, the high thermal mass building showed an increased heating demand compared to the other two structures due to the slow response of the exposed mass to changes in boundary conditions. During that period, ICF exhibited characteristics similar to the low thermal mass construction in terms of quick responding to indoor conditioning. The transient heat transfer analysis showed that the concrete core of ICF wall was kept at a relatively constant temperature, acting as a buffer to transmission heat flow in and out of the building. This resulted in reduced heat losses and gains in comparison to the low thermal mass building. Considering that the only difference between the two construction methods was the level of thermal mass due to the concrete layer (i.e. same U-value, same finishing materials), any reduction to heat transfer is solely attributed to the inherent thermal mass of the ICF concrete core. This finding was also evident in Armstrong et al. (2011) and Saber et al. (2011). The comparison of ICF to high thermal mass building with regards to transmission heat transfer showed that the former could be more vulnerable to overheating than the latter, depending on the use, the design and the location of the building. Although ICF is often thought of as an insulated panel acting thermally as a lightweight structure, the thermal mass of its concrete core affects the dynamic heat transmission of the wall and plays a significant role in tempering heat losses and gains to and from the exterior. Consequently, it helps moderate internal temperature swings resulting ultimately in reduced energy consumption in comparison to a timber-frame construction with equal levels of insulation. Therefore, the computational and empirical evaluation of ICF, conducted as part of this EngD, have shown that, in terms of both energy consumption and internal thermal condition, an ICF building behaves mostly as a heavyweight structure.

5.2 CONTRIBUTION TO EXISTING THEORY AND PRACTICE

The role of a doctoral thesis is to make an original contribution to knowledge (QAA, 2015). Wellington (2010) discusses that the originality of a research study may be evident in the study's design, the knowledge synthesis, the implications and/or the way in which the research is presented. However, at the same time, it is important to also consider the significance of a study for researchers, practitioners and the general audience of the subject area. Accordingly, Baptista et al. (2014, p.62) suggest that: *"doctoral theses are expected to make not just an* *original but also a significant contribution to the field, the implication being that there is little value in originality if it is not also significant".* The significance of a research project could be elaborated by (Creswell, 2009):

- The ways in which the study adds to the scholarly research and literature in the field
- The ways in which the study helps improve practice
- The reasons why the study will improve policy

The findings from this research provide four clear contributions to existing theory and practice.

Contribution 1

A new evidence-base was developed on the transient thermal performance of ICF wall construction, showing that ICF combines characteristics of both heavyweight and lightweight structures. The internal layer of insulation in the ICF assembly reduces the thermal admittance of the wall making it difficult to quantify the actual thermal mass potentials of the element. Hence, based on simplified calculation methods used for compliance, ICF would be characterised as a thermally lightweight structure (BS EN ISO 13790, 2008; BRE, 2012).

The work reported in this EngD project, followed a stratified research approach, including:

1) ***Theoretical simulation studies*** on internal air temperatures and building energy consumption to get some basic understanding with regards to ICF's thermal performance and the modelling uncertainties associated to ICF simulation.
2) ***Field-study analysis/ empirical evaluation*** of a real ICF building to collect high resolution data on the whole building performance (i.e. internal air temperature, energy consumption, dynamic performance of building fabric), which would serve as a reference point to validate the accuracy of simulation output against.

3) ***Calibrated, empirically validated simulation***, which framed the basis for understanding the key features associated to thermal mass, such as the transient heat transmission in and out of the building and the sensitivity of the internal environment to the physical properties of the construction related to its thermal storage capacity.

By doing so, this EngD project has proven that the element's concrete core is not as thermally decoupled from the internal space as has been thought to be the case. Rather, the concrete core of the ICF element was found to act as a buffer to the heat flow that occurs in and out of the building. Due to its high thermal inertia the concrete was kept at a relatively constant temperature, thereby reducing transmission losses and gains (compared to a low thermal mass wall with equal levels of insulation). Calibrated dynamic simulation was used to contrast the thermal performance and the energy consumption of an ICF building with an equivalent building built in heavyweight and lightweight wall constructions. During summer, the ICF building fabric provided a relatively stable internal environment, with decreased internal air temperatures by an average of 2^{o}C compared to the low thermal mass structure. Undoubtedly, the internal insulation layer reduced the admittance of the wall, so decreasing the amount of heat penetrating the ICF fabric (compared to a similar wall with exposed thermal mass). Therefore, a higher risk of overheating might be anticipated for an ICF building compared to a high thermal mass building in scenarios with increased internal loads or in a building located in warmer climates than the UK. Nevertheless, in terms of internal thermal conditions, particularly during warm weather, the ICF building was found to perform mostly as a heavyweight structure. The analysis of the heating energy consumption however, showed that during the beginning of the heating season, ICF exhibited characteristics similar to a low thermal mass construction in terms of its quick response to indoor conditioning.

In other words, the research conducted on this EngD project has shown that the ICF wall assembly behaves on average in between a conventional low thermal mass and high thermal mass wall during the year, yet its behaviour changes depending on the season. In summer, ICF was found to perform closer to a heavyweight structure (stable internal environment, reduced internal daily temperature swings). In winter, it exhibited favourable characteristics of a lightweight structure in terms of a quick response to space heating.

Contribution 2

A new methodology was proposed to investigate the *modelling gap* originating from errors in the representation of thermal mass using Building Performance Simulation (BPS). This study is the first detailed analysis to evaluate the implications of modelling decisions and modelling uncertainty in the representation of thermal mass using BPS. Large discrepancies can occur in the simulation predictions provided by the various BPS tools, referred to as modelling uncertainties. A step-wise method for minimising the differences in simulation models during an inter-model comparative analysis was proposed by changing into identical calculation algorithms sequentially. This model "equivalencing" method is further described in Mantesi et al., 2018, Appendix B. The analysis reflected on the impacts that these algorithms had on the divergence in results regarding three specific construction methods, ICF, high thermal mass (exposed concrete) and low thermal mass (timber-framed) buildings. However, the proposed model "equivalencing" method has a rather generic configuration and it could be used to evaluate the *modelling gap* in the representation of other construction methods and materials as well.

The findings of this EngD highlighted that the selection of BPS tool and the decisions of the modeller about the specification of the model could potentially give rise to significant variation in the simulation outputs for the same building. In new materials, such as ICF, of which there is little research on evaluating their performance, this could cause them to appear less desirable and affect market penetration.

Contribution 3

New monitoring data were collected for the thermal performance and the energy consumption of an occupied ICF building located in the UK climate. This project was the first whole building monitoring study conducted in a real ICF occupied detached building in Europe (namely in the UK). The monitoring project lasted for 18 months and provided a holistic approach for the evaluation of ICF in buildings. The measured data delivered evidence on internal air temperatures, energy consumption, and on the dynamic heat transmission of the building fabric. They also allowed to examine and quantify the actual energy and thermal performance of the ICF construction system in the UK climatic context. The project delivered a useful data set that could allow a detailed comparison of monitoring data with simulation results, helping to investigate the accuracy of BPS predictions and identify the factors contributing to modelling uncertainties in ICF simulation. The findings of the monitoring project have been published in two papers (see Appendices C and D) and are available to the wider academic and industrial community.

Contribution 4

Contribution to existing literature in the subject area. Throughout the four years of the EngD project, seven academic papers were produced, five conference papers, a published journal paper, and one journal paper under review at the time of submission. Three of the seven publications are not included in the Appendices of this thesis for reasons of brevity, but all are in the public domain. The rest can be found in Appendix A-D. All seven papers make an incremental contribution to existing knowledge with a particular focus on the modelling uncertainties associated with thermal mass and ICF simulation (Appendix A-B), empirical validation of ICF simulation results using measured data (Appendix C-D), and the thermal performance and thermal storage capacity of the ICF construction method (Appendix D).

The findings of this research were presented in four conferences:

- 14th International Building Performance Association (IBPSA) Building Simulation Conference BS2015, Hyderabad, India, 07-09 December 2015.
- 3rd Building Simulation and Optimization Conference BSO2016, Newcastle, UK, 12-14 September 2016.
- 15th International Building Performance Association (IBPSA) Building Simulation Conference BS2017, San Francisco, USA, 07-09 August 2017.
- 7th Masters Conference: People and Buildings MC2017, London, UK, 22 September 2017.

The author's participation in academic conferences helped expand her network and this consequently resulted in collaborative research with other universities (i.e. Strathclyde University, see paper in Appendix B) and external research communities, including her participation in the International Energy Agency (IEA) EBC Annex 71 project – Building Energy Performance Assessment Based on In-situ Measurements (IEA - EBC, n.d.).

Moreover, a number of presentations have been given to several industrial events (more details can be found in Appendix G) aiming to disseminate the research findings to the wider industry (representing both Loughborough University and the sponsoring company).

5.3 IMPLICATIONS/IMPACT ON THE SPONSOR

As building regulation and energy reduction targets become more and more stringent, energy efficiency in buildings is primarily focused on enhanced fabric performance. As such, increased fabric resistance and better insulation along with high-quality building air-tightness are two areas of great importance in the construction of new buildings. However, existing knowledge suggests that highly insulated, super air-tight buildings are vulnerable to overheating (Davies & Oreszczyn, 2012; McLeod et al., 2013; Lomas & Porritt, 2017). Hence, exploiting the thermal mass of the fabric can be used as a passive design strategy and an adaptation mechanisms against climate change (Williams et al., 2012; Shafigh et al., 2018).

As already discussed, the aim of the EngD is to develop engineers who are capable of demonstrating innovation in the application of knowledge to the engineering sector (CICE, 2014) and to ensure that the business obtains scientifically valid and commercially competitive outcomes. In that respect, the outcome of this EngD project to the industrial sponsor was:

> *A combined computational and empirical analysis of the thermal performance of ICF that was used to create and exploit a new evidence base for the use of ICF in the UK housing construction industry.*

As part of its R&D department, the sponsoring company aims to accelerate the development of new and innovative products and solutions. There are several barriers influencing the success of innovation in the construction industry. Loonen et al. (2014) identified some of them:

- There is often a mismatch between information need and availability.
- There is often a disconnection between material science and how they perform in building scale.
- There is a lack of information on building integration issues.
- There is a lack of experimental results.
- There is a lack of *what-if* analysis (in the conventional product development process, only a limited number of scenarios is usually examined).

ICF is relatively new and innovative wall construction technology, which combines all the benefits of a site-based MMC. However, there is a lack of empirical knowledge with regards to its thermal performance and a lack of consensus within the building energy community on whether ICF should be considered as a thermally lightweight or heavyweight structure. The research project conducted as part of this EngD, used a combination of research methods to address the main limitations of the R&D process, as listed above and formed the first thorough investigation of the thermal performance of ICF. The results of the analysis have shown that ICF could be a viable alternative to heavyweight housing construction, combining also some of the benefits of low thermal mass, in terms of a quicker response to indoor conditioning.

Consequently, the main impact of this EngD project to the sponsoring company was to enhance their competitive advantage in innovative building envelope technologies, by delivering:

1) Valid and robust data analyses that can underpin the commercial proposition of Aggregate Industries UK Ltd for ICF construction method.
2) New understandings about the thermal behaviour of high thermal mass buildings that can form the basis for new construction techniques, building methodologies and new product development ideas.

Moreover, during the duration of the EngD project, a number of presentations were given to non-academic, commercial and other audiences, helping disseminate the findings of the research project. More details on the participation of the author to industrial events can be found in Appendix G.

5.4 IMPACT ON WIDER INDUSTRY

ICF is classed among the MMC and it is often characterised as an "innovative" approach to building construction although it dates back in Europe since the late 1960's (Armstrong et al., 2011). To be able to support the commercial proposition of new materials and innovative building technologies, it is important to predict and communicate their thermal behaviour and energy performance accurately.

Computer simulation can be used to provide quantitative data and support the decision-making process. Large discrepancies are widely accepted when modelling an identical building using various BPS tools (Neymark et al., 2002; Brun et al., 2009; Zhu et al., 2012; Raslan & Davies, 2010). In this research, a variation of up to 57% was evident in the results provided by the different tools in the simulation of a simple ICF building (see Section 4.1). However, the analysis also indicated that a significant part of the disparity in results was irrelevant to the capabilities of the various BPS tools and it was attributed to the modelling decisions made by the user during the specification of the ICF simulation model, be it intentional or unintentional (i.e. relying on the default settings of the tools). Either way, when evaluating simulation predictions for decision-making, particularly in new materials (such as ICF), of which there is currently little research on modelling and evaluating their performance, the impact of choosing a particular BPS tool or method should be acknowledged by modellers.

The general remark of the computational analysis was that current BPS tools are able to predict the actual thermal performance of an ICF building with a relatively good accuracy if/when correct and up-to-date information is used in the simulation, hence ensuring an adequate representation of reality.

In terms of its thermal storage capacity, designers and practitioners often consider ICF as just an insulated panel that thermally acts as a lightweight structure. There is a view that the internal layer of insulation isolates the thermal mass of the concrete from the internal space and interferes with thermal interaction. The findings of this EngD research showed that the thermal mass in ICF does in fact have a much more significant effect on indoor temperatures and internal conditions than what is commonly expected. This finding becomes particularly relevant when considering several simplified methods regularly used in industry for the calculation of energy use in buildings for regulatory compliance, such as the BS EN ISO 13790: 2008 (BS EN ISO 13790, 2008) and the UK Government's standard assessment procedure for energy rating of dwellings (SAP2012) (BRE, 2012). Taking SAP as an example, to calculate the thermal mass parameter of an element, one needs to calculate the heat capacity of all its layers. However, it is specifically stated that starting from the internal surface, the calculations should stop when one of the following conditions occurs:

- an insulation layer (thermal conductivity <= 0.08 W/m·K) is reached;
- total thickness of 100 mm is reached.
- half way through the element;

Similarly, in ISO 13790: 2008 the internal heat capacity of the building is calculated by summing up the heat capacities of all the building elements for a maximum effective thickness of 100mm. In other words, according to SAP and ISO 13790, the thermal storage capacity of ICF concrete core should be completely disregarded, which this research has clearly shown to be problematic and inaccurate.

To sum up, the outcome of this EngD to the wider industry was to deliver:

1) New insights on the significance of using validated, dynamic BPS for both decision-making and regulatory compliance, particularly when evaluating the thermal performance of non-conventional and innovative construction methods.
2) Guidance to modellers and practitioners on the implications of modelling decisions during the specification of a building in BPS.
3) New database and published analyses of several important aspects associated to the thermal performance of ICF that can inform subsequent research in the area.

5.5 CRITICAL EVALUATION OF THE RESEARCH

There are several constraints and limitations associated with this EngD project and these are listed below:

Single-Zone Case Study in Inter-Model Comparison

The single-zone building case study selected for the inter-model comparison of different BPS tools prevented several important factors related to thermal mass and ICF simulation from being analysed, such as the impact of variable internal gains and air flows, the impact of intermittent occupation, and others. The case study set up was selected in order to reduce the specification and scenario uncertainties as much as possible. The specification uncertainties are associated with incomplete or inaccurate specification of building input parameters (Hopfe & Hensen, 2011). The scenario uncertainties are all the external conditions imposed on the building due to weather conditions, occupants' behaviour and others (De Wit & Augenbroe, 2002). From that perspective, the case study selection served well the main purpose of analysing the "modelling gap". Certainly, it was difficult to derive solid conclusions about the actual thermal performance of ICF construction method in such a simplified simulation scenario.

Lack of Real Data in Inter-Model Comparison

Various previous studies analysed the predictive variability found between different BPS tools for the same building (Brun et al., 2009; Raslan & Davies, 2010; Zhu et al., 2012). The inter-modelling comparative analysis performed as part of this EngD was the first one to report on the modelling uncertainties associated to ICF simulation. A significant limitation, however, was the lack of real data that could serve as a validation reference for the accuracy of simulation predictions. In other words, it should be acknowledged that due to the absence of an absolute truth, it was impossible to say what is correct and what is wrong or whether one tool performs closer to reality than the other.

Single Building Case Study

As discussed in Section 3.3.3.1, the case study research method allows for an empirical and in-depth investigation of a specific phenomenon within its real-life context (Yin, 2009). However, the scope of a case study is bounded and care must be taken not to draw generalised conclusions to ensure academic rigor (Brown, 2008). In that respect, it is important to emphasize that the building case study selected in this project was built to achieve close to Passivhaus standards. It is a high-end, low-energy construction, which might not be fully representative of ordinary buildings and more conventional constructions. Furthermore, the impacts of building design and operation on the thermal performance of ICF were not investigated as part of this research.

Source of Experimental Errors in Empirical Validation

There are several advantages when pursuing an empirical validation of BPS predictions especially under realistic conditions of monitoring a real building case study. Empirical validation allows to test the combined effect of all internal errors in a program (Lomas et al., 1997). Moreover, doing it under realistic conditions allows to interpret the impact of occupants' behaviour instead of focussing only on the effects of the building structure and HVAC systems (Ryan & Sanquist, 2012). However, there are also some disadvantages. Firstly, in empirical validation, it is difficult to interpret the results and to draw conclusions on the possible sources of errors in the simulation because they are all simultaneously in effect. Moreover, there is a fair possibility for experimental errors to occur (Judkoff & Neymark, 1995).

It is generally accepted that there is a level of experimental uncertainty associated with in-situ measurements that may arise from random or systemic errors and could compromise the validity of the measurements (Evangelisti et al., 2018). Systemic errors are standard errors introduced to the system due to inaccuracies and sensitivities of the instrumentation used for the measurements (Coleman, 2009). The range of systemic uncertainty in the recording of the monitoring sensors was considered and included in the analysis of results. Nevertheless, other sources of experimental errors should be acknowledged. One example is the recording of zone mean air temperatures. The internal air temperature was measured in one location within each room by using HOBO U12 stand-alone loggers. The loggers were placed at the height of 1.5m from the floor, away from heat sources and direct solar radiation, as suggested in literature (Singh et al., 2010; Kumar et al., 2017). However, this decision does not account for the effects of air stratification that may arise in the room due to buoyancy. Another example is the simulation of natural ventilation. Although monitored data were available for windows operation (opening and closing incidents), several assumptions had to be made due to two reasons. First, the set of data was incomplete, including a lot of noise, and, secondly, other critical information such as opening factors were not available.

Empirical Validation of Two BPS Tools

Due to time restrictions, the empirical validation of simulation results based on measured data from the monitoring project was performed for two of the nine tools included in the initial comparative analysis. Although some insights were provided on the accuracy of ICF simulation and the key factors contributing to the modelling uncertainties, these findings concerned just two BPS tools that were chosen as representative examples of the modelling methods employed in whole building simulation. There are, however, several algorithms and calculation methods -for example, the impact of frequency domain conduction solution method, or the impact of combined convective and radiative surface coefficients, among others- that were not included in the analysis.

Limitations of Simulation Models

The internal thermal mass due to furnishing was not included in all simulation models and this was identified as one of the reasons contributing to the divergence between simulation results and measured data. Simultaneously, the comparison of simulation to monitoring results showed that the models were very much influenced by the availability of solar radiation. A limitation of the study was that, during the monitoring period, only global horizontal radiation was recorded on site. The split between direct normal and diffuse horizontal components was performed in EnergyPlus using the Perez model (Perez, 1992). This, however, introduced a certain level of modelling uncertainty since there were no monitoring data available to use as a reference point for direct and diffuse radiation values used in the simulation.

Assumptions on Range of Uncertainty

Finally, the uncertainty and sensitivity analyses conducted as part of this research, relied on information found in literature and used indicative values for the range of uncertainty in the wall material properties. Quantifying the actual range of uncertainty in the material properties of ICF would definitely improve the rigour and reliability of the findings.

Application to Other Climates

The analysis conducted, as part of this EngD, on the thermal performance of ICF was focused on two climates:

- The DRYCOLD typical meteorological year (TMY) weather file, used in the ASHRAE standard 140 (ASHRAE, 2014), representing a climate with cold clear winters and hot dry summers.
- The weather data, as recorded on site, in the temperate climate of Guildford, UK.

Hence, it is important to highlight that the research findings are highly relevant to these two climatic scenarios. Further investigation is required to assess the thermal performance of ICF is different climatic patterns, in other climates (such as cooling dominating locations) and under future climatic predictions.

5.6 FURTHER RESEARCH

The findings of the EngD research could potentially be used to point towards further research in the area. The possibility of including an additional lab experiment as part of the wider research methodology was under consideration during the third year of this EngD project but it was omitted from the project due to time restrictions. Loonen et al. (2014) described the characteristic phases that a new product typically undergoes in product development cycles. As such, the product is initially tested in laboratory scale and undergoes reduced-scale experiments in controlled environments before it can be tested in a full-scale pilot study. Influenced by the above, the additional lab experiment was proposed to take place in a hygrothermal facility (HTF) with the aim of analysing the thermal performance of the ICF wall assembly (heat, air and moisture transfer) under controlled simulated outdoor and indoor conditions by using the hotbox method. The rationale underlying this decision was to enhance the robustness of the research findings regarding both the ICF performance and BPS accuracy. The ICF analysis, including the HTF experiment would follow a measuring stratification, (e.g. Fig.5.1).

Since it was not feasible to include this additional experiment in this EngD research project, it could be suitable area for further research. The expected outcome of the HTF experiment will be a data set allowing quantification of the thermal storage capacity of the ICF wall component under idealised, controlled conditions, excluding the influence of other factors, which are inevitably present in a full-scale building project (such as floors, slabs, furnishing and other). The delivered data set would help to characterise the thermal properties of the specific construction method, but also to quantify the range of physical uncertainties associated to the material properties of ICF, hence experimentally evaluate its robustness and/or defects.

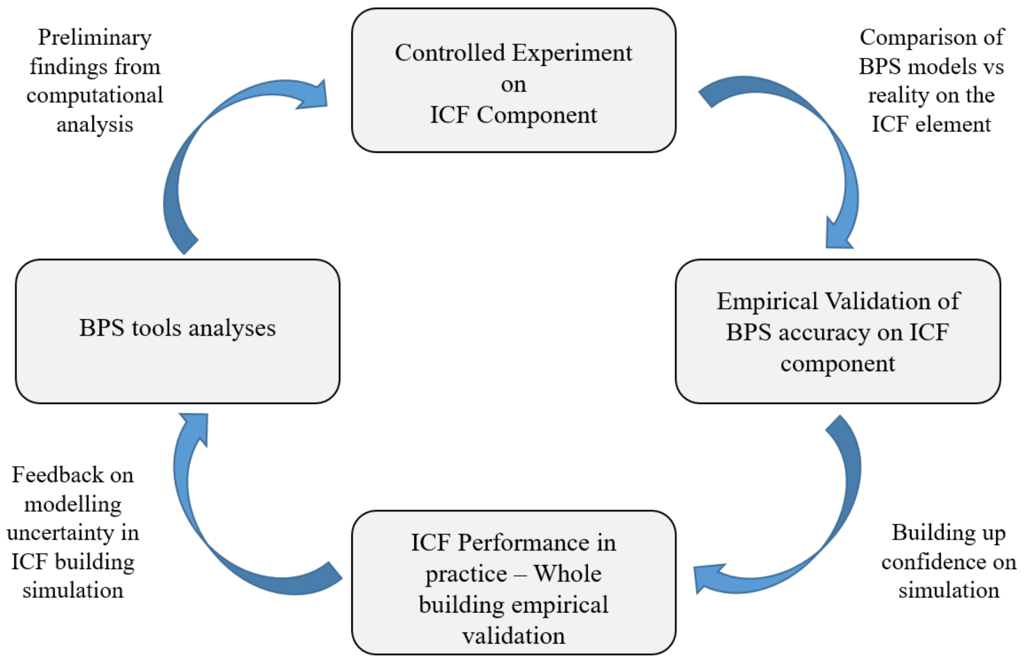


Figure 5.1 *Measuring Stratification of ICF Simulation Analysis*

Further investigation is also required to assess the influence of building design and operation on the thermal performance of ICF. As discussed previously, this research excluded the impacts of occupancy patterns and alternative building designs from the analysis. To evaluate the suitability of ICF for the UK housing construction industry, it is imperative to test that its performance remains robust under a range of design scenarios and operating conditions.

6 REFERENCES

Ahmed, V., Opoku, A. & Aziz, Z. 2016. *Research methodology in the built environment : a selection of case studies*. London: Routledge.

Al-Sanea, S. A. & Zedan, M. F. 2011. Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass, *Applied Energy*. Elsevier Ltd, 88(9), pp. 3113–3124. doi: 10.1016/j.apenergy.2011.02.036.

Al-Sanea, S. A., Zedan, M. F. & Al-Hussain, S. N. 2012. Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential, *Applied Energy*. Elsevier Ltd, 89(1), pp. 430–442. doi: 10.1016/j.apenergy.2011.08.009.

ANSI/ASHRAE. 2014. *Standard 140-2014, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*, Atlanda, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Armstrong, M. M., Maref, W., Saber, H. H., Rousseau, M. Z., Ganapathy, G. & Swinton, M. C. 2011. *The impact of the thermal mass on field energy performance of insulating concrete form (ICF) wall*. Canada: National Research Council.

Asan, H. 2000. Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view, *Energy and Buildings*, 32(2), pp. 197–203. doi: 10.1016/S0378-7788(00)00044-X.

ASHRAE. 2009. *ASHRAE Handbook - Fundamentals*. Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers.

ASHRAE. 2014. *Guideline 14 - 2014: Measurement of Energy Demand and Water Savings*. Atlanda, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers.

Aste, N., Leonforte, F., Manfren, M. & Mazzon, M. 2015. Thermal inertia and energy efficiency – Parametric simulation assessment on a calibrated case study, *Applied Energy*, 145, pp. 111–123. doi: 10.1016/j.apenergy.2015.01.084.

Aste, N., Angelotti, A. & Buzzetti, M. 2009. The influence of the external walls thermal inertia on the energy performance of well insulated buildings, *Energy and Buildings*, 41(11), pp. 1181–1187. doi: 10.1016/j.enbuild.2009.06.005.

Attia, S., Hensen, J. L. M., Beltran, L. & DeHerde, A. 2012. Selection criteria for building performance simulation tools: contrasting architects' and engineers' needs, *Journal of Building Performance Simulation*, 5(3), pp. 155–169. doi: 10.1080/19401493.2010.549573.

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), pp. 1–10. doi: 10.1016/0378-7788(95)00956-6.

Batista, A. P., Frick, L., Holley, K., Remmik, M., Tesch, J. & Akerlind, G. 2015. The doctorate as an original contribution to knowledge: considering relationship between originality, creativity and innovation. *Frontline Learning Research*, 3, pp.55-67. doi.org/10.14786/flr.v3i3.147.

Becker, K. & Parker, J. R. 2009. A Simulation Primer, in *Digital Simulations for Improving Education: learning through artificial teaching environments*. Hershey, PA: IGI Global, pp. 1–24. doi: 10.4018/978-1-60566-322-7.ch001.

BEIS - Department for Business, Energy and Industrial Strategy. 2018. Energy Consumption in the UK. Available at: https://data.gov.uk/dataset/26afb14b-be9a-4722-916e-10655d0edc38/energy-consumption-in-the-uk, [Accessed on: 19/06/18].

Beizaee, A., Lomas, K. J. & Firth, S. K. 2013. National survey of summertime temperatures and overheating risk in English homes, *Building and Environment*. Elsevier Ltd, 65, pp. 1–17. doi: 10.1016/j.buildenv.2013.03.011.

Bell, J. 2010. *Doing your research project : a guide for first-time researchers in education, health and social science*. 5th ed. Maidenhead, Berkshire ; New York: McGraw-Hill Open **University Press.**

Berkeley, P., Haves, P. & Kolderup, E. 2014. Impact of Modeler Decisions on Simulation Results. In *2014 ASHRAE/IBPSA-USA Building Simulation Conference Atlanta, GA September 10-12, 2014, Conference Proceedings*.

Blight, T. 2015. *Low-Energy Domestic Architecture: The Impact Of Household Behaviour On The Expected Energy Use Of Passive House Dwellings*. PhD Thesis, University of Bath, UK.

Blumberg, B., Cooper, D. R. & Schindler, P. S. 2005. *Business research methods*. Maidenhead: McGraw-Hill Education.

Box, G. E. P. & Draper, N. R. 1987. *Empirical model-building and response surfaces*. Edited by N. R. Draper. New York ; Chichester: Wiley.

BRE. 2012. *SAP 2012 The Government ' s Standard Assessment Procedure for Energy Rating of Dwellings*, London. doi: 10.1007/s13398-014-0173-7.2.

Brown, P. A. 2008. A Review of the Literature on Case Study Research, *Canadian Journal for New Scholars in Education*, 1(1).

Brun, A., Spitz, C., Wurtz, E. & Mora, L. 2009. Behavioural Comparison of Some Predictive Tools Used in a Low-Energy Building. In *11th International Building Performance Association (IBPSA), Building Simulation Conference, BS2009, Glasgow, Scotland, 27-30 July, 2009, Conference Proceedings*.

Bryman, A. & Bell, E. 2011. *Business research methods*. 3rd ed. Oxford: Oxford University Press.

BS EN ISO 13790. 2008. *Energy Performance of Buildings - calculation of energy use for space heating and cooling*. Geneva, International Organization for Standardization.

BS EN ISO 13786, 2017. *Thermal performance of building components - Dynamic thermal* *characteristics - Calculation methods*. Geneva, International Organization for Standardization.

Burman, E., Rigamonti, D., Kimpain, J. & Mumovic, D. 2012. Performance gap and thermal modelling: A comparison of simulation results and actual energy performance for an academy in North West England. In *1st Building Simulation and Optimization Conference, BSO2012, Loughborough, UK, 10-11 September 2012, Conference Proceedings*.

Brun, W., Keren, G., Kirkeboen, G. & Montgomery, H. 2011. *Perspectives on Thinking, Judging and Decision Making.* Oslo: Universitetforlaget.

Cambridge Advanced Learner's Dictionary. 2006. *Cambridge Advanced Learner's Dictionary*. Klett.

Campolongo, F., Cariboni, J. & Saltelli, A. 2007. An effective screening design for sensitivity analysis of large models, *Environmental Modelling and Software*, 22(10), pp. 1509–1518. doi: 10.1016/j.envsoft.2006.10.004.

Chambers 21st Century Dictionary. 1999. *Chambers 21st Century Dictionary*. Chambers Harrap Pub Limited.

CIBSE. 2015. *Guide A: Environmental Design.* London: The Chartered Institude of Building Services Engineers.

CIBSE AM11. 2015. *Building Energy and Environmental Modelling, Application Manual AM11*. London: The Chartered Institude of Building Services Engineers.

CICE. 2014. *Doctor of engineering (EngD) handbook*. Loughborough.

CICE. *Centre for Innovative and Collaborative Construction Engineering, About the EngD*. Available at: http://goo.gl/1ylxX0 [Accessed: 28 May 2018].

Clarke, J. A. 2001. *Energy Simulation in Building Design*. 2r.e. ed. London: Oxford, Butterworth-Heinemann.

Clarke, J. A. & Hensen, J. L. M. 2015. Integrated building performance simulation: Progress, prospects and requirements, *Building and Environment*. Elsevier Ltd, 91, pp. 294–306. doi: 10.1016/j.buildenv.2015.04.002.

Clarke, J., Strachan, P. A. & Pernot, C. 1993. An approach to the calibration of building energy simulation models, *Transitions-American Society of Heating Refrigerating and Air Conditioning Engineers*, pp. 917–930.

Coakley, D., Raftery, P. & Keane, M. 2014. A review of methods to match building energy simulation models to measured data, *Renewable and Sustainable Energy Reviews*. Elsevier, 37, pp. 123–141. doi: 10.1016/j.rser.2014.05.007.

Coleman, H. W. 2009. *Experimentation, validation, and uncertainty analysis for engineers*. 3rd ed. Hoboken, N.J. : Chichester: Wiley ; John Wiley.

Committee on Climate Change. 2016. UK Climate Change Risk Assessment 2017, p. 86. Available at: ISBN: 9780108511257.

Concise Oxford English Dictionary. 1995. *Concise Oxford English Dictionary*. Oxford: Oxford University Press.

Crawley, D. B. 2008. Estimating the impacts of climate change and urbanization on building performance, *Journal of Building Performance Simulation*, 1(2), pp. 91–115. doi: 10.1080/19401490802182079.

Crawley, D. B., Hand, J. W., Kummert, M. & Griffith, B.T. 2008. Contrasting the capabilities of building energy performance simulation programs, *Building and Environment*. 43 661–673. doi:10.1016/j.buildenv.2006.10.027.

Creswell, J. W. 2009. *Research design : qualitative, quantitative, and mixed method approaches*. 2nd ed. London: SAGE.

Csáky, I. & Kalmár, F. 2015. Effects of thermal mass, ventilation, and glazing orientation on indoor air temperature in buildings, *Journal of Building Physics*, 39(2), pp. 189–204. doi: 10.1177/1744259115579060.

Davies, M. 2004. *Building Heat Transfer*. Sussex: Wiley and Sons, Ltd.

Davies, M. & Oreszczyn, T. 2012. The unintended consequences of decarbonising the built environment: A UK case study, *Energy and Buildings*, 46, pp. 80–85. doi: 10.1016/j.enbuild.2011.10.043.

DCLG. 2012. *Investigation into overheating in homes: literature review*. Available at: ISBN 9781409835929.

DCLG. 2015. *SBEM: Simplified Building Energy Model. A Technical Manual for SBEM.* London: Department for Communities and Local Government.

DCLG. 2016. *National Calculation Methodology (NCM). Modelling Guide.* London: Department for Communities and Local Government.

DEFRA Department of Environment Food and Rural Affairs. 2012. *UK Climate Change Risk Assessment: Government Report*. London.

Dengel, A. & Swainson, M. 2012. *Overheating in new homes; A review of the evidence*, London: NHBC Foundation.

Dessler, A. E. 2012. *Introduction to climate change*. New York: Cambridge University Press.

Dincer, I. & Rosen, M. 2011. *Thermal Energy Storage Systems and Applications*, 2nd ed., Chichester: John Wiley and Sons, Ltd.

Dodoo, A., Gustavsson, L. & Sathre, R. 2012. Effect of thermal mass on life cycle primary energy balances of a concrete- and a wood-frame building, *Applied Energy*, 92, pp. 462–472. doi: 10.1016/j.apenergy.2011.11.017.

Easterby-Smith, M. 2018. *Management and Business Research*. 6th ed., London: Sage.

EnergyPlus. *EnergyPlus*. Available at: https://energyplus.net/ [Accessed on: 28 May 2018].

European Commission. *Energy Efficiency Directive*. Available at: https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive

[Accessed: 3 May 2018].

European Commission. *Paris Agreement*. Available at: https://ec.europa.eu/clima/policies/international/negotiations/paris_en [Accessed on: 3 May 2018].

European Parliament and Council. 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. *Official Journal of the European Union*, pp. 13–35. doi: doi:10.3000/17252555.L_2010.153.eng.

Evangelisti, L., Guattari, C. & Asdrubali, F. 2018. Influence of heating systems on thermal transmittance evaluations: Simulations, experimental measurements and data post-processing, *Energy and Buildings*, 168, pp. 180–190. doi: 10.1016/j.enbuild.2018.03.032.

EVO. 2012. *International Performance Measurement and Verification Protocol*. Canada: Efficiency Valuation Organization. doi: 10.1126/science.15.390.961.

Fellows, R. & Liu, A. 2008. *Research methods for construction*. 3rd ed. Edited by A. Liu. Oxford: Wiley-Blackwell.

Foucquier, A., Roberts, S., Suard, F., Stephan, L. & Jay, A. 2013. State of the art in building modelling and energy performances prediction: A review, *Renewable and Sustainable Energy Reviews*, 23, pp. 272–288. doi: 10.1016/j.rser.2013.03.004.

Fumo, N. 2014. A review on the basics of building energy estimation, *Renewable and Sustainable Energy Reviews*. Elsevier, 31, pp. 53–60. doi: 10.1016/j.rser.2013.11.040.

Gaetani, I., Hoes, P. J. & Hensen, J. L. M. 2015. Occupant behavior in building energy simulation: Towards a fit-for-purpose modeling strategy, *Energy and Buildings*, 121, pp. 188–204. doi: 10.1016/j.enbuild.2016.03.038.

Gajda, J. & VanGeem, M. 2000. *Energy use in residential housing: A comparison of insulating concrete form and wood frame walls*, Prortland Cement Association.

Gibb, A. G. F. 1999. *Off-site fabrication : prefabrication, pre-assembly and modularisation*. Latheronwheel: Whittles.

Givoni, B. 1979. Passive cooling of buildings by natural energies, *Energy and Buildings*, 2(4), pp. 279–285. doi: 10.1016/0378-7788(79)90039-2.

Granderson, J. & Price, P. N. 2013. *Development and Application of a Statistical Methodology to Evaluate the Predictive Accuracy of Building Energy Baseline Models*. USA: Lawrence Berkeley National Laboratory.

Guyon, G. 1997. Role of the model user in results obtained from simulation software program. In *5th Conference of International Building Performance Simulation Association (IBPSA), Building Simulation. BS1997, Prague, Czech Republic, 8-10 September 1997, Conference Proceedings*.

Haberl, J. S. & Bou-Saada, T. E. 1998. Procedures for Calibrating Hourly Simulation Models to Measured Building Energy and Environmental Data, *Journal of Solar Energy*

Engineering, 120(3), p. 193. doi: 10.1115/1.2888069.

Hacker, J. N., DeSaulles, 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(3), pp. 375–384. doi: 10.1016/j.enbuild.2007.03.005.

Hamby, D. M. 1994. A review of techniques for parameter sensitivity analysis of environmental models., *Environmental Monitoring and Assessment*, 32(2), pp. 135–154. doi: 10.1007/BF00547132.

Hart, R., Mendon, V. & Taylor, T. 2014. *Residential Wall Type Energy Impact Analysis*, Florida Masonry Apprentices & Education Foundation.

Helton, J. C. & Davis, F. J. 2003. Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems, *Reliability Engineering and System Safety*, 81(1), pp. 23–69. doi: 10.1016/S0951-8320(03)00058-9.

Hill, D. & Monsour, R. 2007. *Monitored Performance of an Insulating Concrete Form Multi-Unit Residential Building*. Canada: Canada Mortgage and Housing Corporation.

van Hooff, T., Blocken, B., Hensen, J. L. M. & Timmermans, H. J. P. 2014. On the predicted effectiveness of climate adaptation measures for residential buildings, *Building and Environment*, 82, pp. 300–316. doi: 10.1016/j.buildenv.2014.08.027.

HM Government. Conservation of fuel and power: Approved Document L. Available at: https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l [Accessed March 18, 2018].

Hopfe, C. J. 2009. *Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization*, PhD Thesis, Eidhoven University of Technology, doi: 10.1016/j.enbuild.2015.09.010.

Hopfe, C. J. & Hensen, J. L. M. 2011. Uncertainty analysis in building performance simulation for design support, *Energy and Buildings*, 43(10), pp. 2798–2805. doi: 10.1016/j.enbuild.2011.06.034.

Hopfe, C. J. & McLeod, R. S. 2015. *The passivhaus designer's manual a technical guide to low and zero energy buildings*. 1st ed. Edited by N. Routledge. New York.

IBPSA USA. BEST Directory. Available at: https://www.buildingenergysoftwaretools.com/ [Accessed on: 18 March 2019].

IEA - EBC. *EBC ANNEX 71 Building Energy Performance Assessment Based on In-situ Measurements*. Available at: http://www.iea-ebc.org/projects/project?AnnexID=71 [Accessed: 25 June 2018].

IES VE. Integrated Environmental Solutions. Available at: https://www.iesve.com/ [Accessed on: 18 March 2019).

IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Geneva: Intergovernmental Panel of Climate Change. doi:

10.1017/CBO9781107415324.

Irving, A. D. 1988. Validation of dynamic thermal models, *Energy and Buildings*, 10(3), pp. 213–220. doi: 10.1016/0378-7788(88)90007-2.

Irving, S. J. 1982. Energy program validation: conclusions of IEA Annex I, *Computer-Aided Design*, 14(I), pp. 33–38. doi: 10.1016/0010-4485(82)90009-4.

Jankovic, L. 2012. *Designing zero carbon buildings using dynamic simulation methods*. 1st edn. Oxon: Routledge.

Jenkins, D. P., Patidar, S., Banfill, P. F. G. & Gibson, G. J. 2011. Probabilistic climate projections with dynamic building simulation: Predicting overheating in dwellings, *Energy and Buildings*, 43(7), pp. 1723–1731. doi: 10.1016/j.enbuild.2011.03.016.

JEPlus. *jEPlus User's Manual, Version 1.4*. Available at: http://www.jeplus.org/wiki/doku.php?id=docs:manual_1_4 [Accessed: 12 March 2018].

Jimenez, M., Madsen, H., Andersen, K., 2008. Identification of the main thermal characteristics of building components using MATLAB, *Building and Environment*, 43, pp.170-180.

Johannesson, G. 1981. *Active Heat Capacity. Models and Parameters for the Thermal Performance of Buildings*. Lund Institute of Technology, Sweden.

Johnson, R. B., Onwuegbuzie, A. J. & Turner, L. A. 2007. Toward a Definition of Mixed Methods Research, *Journal of Mixed Methods Research*, 1(2), pp. 112–133. doi: https://doi.org/10.1177/1558689806298224.

Johra, H. & Heiselberg, P. 2017. Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review, *Renewable and Sustainable Energy Reviews*, 69, pp. 19–32. doi: 10.1016/j.rser.2016.11.145.

Jones, R. V., Goodhew, S. & de Wilde, P. 2016. Measured Indoor Temperatures, Thermal Comfort and Overheating Risk: Post-occupancy Evaluation of Low Energy Houses in the UK, *Energy Procedia*, 88(June), pp. 714–720. doi: 10.1016/j.egypro.2016.06.049.

Judkoff, R. &Neymark, J. 1995. *International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method*. Colorado: NREL.

Judkoff, R. & Neymark, J. 2013. Twent Years On: Updating the IEA BESTEST Building Thermal Fabric Test Cases for ASHRAE Standard 140. In *13th Conference of International Building Performance Simulation Association (IBPSA), Building Simulation, BS2013, Chambéry, France, August 26-28, Conference Proceedings.*

Kagioglou, M., Cooper, R., Ghassan, A. & Sexton, M. 2000. Rethinking construction: the Generic Design and Construction Process Protocol, *Engineering, Construction and Architectural Management*, 2, pp. 141–153.

Kalema, T., Johannesson, G., Pylsy, P. & Hagengran, P. 2008. Accuracy of Energy Analysis of Buildings: A Comparison of a Monthly Energy Balance Method and Simulation

Methods in Calculating the Energy Consumption and the Effect of Thermal Mass, *Journal of Building Physics*, 32(2), pp. 101–130. doi: 10.1177/1744259108093920.

Kendrick, C., Ogden, P., 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, pp. 40–49. doi: 10.1016/j.enbuild.2012.01.009.

Khare, S., Hajat, S., Kovats, S., Lefevre, C. E., DeBruin, W. B., Dessai, S. & Bone, A. 2015. Heat protection behaviour in the UK: Results of an online survey after the 2013 heatwave, *BMC Public Health*, 15(1). doi: 10.1186/s12889-015-2181-8.

Kim, Y., & Kim, K. 2007. Simplified Energy Prediction Method Accounting for Part-load Performance of Chiller. *Building and Environment* 42(1): 507-515.

Knight, A. & Ruddock, L. 2008. *Advanced research methods in the built environment*. Chichester: Wiley-Blackwell.

Kokogiannakis, G., Strachan, P.& Clarke, J. 2008. Comparison of the simplified methods of the ISO 13790 standard and detailed modelling programs in a regulatory context, *Journal of Building Performance Simulation*. 1, pp.209–219. doi:10.1080/19401490802509388.

Kolokotsa, D., Rovas, D., Kosmatopoulos, E. & Kalaitzakis, K. 2011. A roadmap towards intelligent net zero- and positive-energy buildings, *Solar Energy*, 85(12), pp. 3067–3084. doi: 10.1016/j.solener.2010.09.001.

Kontoleon, K. J. & Bikas, D. K. 2007. The effect of south wall's outdoor absorption coefficient on time lag, decrement factor and temperature variations, *Energy and Buildings*, 39(9), pp. 1011–1018. doi: 10.1016/j.enbuild.2006.11.006.

Kossecka, E., & Kosny, J. 1998. Effect of insulation and mass distribution in exterior walls on dynamic thermal performance of whole buildings. *Performance of the Exterior Envelopes of Buildings*, 721–732.

Kosny, J., Petrie, T., Gawin, D., Childs, P., Desjarlais, A. & Christian, J. 2001a. *Energy Savings Potential in Residential Buildings*, USA: Oak Ridge National Laboratory.

Kosny, J., Petrie, T., Desjarlais, A., Atchley, J. A., Childs, P., Ternes, M. & Christian, J. 2001b. *How Insulating Concrete Form vs . Conventional Construction of Exterior Walls Affects Whole Building Energy Consumption : Results from a Field Study and Simulation of Side-by-Side Houses*. USA: Oak Ridge National Laboratory.

Kośny, J. & Kossecka, E. 2002. Multi-dimensional heat transfer through complex building envelope assemblies in hourly energy simulation programs, *Energy and Buildings*, 34(5), pp. 445–454. doi: 10.1016/S0378-7788(01)00122-0.

Kovats, S. & Osborn, D. 2017. Chapter 5 : People and the built environment, *UK Climate Change Risk Assessment 2017: Evidence Report*, pp. 1–168.

Kumar, S., Tewari, P., Mathur, S. & Mathur, J. 2017. Development of mathematical correlations for indoor temperature from field observations of the performance of high thermal mass buildings in India, *Building and Environment*, 122, pp. 324–342. doi: 10.1016/j.buildenv.2017.06.030.

LafargeHolcim. *About LafargeHolcim*. Available at: https://www.lafargeholcim.com/ [Accessed: 21 June 2018].

Lomas, K. J., Eppel, H., Martin, C.J. & Bloomfield, D. P. 1997. Empirical validation of building energy simulation programs, *Energy and Buildings*, 26(3), pp. 253–275. doi: 10.1016/S0378-7788(97)00007-8.

Lomas, K. J. & Eppel, H. 1992. Sensitivity analysis techniques for building thermal simulation programs, *Energy and Buildings*, 19(1), pp. 21–44. doi: 10.1016/0378-7788(92)90033-D.

Lomas, K. J. & Porritt, S. M. 2017. Overheating in buildings: lessons from research, *Building Research & Information*, 45(1–2), pp. 1–18. doi: 10.1080/09613218.2017.1256136.

Loonen, R. C. G. M., Singaravel, S., Trcka, M., Costola, D. & Hensen, J. L. M. 2014. Simulation-based support for product development of innovative building envelope components, *Automation in Construction*, 45, pp. 86–95. doi: 10.1016/j.autcon.2014.05.008.

Love, P. E. D., Holt, G. D. & Li, H. 2002. Triangulation in construction management research, *Construction and Architectural Management*, 9(4), pp. 294–303.

MacDonald, I. 2002. *Quantifying the Effects of Uncertainty in Building Simulation*. PhD Thesis, University of Strathclyde.

Macdonald, I. A. & Strachan, P. 2001. Practical application of uncertainty analysis, *Energy and Buildings*, 33(3), pp. 219–227. doi: 10.1016/S0378-7788(00)00085-2.

Mantesi, E., Cook, M. J., Glass, J. & Hopfe, C.J. 2015. Review of the assessment of thermal mass in whole building performance simulation tools. In *14th Conference of International Building Performance Simulation Association (IBPSA), Building Simulation, BS 2015,Hyderabad, India, 07-09 December 2015, Conference Proceedings*.

Mantesi, E., Hopfe, C. J., Cook, M. J., Class, J. & Strachan, P. 2018. The modelling gap: Quantifying the discrepancy in the representation of thermal mass in building simulation, *Building and Environment*, (131), pp. 74–98. doi: 10.1016/j.buildenv.2017.12.017.

Maref, W., Armstrong, M. M., Saber, H., Swinton, M. C., Ganapathy, G. & Rousseau, M. 2010. *Field Energy Performance of an Insulating Concrete Form (ICF) Wall*, Canada: National Research Council Canada.

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P. & Oikonomou, E. 2012. Building characteristics as determinants of propensity to high indoor summer temperatures in London dwellings, *Building and Environment*, 55, pp. 117–130. doi: 10.1016/j.buildenv.2011.12.003.

McLeod, R. S. & Hopfe, C. J. 2013. Hygrothermal implications of low and zero energy standards for building envelope performance in the UK, *Journal of Building Performance Simulation*, 6, pp. 367–384. doi: 10.1080/19401493.2012.762809.

McLeod, R. S., Hopfe, C. J. & Kwan, A. 2013. An investigation into future performance and overheating risks in Passivhaus dwellings, *Building and Environment*, 70, pp. 189–209. doi: 10.1016/j.buildenv.2013.08.024.

Menezes, A. C., Cripps, A., Bouchlanghem, D. & Buswell, R. 2012. Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap, *Applied Energy*, pp. 355–364. doi: 10.1016/j.apenergy.2011.11.075.

Met Office. *Met Office: weather and climate data*. Available at: https://www.metoffice.gov.uk/ [Accessed: 12 March 2018].

Mithraratne, K., & Vale, B. 2006. Modelling of Thermal Characteristics of Insulated Mass in Zero-heating Passive Solar Houses: Part 1 – Theoretical Analysis. *Architectural Science Review*, 49(3), 213–220.

Monahan, J. & Powell, J. C. 2011. An embodied carbon and energy analysis of modern methods of construction in housing : A case study using a lifecycle assessment framework, *Energy & Buildings*, 43(1), pp. 179–188. doi: 10.1016/j.enbuild.2010.09.005.

Monari, F. & Strachan, P. 2014. Coupling stochastic methods and detailed dynamic simulation programs for model calibration: two preliminary case studies, in *2nd Building Simulation and Optimization Conference, BSO2014. London, UK, 23-24 June 2014, Conference Proceedings*.

Morris, M. D. 1991. Factorial Sampling Plans for Preliminary Computational Experiments, *Technometrics*, 33(2), pp. 161–174. doi: 10.1080/00401706.1991.10484804.

Mousa, W. A. Y., Lang, W. & Yousef, W. A. 2017. Simulations and quantitative data analytic interpretations of indoor-outdoor temperatures in a high thermal mass structure, *Journal of Building Engineering*, 12(March), pp. 68–76. doi: 10.1016/j.jobe.2017.05.007.

Mustafaraj, G., Marini, D., Costa, A. & Keane, M. 2014. Model calibration for building energy efficiency simulation, *Applied Energy*, 130, pp. 72–85. doi: 10.1016/j.apenergy.2014.05.019.

NAHB. 1999. *Insulating Concrete Forms: Comparative Thermal Performance*, USA: Department of Housing and Urban Development.

Naoum, S. G. 2013. *Dissertation research and writing for construction students*. 3rd ed. London: Routledge.

Navarro, L., DeGracia, A., Niall, D., Castell, A., Browne, M., McCormack, S. J., Griffiths, P. & Cabeza, L. F. 2016. Thermal energy storage in building integrated thermal systems: A review. Part 2. Integration as passive system, *Renewable Energy*, 85, pp. 1334–1356. doi: 10.1016/j.renene.2015.06.064.

Neymark, J., Judkoff, r., Knabe, G., Le, H. T., Durig, M., Glass, A. & Zweifel, G. 2002. Applying the building energy simulation test (BESTEST) diagnostic method to verification of space conditioning equipment models used in whole-building energy simulation programs, *Energy and Buildings*, 34, pp. 917–931. doi: 10.1016/S0378-7788(02)00072-5.

NHBC_Foundation. 2016. *Modern Methods of Construction: views from the industry*, London: NHBC Foundation.

NHBC Foundation. 2012. *Understanding overheating - where to start: An introduction for house builders and designers*. London: NHBC Foundation.

Nikolaidou, E., Wright, J. & Hopfe, C.J. 2015. Early and detailed design stage modelling using passivhaus design ; what is the difference in predicted building performance? In *14th Conference of International Building Performance Simulation Association (IBPSA), Building Simulation, BS 2015,Hyderabad, India, 07-09 December 2015, Conference Proceedings*.

Norford, L. K., Socolow, R. H., Hseih, E. S. & Sparado, G. V. 1994. Two-to-one discrepancy between measured and predicted performance of a "low-energy" office building: insights from a reconciliation based on the DOE-2 model, *Energy and Buildings*, 21(2), pp. 121–131. doi: 10.1016/0378-7788(94)90005-1.

Omrany, H., GhaffarianHoseini, A., GhaffarianHoseini, A., Raahemifar, K. & Tookey, J. 2016. Application of passive wall systems for improving the energy effciency in buildings: A comprehensive review, *Renewable and Sustainable Energy Reviews*, 62, pp. 1252–1269. doi: 10.1016/j.rser.2016.04.010.

Ozel, M. & Pihtili, K. 2007. Optimum location and distribution of insulation layers on building walls with various orientations, *Building and Environment*, 42(8), pp. 3051–3059. doi: 10.1016/j.buildenv.2006.07.025.

Pan, W., Gibb, A. & Dainty, A. 2007. Perspectives of UK housebuilders on the use of offsite modern methods of construction, *Construction Management and Economics*, 25 (2), pp.183-194.

Parliament of the United Kingdom. 2008. Climate Change Act 2008, *HM Government*, pp. 1–103. doi: 10.1136/bmj.39469.569815.47.

Passivhaus. *Word's Leading Fabric First Approach to Low Energy Buildings*. Available at: http://www.passivhaus.org.uk/ [Accessed: 27 April 2018].

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(7), pp. 3277–3288. doi: 10.1016/j.enpol.2010.01.021.

Perez, R. 1992. Dynamic global-to-direct irradiance conversion models, *Ashrae*, 98(1), pp. 354–369.

Porritt, S., Shao, I., Cropper, P. & Goodier, C. 2011. Adapting dwellings for heat waves, *Sustainable Cities and Society*, 1(2), pp. 81–90. doi: 10.1016/j.scs.2011.02.004.

Prada, A., Cappelletti, F., Baggio, P. & Casparella, A. 2014. On the effect of material uncertainties in envelope heat transfer simulations, *Energy and Buildings*, 71, pp. 53–60. doi: 10.1016/j.enbuild.2013.11.083.

QAA. 2015. *UK Quality Code for Higher Education: Doctoral Degree Characteristics*. Gloucester: Quality Assurance Agency for Higher Education. doi: ISBN 978 1 84979 550 0.

Rajagopalan, N., Bilec, M. M. & Landis, A. E. 2009. Comparative life cycle assessment of insulating concrete forms with traditional residential wall sections. In *2009 IEEE International Symposium on Sustainable Systems and Technology, ISSST '09 in Cooperation with 2009 IEEE International Symposium on Technology and Society, ISTAS. Conference Proceedings.* doi: 10.1109/ISSST.2009.5156707.

Raslan, R. M. S. 2010. *Performance Based Regulations: The Viability of the Modelling Approach as a Methodology for Building Energy Compliance Demonstration*, PhD Thesis, University College London, UK.

Raslan, R. M. S. & Davies, M. 2010. Results variability in accredited building energy performance compliance demonstration software in the UK: an inter-model comparative study, *Journal of Building Performance Simulation*, 3(1), pp. 63–85. doi: 10.1080/19401490903477386.

Reddy, T. A. 2006. Literature review on calibration of building energy simulation programs: Uses, problems, procedures, uncertainty, and tools, *ASHRAE Transactions*, 112(1), pp. 226–240. doi: Article.

Reilly, A. & Kinnane, O. 2017. The impact of thermal mass on building energy consumption, *Applied Energy*, 198, pp. 108–121. doi: 10.1016/j.apenergy.2017.04.024.

Robson, C. 2011. *Real world research : a resource for social scientists and practitioner-researchers*. 3rd ed. London: Blackwell.

Rodrigues, L. T. 2010. *An investigation into the use of thermal mass to improve comfort in British housing*. PhD Thesis, University of Nottingham. Available at: http://etheses.nottingham.ac.uk/1872/ [Accessed: 14 July 2014].

Rogelj, J., DenElzen, M., Hohne, N., Fransen, T., Fekete, H. & Winkler, H. 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C, *Nature*, 534(7609), pp. 631–639. doi: 10.1038/nature18307.

Ryan, E. M. & Sanquist, T. F. 2012. Validation of building energy modeling tools under idealized and realistic conditions, *Energy and Buildings*, 47, pp. 375–382. doi: 10.1016/j.enbuild.2011.12.020.

Saber, H. H., Maref, W., Armstrong, M. M. Swinton, M. C., Rousseau, M. Z. & Gnanamurugan, G. 2011. *Numerical Simulations to Predict the Thermal Response of Insulating Concrete Form (ICF) Wall in Cold Climate*, Canada: National Research Council.

Sadineni, S. B., Madala, S. & Boehm, R. F. 2011. Passive building energy savings: A review of building envelope components, *Renewable and Sustainable Energy Reviews*, 15(8), pp. 3617–3631. doi: 10.1016/j.rser.2011.07.014.

Saltelli, A., Tarantola, S., Campolongo, F. & Ratto, M. 2004. *Sensitivity analysis in practice : a guide to assessing scientific models*. Chichester: John Wiley.

Saltelli, A., Tarantola, S. & Campolongo, F. 2000. Sensitivity Anaysis as an Ingredient of Modeling, *Statistical Science*, 15(4), pp. 377–395. doi: 10.1214/ss/1009213004.

Shafigh, P., Asadi, I. & Mahyuddin, N. B. 2018. Concrete as a thermal mass material for building applications - A review, *Journal of Building Engineering*, 19, pp. 14–25. doi: 10.1016/j.jobe.2018.04.021.

Silva, A. S. & Ghisi, E. 2014. Uncertainty analysis of user behaviour and physical parameters in residential building performance simulation, *Energy and Buildings*, 76. doi: 10.1016/j.enbuild.2014.03.001.

SimLab. *SimLab 2.2, Reference Manual*. Available at: https://ec.europa.eu/jrc/en/samo/simlab [Accessed: 12 March 2018].

Singh, M. K., Mahapatra, S., Atreya, S. K. & Givoni, B. 2010. Thermal monitoring and indoor temperature modeling in vernacular buildings of North-East India, *Energy and Buildings*, 42(10), pp. 1610–1618. doi: 10.1016/j.enbuild.2010.04.003.

Slee, B., Parkinson, T. & Hyde, R. 2014. Quantifying useful thermal mass: How much thermal mass do you need?, *Architectural Science Review*, 57(4), pp. 271–285. doi: 10.1080/00038628.2014.951312.

Sun, Y. 2014. *Closing the building energy performance gap by improving our predictions*. PhD Thesis, Georgia Institute of Technology.

Swann, R., Baird, E., Vaughan, P., Dixon, J., Douthwaite, R., Mairs, I. & Davies, J. 2012. *Population Growth and Housing Expansion in the UK. Some preliminary considerations*. London.

Threlkeld, J. L. 1970. *Thermal Environmental Engineering.* New Jersey: Prentice Hall, Inc.

Thumann, A. & Younger, W. J. 2009. *Handbook of energy audits*. 8th ed. London: Taylor & Francis.

Troop, D. 2013. *Tackling the Housing Crisi in England. CLA Policy on Securing and Increasing Housing Supply in England 2013-2018.* London.

UKCP. *UK Climate Projections*. Available at: http://ukclimateprojections.metoffice.gov.uk/21684 [Accessed: 8 May 2018].

UNFCCC. *The Kyoto Protocol*. Available at: https://unfccc.int/process/the-kyoto-protocol [Accessed: 3 May 2018].

United States of America: Communication. 2017. ‘C.N.464.2017.TREATIES-XXVII.7.d (Depositary Notification)’.

US DOE, Department of Energy. *EnergyPlus*. Available at: https://energyplus.net/ [Accessed on: 28 May 2018].

Vardoulakis, S., Dimitroulopoulou, C., Thornes, J., Lai, K., Taylor, J. & Myers, I. 2015. Impact of climate change on the domestic indoor environment and associated health risks in the UK, *Environment international*, 85, pp. 299–313. doi: 10.1016/j.envint.2015.09.010.

Victor, D. G., Akimoto, K., Kaya, Y., Yamaguchi, M., Cullenward, D. & Hepburn, C. 2017. Prove Paris was more than paper promises, *Nature*, 548(7665), pp. 25–27. doi: 10.1038/548025a.

Waltz, P. J. 2000. *Computerized Building Energy Simulation Handbook*. Lilburn, GA: The Fairmont Press.

Wang, H. & Zhai, Z. (John). 2016. Advances in building simulation and computational techniques: A review between 1987 and 2014, *Energy and Buildings*, 128, pp. 319–335. doi: 10.1016/j.enbuild.2016.06.080.

Wang, S., Yan, C. & Xiao, F. 2012. Quantitative energy performance assessment methods for existing buildings, *Energy and Buildings*, 55, pp. 873–888. doi: 10.1016/j.enbuild.2012.08.037.

Wellington, J. 2010. *Making supervision work for you*. London: SAGE.

De Wilde, P. 2014. The gap between predicted and measured energy performance of buildings: A framework for investigation, *Automation in Construction*, 41, pp. 40–49. doi: 10.1016/j.autcon.2014.02.009.

De Wilde, P. & Coley, D. 2012. The implications of a changing climate for buildings, *Building and Environment*, 55, pp. 1–7. doi: 10.1016/j.buildenv.2012.03.014.

Williams, D., Elghali, L., Wheeler, R. & France, C. 2012. Climate change influence on building lifecycle greenhouse gas emissions: Case study of a UK mixed-use development, *Energy and Buildings*, 48, pp. 112–126. doi: 10.1016/j.enbuild.2012.01.016.

De Wit, M. S. 2001. *Uncertainty in Predictions of Thermal Comfort in Buildings*. PhD Thesis, DELFT University of Technology. doi: 90-9014884-1.

De Wit, S. & Augenbroe, G. 2002. Analysis of uncertainty in building design evaluations and its implications, *Energy and Buildings*, 34(9), pp. 951–958. doi: 10.1016/S0378-7788(02)00070-1.

Woods, M. & Trexler, C. J. 2001. Linking interpretative theory to practice: Examining an underused research tool in agricultural education, *Journal of Agricultural Education*, 42(2), pp. 68–77.

Yin, R. K. 2009. *Case study research : design and methods*. 4th ed. Los Angeles, California. London: SAGE.

Zhang, X. & Cheng, F. 2018. Comparative assessment of external and internal thermal insulation for energy conservation of intermittently air-conditioned buildings, *Journal of Building Physics*, 1-17 (4800). doi: 10.1177/1744259118777677.

Zhu, D., Hong, T., Yan, D. & Wang, C. 2012. *Comparison of Building Energy Modeling Programs: Building Loads*, USA: Ernest Orlando Lawrence Berkeley National Laboratory.

Zhu, L., Hurt, R., Correia, D. & Boehm, R. 2009. Detailed energy saving performance analyses on thermal mass walls demonstrated in a zero energy house, *Energy and Buildings*, 41(3), pp. 303–310. doi: 10.1016/j.enbuild.2008.10.003.

APPENDIX A PAPER 1: INVESTIGATING THE IMPACT OF MODELLING UNCERTAINTY ON THE SIMULATION OF ICF FOR BUILDINGS

Full Reference

Mantesi, E., Hopfe, C. J., Glass, J., Cook, M. J., 2016. Investigating the Impact of Modelling Uncertainty on the Simulation of ICF for Buildings, In *3rd Building Simulation and Optimization Conference BSO2016. Newcastle, UK, 12-14 September 2016, Conference Proceedings.* URI: https://dspace.lboro.ac.uk/2134/21972.

Abstract

Insulating Concrete Formwork (ICF) walls consist of cast in situ concrete poured between two layers of EPS insulation. The system can achieve very low U-values and high levels of air-tightness. This paper investigates the inconsistency in simulation results provided by nine widely used Building Performance Simulation (BPS) tools when calculating the energy consumption and the thermal performance of buildings using ICF. The aim is to identify the impact that the various modelling methods have on the simulation results. There were significant inconsistencies in the simulation results, especially for the annual and peak heating demand. Moreover, among the different calculation methods, the surface emissivity, the infiltration rate and the specification of the internal gains were found to cause significant variations.

Key Words

Thermal Mass; Building Performance Simulation; Modelling Uncertainties; Default Settings; Calculation Algorithms; Inter-Model Comparative Analysis.

Paper Type – Conference Paper

1 INTRODUCTION

In Europe, the built environment accounts for 40% of the total energy use and 36% of the total CO_2 emissions (Foucquier et al., 2013; McLeod et al., 2013). The UK Government, through the Climate Change Act 2008, has set targets to embrace a long-term climate change mitigation and adaptation strategy and to reduce CO_2 emissions by 80% in 2050 (compared to 1990 levels) (Climate Change Act, 2008).

Alongside carbon reduction targets, the government has to deal with the challenges imposed by the current housing shortage (Pan et al., 2007). Since 1990, population growth increased, whilst the number of completed dwellings per year dropped (Swann et al., 2012). The UK government is committed to increase the number of new houses, since further increase of population to 10.2 million people is expected by 2033 (compared to 2008 levels) (Monahan & Powel, 2011; Swann et al., 2012). One solution to this problem is the increased use of offsite Modern Methods of Construction (MMC). MMC are defined as a number of mostly off-site innovative prefabricated technologies in house building (Pan et al., 2007).

The present study focuses on one of the site-based MMC, called Insulated Concrete Formwork (ICF). ICF consists of modular prefabricated EPS hollow blocks and cast in situ concrete. The blocks are assembled on site and the concrete is poured in the void. Once the concrete has cured, the insulating formwork stays in place permanently. The resulting structure is a typical reinforced concrete wall (Chant, 2012). The ICF wall system has two main advantages in comparison to other lightweight MMC and conventional construction methods; when the concrete is placed, the structural performance of ICF is able to support concrete floors and staircases, increasing the overall thermal mass of the entire structure. Moreover, the system provides complete external and internal wall insulation, eliminating the existence of thermal bridging, providing very low U-values and high levels of air-tightness, when applied properly (Rajagopalan et al., 2009; Chant, 2012). The amount of research associated with ICF is limited in the UK. Nevertheless, previous studies conducted elsewhere (i.e. USA, Canada, New Zealand) describe a number of advantages, such as its thermal resistance and air-tightness, its resilience to fire and other natural disasters, sound reduction, structural strength and durability (NAHB, 1997; Chant, 2012).

ICF is generally perceived as merely an insulated panel. The internal layer of the insulation isolates the thermal mass of the concrete from the internal space and interferes with their thermal interaction. However, there is anecdotal evidence supporting the thermal storage capacity of the element's concrete core (Chant, 2012). The overall aim of this research is to effectively quantify the "Thermal Mass" of ICF. One important aspect is therefore to understand how dynamic whole Building Performance Simulation (BPS) assesses transient heat transfer in and out of the ICF building fabric.

Spitler defines BPS as the simulation of building thermal performance using digital computers (Clarke & Hensen, 2015). BPS was first introduced in 1960s and it has been an active area of research ever since (Zhu et al., 2012; Clarke & Hensen, 2015). Based on descriptions of the construction, occupancy patterns and HVAC systems, BPS tools perform detailed heat-balance calculations at specified time-steps and are able to predict the energy required to maintain comfortable conditions under the influence of external inputs (i.e. weather, occupancy, infiltration) (Coakley et al., 2014). However, it is generally accepted that there is a high level of uncertainty and sensitivity associated with current BPS methods and tools (Hopfe & Hensen, 2011; Burman et al., 2012). This can lead to a lack of confidence in building simulation.

The main factors contributing to uncertainties and inaccuracies of the simulation predictions reside in the modelling methods and the different algorithms employed by the different BPS tools and are partly a consequence of the user input data (Burman et al., 2012; Zhu et al., 2012; Berkeley et al., 2014; Mantesi et al., 2015a; Strachan et al., 2015).

De Wit, (1997) classified the various sources of uncertainty as follows:

- Specification uncertainties, (incomplete or inaccurate specification of building input parameters)
- Modelling uncertainties, (simplifications and assumptions of complex physical processes)
- Numerical uncertainties, (errors introduced in the discretation and the simulation model)
- Scenario uncertainties, (the external conditions imposed on the building)

All models represent a simplification of reality. In order to rely on BPS prediction with a degree of confidence, it is important to represent the actual performance of a building as accurately as possible (Hopfe, 2009). Current state-of-the-art BPS tools have several limitation related to air flow, lighting, HVAC systems, occupants representation and others (Clarke & Hensen, 2015). This paper is a follow up study (Mantesi et al., 2015a; Mantesi et al., 2015b) aiming to analyse the divergence in the simulation results provided by nine state-of-the-art BPS tools when modelling the energy consumption and thermal performance of an ICF building. The analysis will contrast the simulation results provided by each of the nine BPS tools for the annual energy consumption and the peak thermal loads produced for a single zone test building and for three different construction methods, low mass, high mass and ICF wall assemblies (Figure 1). Furthermore, the paper aims to investigate the implications of the modelling uncertainties associated with the various calculation methods in the simulation results provided by two of the nine BPS tools. The research objectives are:

- To investigate the extent of divergence in the simulation results provided by the BPS tools.
- To investigate the deviation in the energy use when comparing ICF to low and high thermal mass construction methods.

- To identify the key parameters on the calculation algorithms responsible for discrepancies in the simulation results.

2 METHODOLOGY

The BESTEST method was used in the first step of the analysis to validate the models and to evaluate how each of the BPS tools calculate the effect of thermal mass in the loads calculation. The same single-zone test building was used in the following stages of the study to minimise the variables in the input data related to geometry and zoning, which were specified according to the BESTEST method. Three different construction methods were simulated; ICF, high mass and low mass. The ICF fabric description was based on actual construction details and was used as a reference to specify the U-values of the construction elements, which were kept constant among the three constructions. The main difference among the three building models was the level of thermal mass in the fabric. The input data used for the building models are summarised in Table 1.

Table 1 *Input data used for the building model*

Building Model Details	
Floor Area	6m x 8m = 48m^2
Orientation	Long axis on East-West direction
Windows	Two double glazed windows, 2m x 3m each, on south façade
HVAC system	Ideal loads
HVAC Set points	20º Heating/ 27º Cooling
Internal Gains	200W (other equipment)
Infiltration	0.5ach

The DRYCOLD weather file, downloaded from NREL, representing a climate with cold clear winters and hot dry summers, was used for all simulations (Table 2).

Table 2 *Indicative values of the weather file used for the simulations*

Weather Data	
Dry Bulb Temperature (C^o)	
Minimum	-24.4
Maximum	35
Mean	9.7
Direct Horizontal Solar Radiation (kWh/m^2.y)	1339.48
Diffuse Horizontal Solar Radiation (kWh/m^2.y)	492.34

The analysis was carried out in two parts. The first part presents an inter-model comparison on the annual energy consumption and the system peak loads, provided by the nine tools for the ICF building. The calculation were performed based on the default algorithms employed by each tool, aiming to reflect on the extent of variations in the simulation results that a user relying on the default settings of the tool would obtain. Error bars were used in the charts to demonstrate the energy consumption of the low and the high thermal mass building cases. Five of the tools (used for the analysis) were proprietary commercial tools. For reasons of sensitivity and fairness, we have chosen not to name the tools. We do not feel that this distracts from the scientific merit of the paper.

The second stage was a systematic, parametric comparison for two of the BPS tools that provided very similar results in the first instance of the analysis. The aim was to understand the modelling uncertainties associated with the various calculation methods, even when the simulation results are very similar. Prior to proceeding to the parametric analysis it is crucial to determine that any divergence in the results is due to the differences in modelling methods and not caused by other factors. To achieve this, it was important to minimise the differences in the models created. Identical algorithms and consistent values were used in both tools, making the models equivalent for comparison, leaving little ground for differences (i.e internal convective coefficients calculation, longwave radiation exchange etc) (Table 3). These two models will be further referred to as “equivalent models”.

Finally, a number of special test cases was designed and simulated on the equivalent models aiming to investigate the impact of several key parameters when modelling ICF in whole BPS (Table 4). The results of the analysis are presented for the surface heat gains and losses occurring on the ICF South Wall.

3 RESULTS

SYSTEMS LOADS COMPARISON

The system loads comparison indicates that the inconsistency in the simulation results provided by the nine BPS tools for the annual energy consumption (Figures 2 and 4) and the peak thermal loads (Figures 3 and 5) is more significant for heating than for cooling. The relative differences in the results, when comparing the maximum and minimum values provided by the tools is 57% for the annual heating demand (Figure 2) and 25% for the peak heating demand (Figure 3). In both cases, tool I estimates the lowest energy consumption, while tools G and H estimate the highest for annual heating and peak heating respectively.

The deviation in the simulation results is lower for the annual cooling energy consumption (Figure 4) and the peak cooling demand (Figure 5). In both cases, tool G estimates the highest values, around 22% increased, compared to tool D, which gives the minimum value for the annual cooling demand and around 14% higher than tool B for the peak cooling loads.

There are also inconsistencies in the simulation results provided by the tools for the other two construction methods. The divergence is again found to be higher for the heating energy consumption (Figure 2) and the heating peak loads (Figure 3). Table 5 summarises the relative differences between the maximum and minimum values in the simulation results for all three building cases. It can be seen that the divergence is always higher for the high mass case.

Table 5 *Relative differences between the maximum and minimum estimated energy consumption in [%]*

Energy Use	ICF	Low Mass	High Mass
Annual Heating	57%	30%	70%
Peak Heating	25%	18%	34%
Annual Cooling	22%	15%	29%
Peak Cooling	14%	11%	24%

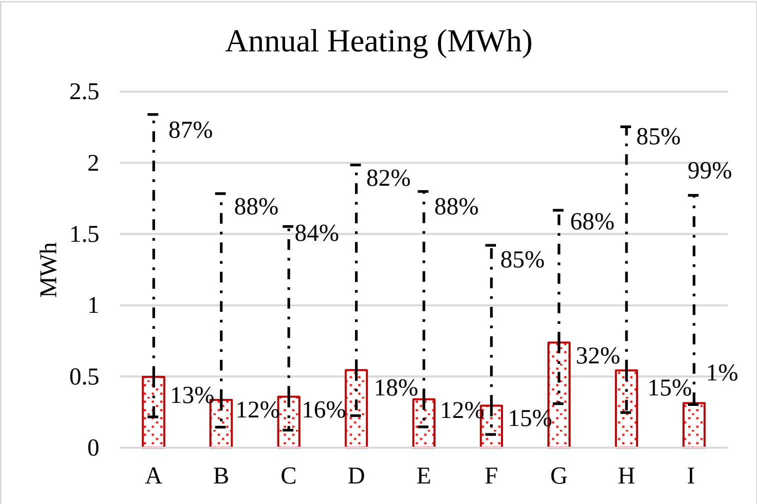


Figure 2 *The graph demonstrates the results for annual heating energy consumption (MWh). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the annual heating energy consumption of the low mass construction and the lower limit showing the results of the high mass construction.*

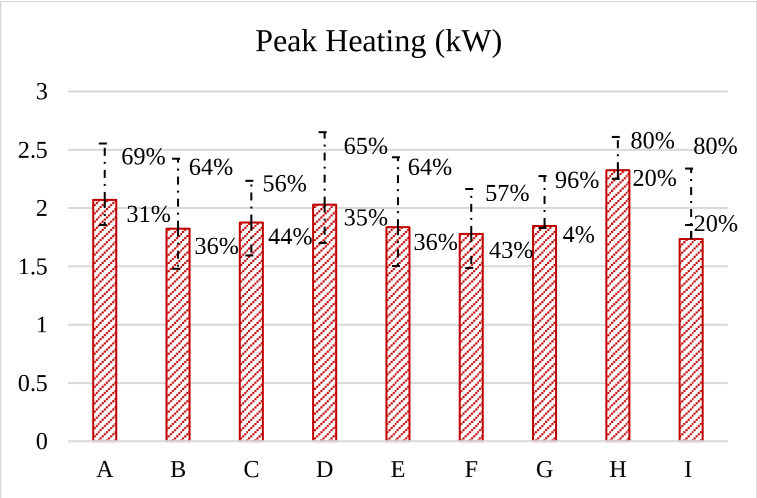


Figure 3 *The graph demonstrates the results for peak hourly integrated heating loads (kW). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the peak heating loads of the low mass construction and the lower limit showing the results of the high mass construction.*

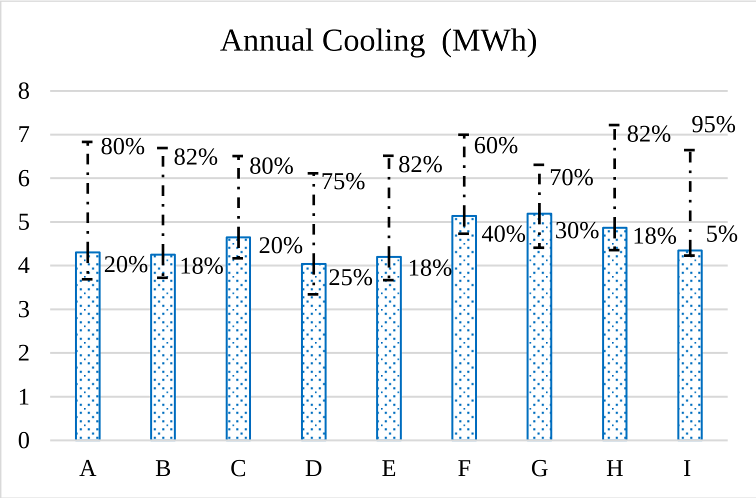


Figure 4 *The graph demonstrates the results for annual cooling energy consumption (MWh). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the annual cooling consumption of the low mass construction and the lower limit showing the results of the high mass construction.*

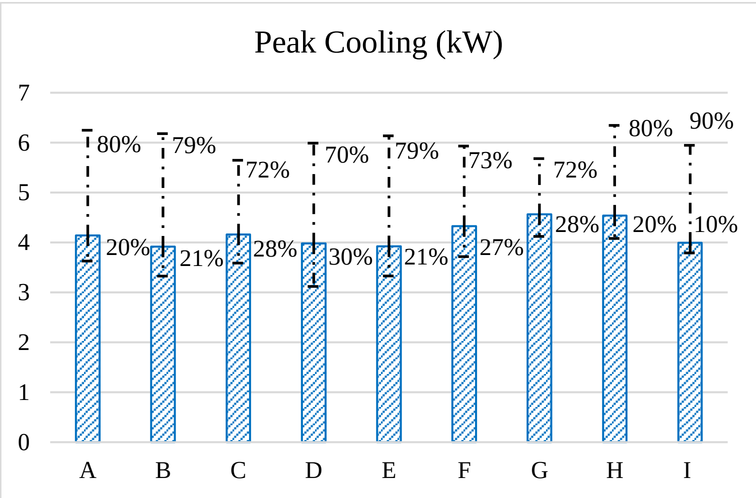


Figure 5 *The graph demonstrates the results for peak hourly integrated cooling loads (kW). The bars illustrate the results for ICF, with the upper limit of the dashed line showing the peak cooling loads of the low mass construction and the lower limit showing the results of the high mass construction.*

In the comparison of ICF thermal performance to the low and the high thermal mass cases, the general observation is that ICF falls between the aforementioned construction methods and behaves closer to the high thermal mass building. Looking at the range of variation in the annual heating energy consumption ICF requires on average 85% less energy than the low mass case. In the annual cooling demand the difference is around 80% (averaged over all nine BPS tools). In the peak heating and cooling loads, the average reduction is 70% for heating and 77% for cooling. The inter-model comparison shows that in all of the cases (with exception to peak heating demand), Tool I estimates the greatest difference in the energy use between ICF and low mass construction, while tool G estimates the least.

"EQUIVALENCING" THE MODELS

Tools E and I provided very similar results in the inter-model comparison and were selected for further analysis. The same algorithms and user input values were applied (Table 3), to reduce the differences in the models created for comparison. Figures 6 to 9 illustrate the annual energy consumption and the peak system loads for the comparable models plotted monthly.

There is an insignificant divergence in the annual cooling energy consumption and the peak cooling loads, where tool I provides slightly increased demand to tool E (Figures 7 and 9). Moreover, there is an incompatibility in the peak heating loads for the month of June, where tool E suggests that there is a relatively small demand, while tool I suggests zero demand. Overall, as it can be seen from the charts, there is a general consistency in the results, which confirms that the differences between the two models are minimised and the equivalent models are suitable for the parametric analysis.

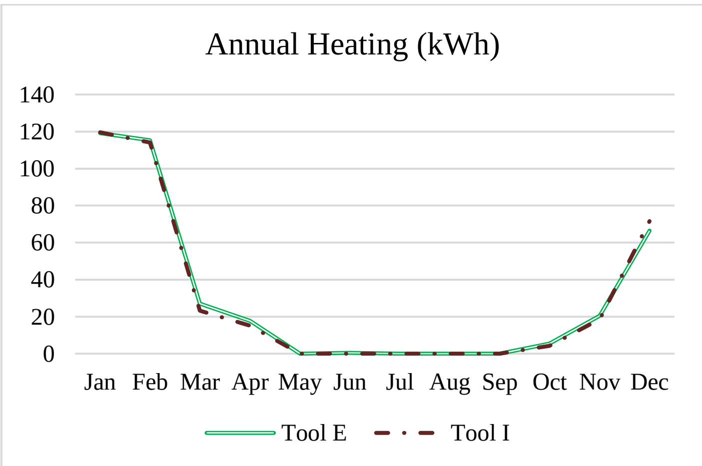


Figure 6 *Annual heating energy consumption of equivalent models. Monthly breakdown*

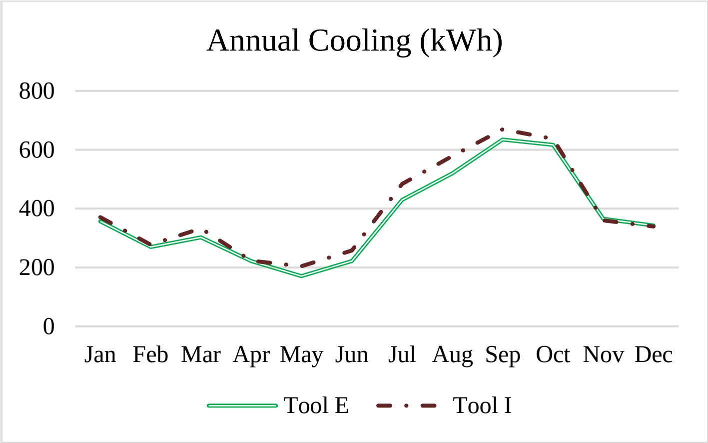


Figure 7 *Annual cooling energy consumption of equivalent models. Monthly breakdown*

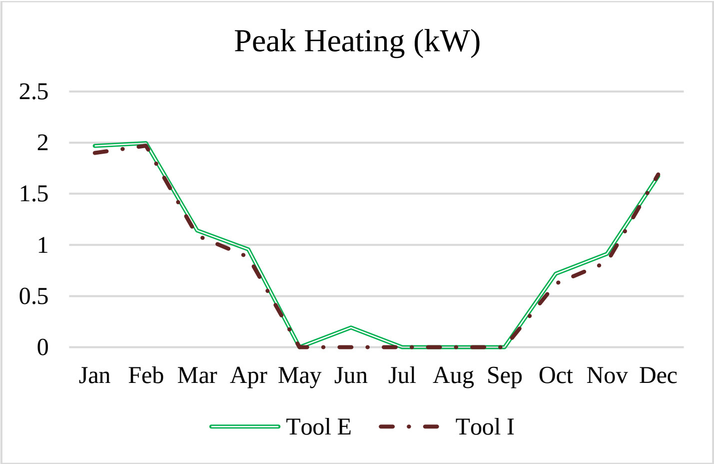


Figure 8 *Peak heating demand of equivalent models. Monthly breakdown*

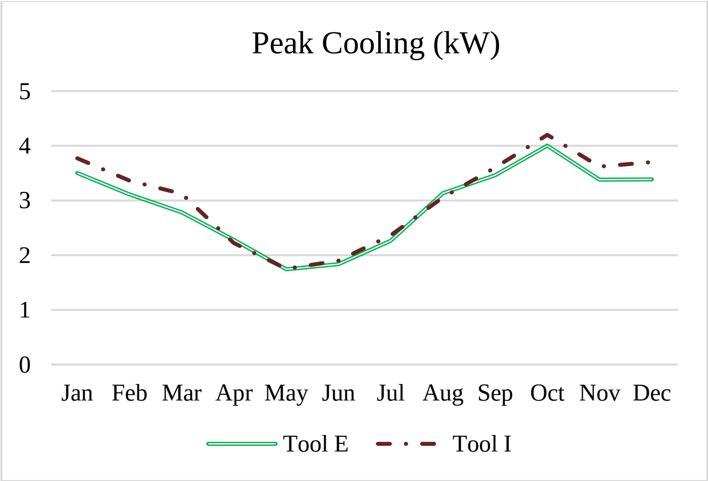


Figure 9 *Peak cooling demand of equivalent models. Monthly breakdown*

SPECIAL TEST CASES RESULTS

The test cases included in the parametric analysis are summarised in Table 4. The results are plotted for the South ICF wall of the test building case. The aim is to analyse how the two BPS tools simulate the performance of ICF with regard to the heat transfer mechanisms that occur in the wall elements. Figure 10 indicates that there is a consistent 9% divergence in the solar gains of the internal surface of the wall in all test cases, which is unaffected of the input variables. Tool E calculates the distribution of beam solar radiation uniformly over the entire wall area, while tool I relies on solar tracking calculations. The results of both tools are slightly decreased in TC4, where the solar absorptance of the wall is increased to 0.6 and the divergence is increased to 11%.

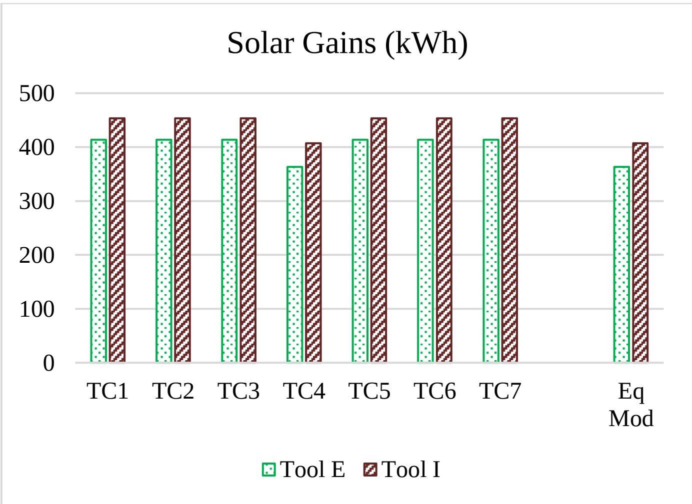


Figure 10 *Solar gains in South ICF wall*

The divergence in the wall's conduction losses varies in the several test cases (Figure 11). There is an initial 12% difference between the two tools in the basecase, which increases to 18% in TC2, when the default algorithms are used to calculate the internal convection coefficient of the wall surface. The divergence decreases to 6% for TC3, where the surface IR emissivity is 0.9 and then increases again (13%) in TC4 when the solar absorptance is 0.6. In the presence of internal gains, either 100% convective (TC5) or 100% radiative (TC6), the difference between the tools in the conduction losses decreases to 4%. Finally, in TC7, when infiltration is introduced in the analysis, the divergence in the simulation results increases to 20%.

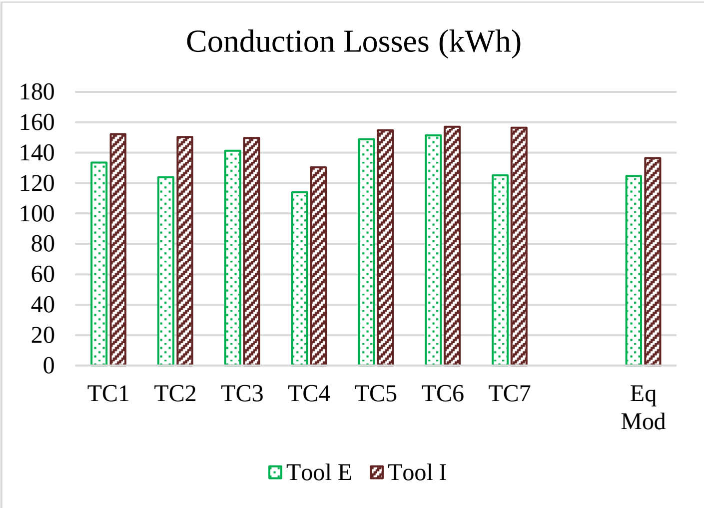


Figure 11 *Conduction losses in South ICF wall*

Even though the same constant value is used in both models for the internal surface convection coefficient, it can be seen that the convection losses of the internal surface of the South ICF wall varies among the test cases (Figure 12). There is a 41% difference in the basecase, which slightly decreases to 37% in TC2 (default algorithm for convection coefficient). The difference is further decreased when the surface IR emissivity is 0.9 in TC3 to 23%. It is interesting to notice that when the internal gains are 100% convective (TC5) there is a difference of 35% in the convection heat losses of the surface between the two tools. Whereas, when the internal gains are 100% radiative (TC6) the divergence in the results decreases to 13%. Tool E calculates the radiant distribution of the internal gains based on surface absorptance, while tool I calculates their distribution proportional to the wall area.

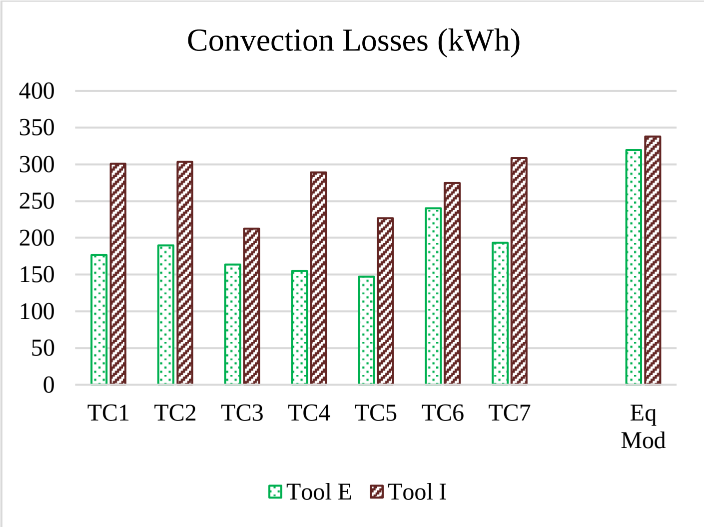


Figure 12 *Convection losses in South ICF wall*

The maximum inconsistency in the simulation results between the different test cases is found to be in the long-wave radiation losses of the internal surface (Figure 13). In the basecase, tool E shows increased long-wave radiation losses by 61% compared to tool I, which is relatively consistent in TC2, TC4 and TC7. When the surface emissivity increases to 0.9 in TC3, TC5 and TC6 the difference between the two tools is reversed. Tool I gives an increased value for the long-wave radiation losses 16% in TC3 and 13% in TC5 and TC6.

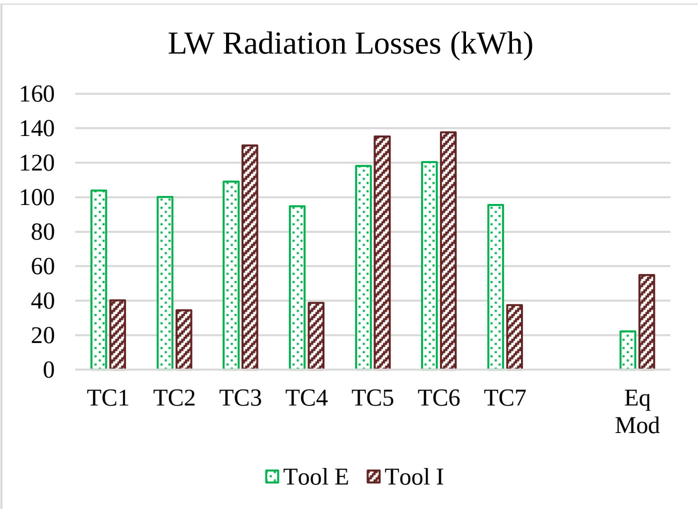


Figure 13 Long-wave radiation losses in South ICF wall

4 DISCUSSION

The analysis shows that there are inconsistencies in the simulation results provided by the nine BPS tools when modelling an ICF building. The relative differences between the maximum and minimum values were more significant for the annual and peak heating demand. The divergence was obvious in the results provided for the other two construction methods. It was also found that the difference between the maximum and minimum values was more substantial for heating demand and it was increasing according to the thermal mass of the fabric (highest divergence for the high mass building).

The results of the comparative analysis between the ICF, low and high mass construction methods are consistent with the findings from previous studies (Gajda & VanGeem, 2000; Rajagopalan et al., 2009). The general observation is that ICF's energy consumption falls between the other two construction methods and sits closer to the performance of the high mass building.

Two of the tools were used in the parametric analysis of the second stage; the same algorithms and user input variables were used, where possible. The results of the special test cases confirm previous work (Zhu et al., 2012; Mantesi et al., 2015a), indicating that the key factors contributing to inconsistencies in the simulation results provided by different BPS tools reside in the different modelling methods adopted by each tool and fall under the category of modelling uncertainties (Hopfe, 2009).

Among the different sources of heat gains and losses calculated for the internal surface of the ICF South wall, long-wave radiation losses were found to exhibit the greatest inconsistency among the different test cases, although the same view factors were specified for all surfaces in both models. The surface IR emissivity was found to have a substantial impact on the results' divergence.

The inconsistencies in the calculation of surface conduction losses were also found to vary according to the different test cases. The difference between the two tools was decreased when the surface IR emissivity was 0.9 and increased in every other case, reaching the highest value when infiltration was introduced.

Concerning convection heat losses, even though constant values were used for the internal surface convection coefficient, there was divergence in the results provided by the two tools, varying according to the different test cases; the difference decreased when the surface IR emissivity was set to 0.9. Moreover, it was interesting that for 100% convective internal gains the divergence between the two tools was relatively high, while when the internal gains were set to 100% radiative, their difference was significantly reduced, although the two tools use different methods in calculating the radiant distribution of internal gains.

Even though the two tools calculate the distribution of solar gains using different modelling methods, it was observed that it had little impact on the results' divergence. Both BPS tools provided relatively consistent results among the different test cases.

5 RESEARCH LIMITATIONS

The analysis presented in this paper was based on a simple, unoccupied, single-zone building, using constant values for the dynamic loads (i.e. internal gains, infiltration rates). The impact of variable airflows (ventilation and infiltration), realistic occupancy patterns and internal gains were excluded from the analysis. Moreover, the special test cases were only performed for two of the nine BPS tools included in the inter-model comparative analysis. In order to draw robust conclusions on the impact of the different calculation methods, the parametric analysis should include more BPS tools.

6 CONCLUSIONS

This paper analysed the divergence in simulation results provided by nine BPS tools, when modelling an ICF single-zone building, aiming to interrogate the extent of variation in the annual energy consumption and the system peak loads estimated by the tools. The results showed that there were significant inconsistencies in the simulation predictions when simulations were performed using the default algorithms employed by the tools. The divergence was found to be more substantial for the annual and peak heating demand and increased accordingly with the level of thermal mass in the fabric. ICF's energy consumption was compared to low and high thermal mass building and it was found to fall between the other two construction methods, performing closer to the high mass building.

Two BPS tools were selected for further analysis. A number of special test cases was designed and simulated, aiming to reflect on the impact of several key input variables on the results divergence. The results of the special test cases indicated that the surface IR emissivity had a significant impact on the simulation of surface long-wave radiation, conduction and convection losses. The infiltration rate affected significantly the inconsistency between the two tools when simulating the surface conduction losses. The divergence in the convection heat losses was affected by the specification of the internal gains to convective or radiative.

7 FUTURE WORK

This work is part of a doctoral research project seeking to investigate the thermal performance of ICF and the accuracy of BPS when modelling an ICF building. The results of the inter-model comparison provided some feedback on the extent of variation among the different tools. However, it is not possible to evaluate the accuracy of BPS predictions. A monitoring study on an ICF building case is planned and it is expected to provide valuable information on the actual energy consumption and the thermal performance of ICF. Moreover, it will serve as a means of empirical validation for the BPS simulation results.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Engineering and Physical Sciences Research Council UK (EPSRC), the Centre for Innovative and Collaborative Engineering (CICE) at Loughborough University, Aggregate Industries UK Ltd and Dr Paul Strachan for their support.

REFERENCES

Berkeley, P., Haves, P., & Kolderup, E., 2014. Impact of Modeler Decisions on Simulation Results. In *2014 ASHRAE/IBPSA-USA Building Simulation Conference Atlanta, GA September 10-12, 2014, Conference Proceedings.*

Burman, E., Rigamonti, D., Kimpain, J., & Mumovic, D., 2012. Performance gap and thermal modelling: A comparison of simulation results and actual energy performance for an academy in North West England. . In *1st Building Simulation and Optimization Conference, BSO2012, Loughborough, UK, 10-11 September 2012, Conference Proceedings.*

Chant, M. H., 2012. *Insulating Concrete Formwork (ICF) and Concrete: An Alternative Construction Approach for Sustainable and Resilient Residential Architecture*. MArch Thesis. University of Auckland

Clarke, J. A., & Hensen, J. L. M., 2015. Integrated building performance simulation: Progress, prospects and requirements. *Building and Environment*, 91, pp.294–306

Coakley, D., Raftery, P., & Keane, M., 2014. A review of methods to match building energy simulation models to measured data. *Renewable and Sustainable Energy Reviews*, 37, pp.123–141. doi.org/10.1016/j.rser.2014.05.007.

De Wit, S., 1997. Influence of modeling uncertainties on the simulation of building thermal comfort performance. In *5th Conference of International Building Performance Simulation Association (IBPSA), Building Simulation, BS2017, Pragues, Czech Republic, 8-10 September 1997, Conference Proceedings.*

Foucquier, A., Robert, S., Suard, F., Stéphan, L., & Jay, A., 2013. State of the art in building modelling and energy performances prediction: A review. *Renewable and Sustainable Energy Reviews*, 23, pp.272–288

Gajda, J., & VanGeem, M., 2000. *Energy use in residential housing: A comparison of insulating concrete form and wood frame walls*. Maryland: Portland Cement Association

Hopfe, C. J., 2009. *Uncertainty and sensitivity analysis in building performance simulation for design support and design oprimization*. PhD Thesis, Technische Universiteit Eindhoven. doi:10.1016/j.enbuild.2015.09.010.

Hopfe, C. J., & Hensen, J. L. M., 2011. Uncertainty analysis in building performance simulation for design support. *Energy and Buildings*, 43 (10), pp.2798-2805

Mantesi, E., Cook, M. J., Glass, J. and Hopfe, C. J., 2015a. Review of the Assessment of Thermal Mass in Whole Building Performance Simulation Tools. In *14th Conference of International Building Performance Simulation Association (IBPSA), Building Simulation, BS 2015, Hyderabad, India, 7-9 December 2015, Conference Proceedings.*

Mantesi, E., Hopfe, C. J., Glass, J. and Cook, M. J., 2015b. Assessment of ICF Energy Saving Potential in Whole Building Performance Simulation Tools. In *14th Conference of International Building Performance Simulation Association (IBPSA), Building Simulation, BS 2015, Hyderabad, India, 7-9 December 2015, Conference Proceedings.*

McLeod, R. S., Hopfe, C. J., & Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment*, 70, pp.189–209

Monahan, J., & Powell, J. C., 2011. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings*, 43(1), pp.179–188

NAHB Research Centre, 1997. *Insulating Concrete Forms for Residential Construction: Demonstration Homes*. Maryland: The Portland Cement Association

Pan, W., Gibb, A.G.F. and Dainty, A.R.J., 2007. Perspectives of UK housebuilders on the use of offsite modern methods of construction. *Construction Management and Economics* 25(2), pp. 183-194

Rajagopalan, N., Bilec, M. M., & Landis, A. E., 2009. Comparative life cycle assessment of insulating concrete forms with traditional residential wall sections. In *2009 IEEE International Symposium on Sustainable Systems and Technology, ISSST '09 in Cooperation with 2009 IEEE International Symposium on Technology and Society, ISTAS, Conference Proceedings.*

Strachan, P., Svehla, K., Heusler, I., & Kersken, M., 2015. Whole model empirical validation on a full-scale building. *Journal of Building Performance Simulation*, 1493, pp.1–20

Swann, R., Baird, E., Vaughan, P., Dixon, J., Douthwaite, R., Mairs, I., & Davies, J., 2012. *Population Growth and Housing Expansion in the UK. Some preliminary considerations*. London: Population Matters

Zhu, D., Hong, T., Yan, D., & Wang, C., 2012. *Comparison of Building Energy Modelling Programs: Building Loads*. USA: Ernest Orlando Lawrence Berkeley National Laboratory

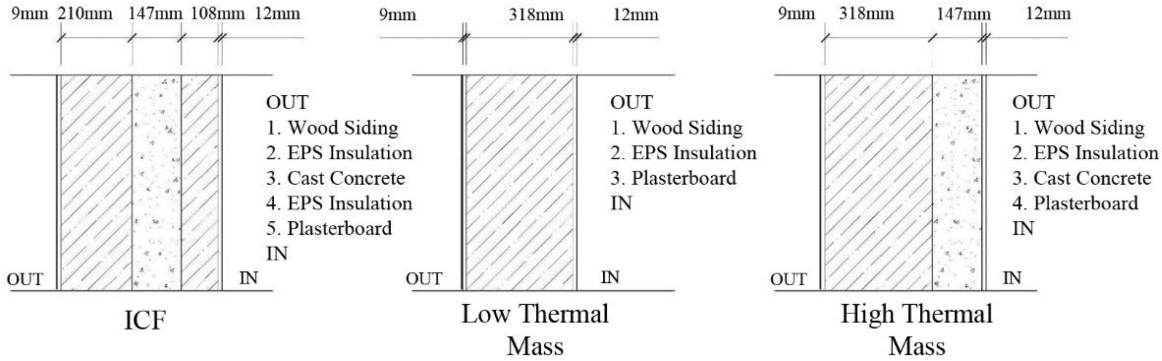


Figure 1 *Cross-section of the three wall construction methods used in the analysis*

Table 3 *Algorithms used in equivalent models*

Simulation Solution (Loads, Plant, System Calculations):	Simultaneous Calculations
Time Step:	6/h (10mins)
Warming up:	25 days
Heat Balance Solution Algorithms:	Surface and Air Heat Balance Equations
Conduction Solution Method:	Finite Difference Solution (Space discretisation : 3)
Internal Convection Coefficient:	Fixed, User-defined value (hi=3.16)
External Convection Coefficient:	Fixed, User-defined value (he=24.17)
Radiant Heat Flow Models:	“Script F”
	Mean Radiant Temperature Model
Interior Surface Long-Wave Radiation Exchange:	User-defined view factors
Exterior Surface Long-Wave Radiation Exchange:	Surface, Air, ground and Sky Temperature dependent
Solar Beam and Diffuse Distribution:	Default Algorithms
Sky Diffuse:	Anisotropic Model
Internal Gains - Radiant Distribution:	Default Algorithms

Table 4 *Description of Specialised Test Cases Used in the Parametric Analysis*

Test cases	**INT GAINS (W)**		**INFILT (ACH)**	**IR EMISSIV**		**SOL ABSORP**		**CONV COEF**		**COMMENTS**
	Conv	Rad		Int	Ext	Int	Ext	Int	Ext	
TC1	0	0	0	0.1	0.1	0.1	0.1	3.16	24.17	BaseCase
TC2	0	0	0	0.1	0.1	0.1	0.1	Default	Default	Convection Coefficient
TC3	0	0	0	0.9	0.9	0.1	0.1	3.16	24.17	Long-Wave Radiation Exchange
TC4	0	0	0	0.1	0.1	0.6	0.6	3.16	24.17	Short-Wave Radiation Exchange
TC5	200	0	0	0.9	0.9	0.1	0.1	3.16	24.17	Convective Internal Gains
TC6	0	200	0	0.9	0.9	0.1	0.1	3.16	24.17	Radiative Internal Gains
TC7	0	0	0.5	0.1	0.1	0.1	0.1	3.16	24.17	Infiltration

APPENDIX B PAPER 2: THE MODELLING GAP: QUANTIFYING THE DISCREPANCY IN THE REPRESENTATION OF THERMAL MASS IN BUILDING SIMULATION

Full Reference

Mantesi, E., Hopfe, C. J., Cook, M. J., Glass, J., Strachan, P., 2018. The Modelling Gap: Quantifying the Discrepancy in the Representation of Thermal Mass in Building Simulation, *Building and Environment* 131, 74-98, doi: 10.1016/j.buildenv.2017.12.017.

Abstract

Enhanced fabric performance is fundamental to reduce the energy consumption in buildings. Research has shown that the thermal mass of the fabric can be used as a passive design strategy to reduce energy use for space conditioning. Concrete is a high density material, therefore said to have high thermal mass. Insulating concrete formwork (ICF) consists of cast in situ concrete poured between two layers of insulation. ICF is generally perceived as a thermally lightweight construction, although previous field studies indicated that ICF shows evidence of heat storage effects.

There is a need for accurate performance prediction when designing new buildings. This is challenging in particular when using advanced or new methods (such as ICF), that are not yet well researched. Building Performance Simulation (BPS) is often used to predict the thermal performance of buildings. Large discrepancies can occur in the simulation predictions provided by different BPS tools. In many cases assumptions embedded within the tools are outside of the modeller's control. At other times, users are required to make decisions on whether to rely on the default settings or to specify the input values and algorithms to be used in the simulation. This paper investigates the "modelling gap", the impact of default settings and the implications of the various calculation algorithms on the results divergence in thermal mass simulation using different tools. ICF is compared with low and high thermal mass constructions. The results indicated that the modelling uncertainties accounted for up to 26% of the variation in the simulation predictions.

Key Words

Insulating Concrete Formwork; Building Performance Simulation; Default Settings; Modelling Uncertainty; Impact of Wind Variations; Solar Timing

Paper Type – Journal Paper

1 INTRODUCTION

In an attempt to combat the impact of climate change, governments have set targets to reduce energy consumption and CO_2 emissions. In Europe, 40% of the total energy consumption and 36% of the total CO_2 emissions derive directly from the built environment (European Parliament and Council, 2010). As a consequence, energy efficient buildings steer a new era of development, including new materials, innovative envelope technologies and advanced design ideas (Sadineni et al., 2011; Kolokotsa et al., 2011; Omrany et al., 2016). Improvements in building energy efficiency are mainly focused on reduction of fabric heat losses (reduced infiltration, better insulation etc.) and the optimal use of solar gains (McLeod & Hopfe, 2013). To quantify the potential of new materials and technologies in energy consumption savings and CO_2 emission reductions, the use of reliable dynamic Building Performance Simulation (BPS) is essential.

1.1 SIMULATION-BASED SUPPORT FOR INNOVATIVE BUILDING ENVELOPE TECHNOLOGIES

Building Performance Simulation (BPS) was first introduced in the 1960s (Zhu et al., 2012) and it has developed significantly ever since. Over the past decades, computer-aided simulation of buildings has become widely available; hence these days, it is used both in research and in industry (Wang & Zhai, 2016). Loonen et al. (2014) analysed the factors that affect the success and failure of innovations in construction industry and demonstrated the potential of using whole-building performance simulation in the domain of research and development. They concluded that the lack of effective communication about performance aspects was one of the most significant barriers to innovative building technologies and components. The conventional product development process, usually focusses on performance metrics at a component level. However, to make well-informed decisions, a more thorough approach, considering a number of different building performance issues is needed. BPS takes into account the complex correlations among the possible heat flow paths in a building model. It incorporates the dynamic interactions between building design, climatic context, HVAC operation and user behaviour; hence it is considered a valuable source of information regarding the thermal performance of new building products. Roberz et al. (2017) performed a simulation-based assessment of the impact of ultra-lightweight concrete (ULWC) on energy performance and indoor comfort in commercial and residential buildings. ULWC is an innovative wall construction material. The authors compared its thermal performance to conventional lightweight and heavyweight structures using EnergyPlus software. They concluded that for the case study under investigation, ULWC behaves closer to the heavyweight building in long-term heating periods and shows a relatively fast heating-up response, comparable to the lightweight building envelope in short-term analysis (Roberz et al., 2017). Another novel approach to wall construction was investigated by Hoes and Hensen (2016). Possible adaptation mechanisms and hybrid-adaptive thermal storage concepts (HATS) were analysed with regards to their energy demand reduction potentials in new lightweight residential buildings in the Netherlands. A computational building performance simulation analysis was performed using ESP-r software (Clarke, 2001). The authors concluded that the HATS approach was able to reduce space heating demand and enhance indoor thermal comfort (Hoes & Hensen, 2016).

The present study focusses on the simulation of three different wall construction methods, insulating concrete formwork (ICF), low thermal mass (timber-frame) and high thermal mass (concrete wall) buildings. The latter two conventional wall construction types have been analysed and compared with each other thoroughly in previous research (Hacker et al., 2008; Zhu et al., 2009; Dodoo et al., 2012; Kendrick et al., 2012; McLeod et al., 2013; Reilly & Kinnane, 2017). However, the amount of research associated with ICF is limited and there is currently a scarcity of data concerning its actual thermal performance in BPS.

1.2 THERMAL MASS AND ICF

The thermal mass of the fabric can be used as a passive design strategy to reduce energy use for space conditioning (Givoni, 1979; Corgnati & Kindinis, 2007; Al-Sanea et al., 2012; Slee et al., 2014; Csaky & Kalmar, 2015; Navarro et al., 2016). The term thermal mass defines the ability of a material to store sensible thermal energy by changing its temperature. The amount of thermal energy storage is proportional to the difference between the material's final and initial temperatures, its density mass, and its heat capacity (Dincer & Rosen, 2011). The fundamental benefit of fabric's thermal mass is its ability to capture the internal, casual and solar heat gains, helping to moderate internal temperature swings and shifting the time that the peak load occurs (Kosny et al., 2001; Hacker et al., 2008; Al-Sanea et al., 2012; Reilly & Kinnane, 2017; Kumar et al., 2017). Previous studies have also shown that the thermal mass of the fabric can be used to prevent buildings from overheating (Guglielmini et al., 1981; Navarro et al., 2016; Adekunle & Nikolopoulou, 2016).

ICF is classed among the site-based Modern Methods of Construction (MMC) (Rodrigues, 2009). Although it dates back in Europe since the late 1960's, it is often characterised as an innovative wall technology because it has only recently become more popular for use in residential and commercial construction (Armstrong et al., 2011). The ICF wall component consists of modular prefabricated Expanded Polystyrene Insulation (EPS) hollow blocks and cast in situ concrete (Fig. 1). The blocks are assembled on site and the concrete is poured into the void. Once the concrete has cured, the insulating formwork stays in place permanently. The resulting construction structurally resembles a conventional reinforced concrete wall.

The ICF wall system has several advantages; apart from its increased speed of construction and its strength and durability, ICF can provide complete external and internal wall insulation, minimising the existence of thermal bridging, providing very low U-values and high levels of air-tightness if installed correctly (Rodrigues, 2009; Rajagopalan et al., 2009). ICF is generally perceived as merely an insulated panel, acting thermally as a lightweight structure. There is the general perception that the internal layer of insulation isolates the thermal mass of the concrete from the internal space and interferes with their thermal interaction. Nonetheless, previous computational, numerical and field studies, indicate that the thermal capacity of its concrete core shows evidence of heat storage effects, which in specific climatic and building cases, could result ultimately in reduced energy consumption when compared to a lightweight conventional timber-framed wall with equal levels of insulation (Kosny et al., 2001; Maref et al., 2010; Armstrong et al., 2011; Saber et al., 2011; Mantesi et al., 2015; Mantesi et al., 2016; Mourkos et al., 2017).

Fig. 1 contrasts a typical cross section, as used in the representation of ICF in numerical simulations against the reality of prefabricated blocks of EPS. The insulation layers are connected with plastic ties, creating the void, where the concrete will then be poured. The figure illustrates one example of possible simplifications when a construction is represented in a model and how it differs from reality and increases the level of modelling uncertainties.

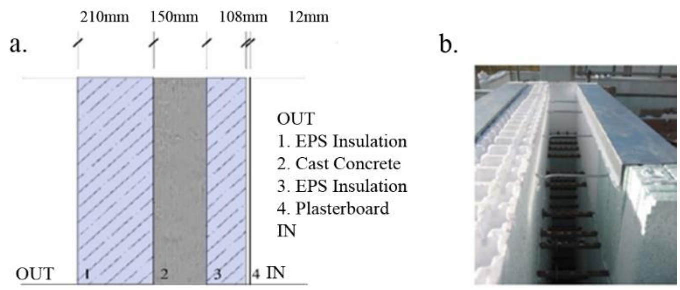


Fig. 1 *(a) Example of ICF geometry as used in numerical simulation versus (b) the reality of prefabricated EPS hollow blocks of ICF, before the concrete is poured*

1.3 BUILDING MODELLING, SIMULATION AND UNCERTAINTY

It is common to see the words "simulation" and "modelling" used interchangeably. However, they are not synonyms. Becker and Parker (2009) defined simulation as the process that implements and instantiates a model. Instead, modelling is the representation of a system that contains objects that interact with each other. A model is often mathematical and describes the system that is to be simulated at a certain level of abstraction. Within a BPS program descriptions of the construction, occupancy patterns and HVAC systems are given and a mathematical model is constructed to represent the possible energy flow-path and their interactions (Clarke, 2001; Wang & Zhai, 2016). Many assumptions, approximations and compromises are inevitably made on the mathematical formulations describing the physical laws within the model (Irving, 1988). Consequently an exact replication of reality should not be expected. There is often a discrepancy between expected energy performance during design stage and real energy performance after project completion (Foucquier et al., 2013). Moreover, there are often inconsistencies in the simulation results when modelling an identical building using different BPS tools, referred to as modelling uncertainties (Hopfe & Hensen, 2011). These can lead to a lack of confidence in building simulation.

Previous research on the uncertainty of simulation predictions concluded that the reliability of simulation outcomes depends on the accuracy and precision of input data, simulation models and the skills of the energy modeller (Irving, 1982; Burman et al., 2012; Berkeley et al., 2014; Mantesi et al., 2015). An estimation of the uncertainty introduced by each of the aforementioned factors can help to increase the awareness of the results reliability. Quality assurance procedures and consideration of the inherent uncertainties in the inputs and modelling assumptions are two areas that require attention in BPS.

There are a vast number of previous studies analysing the various sources of uncertainty in BPS results. De Wit classified the sources of uncertainty as follows (De Wit & Augenbroe, 2002):

- *Specification uncertainties*, associated to incomplete or inaccurate specification of building input parameters (i.e. geometry, material properties etc.)
- *Modelling uncertainties*, defined as the simplifications and assumptions of complex physical processes (i.e. zoning, scheduling, algorithms etc.)

- *Numerical uncertainties*, all the errors that are introduced in the discretisation and the simulation model.
- *Scenario uncertainties*, which are in essence all the external conditions imposed on the building (i.e. weather conditions, occupants behaviour).

Macdonald and Strachan (2001) reviewed the sources of uncertainty in the predictions from thermal simulation programmes and incorporated uncertainty analysis into ESP-r. Hopfe and Hensen (2011) investigated the possibility of supporting design by applying uncertainty analysis in building performance simulation. Prada et al. (2014) studied the effect of uncertain thermophysical properties on the numerical solutions of the heat equation, analysing the difference between Conduction Transfer Functions (CTF) and Finite Difference (FD) model predictions. Mirsadeghi et al. (2013) reviewed the uncertainty introduced by the different external convective heat transfer coefficient models in building energy simulation programs. Silva and Ghisi (2014) examined the discrepancies in the simulation results due to simplifications in the geometry of a computer model. Gaetani et al. investigated the uncertainty and sensitivity of building performance predictions to different aspects of occupant behaviour, by separating influential and non-influential factors (Gaetani et al., 2015; Gaetani et al., 2016). Kokogiannakis et al. (2008) compared the simplified methods used for compliance as described in ISO 13790 standard with two detailed modelling programs (i.e. ESP-r and EnergyPlus). The aim was to determine the magnitude of differences due to the choice of simulation program and whether the different methods under investigation would lead to different compliance conclusions. Irving (1988) investigated several aspects that are related to the validation of dynamic thermal models. Among others, the author highlighted the influence of users in the accuracy of BPS results. The author suggested that even if a model is completely accurate, errors may still arise because little guidance is usually available on how to use the model properly. Guyon (1997) also studied the role of model user in BPS results, by comparing the results provided by 12 users for the same validation exercise. They concluded that the user's experience affected the results variations. A good homogeneity was found among the different categories of participants' expertise. The impact of modeller's decision on the simulation results was also studied by Berkeley et al. (2014). The authors found that the results provided by 12 professional energy modellers for both the total yearly electrical and gas consumption varied significantly.

1.4 AIM OF PAPER

There is a wide range of scientifically validated BPS tools available on the market. Some of the tools are simple and more "user-friendly", others are more detailed, requiring an advanced level of expertise and experience from the modeller. In several cases, there are assumptions embedded in the BPS programme that are outside the modeller's control. In other cases, the modeller is required to make a decision on whether to rely on the default settings of a tool or to specify the solution algorithms and values that are to be used in the simulations. The analysis presented in this paper investigates the implications of the "modelling gap", the different modelling methods on the simulation of three different types of thermal mass in whole BPS using two different tools. Focussing firstly on the impact of default input parameters and then on the effects of the various calculation algorithms on the results divergence, the purpose is to examine the disparity of different modelling assumptions. The order of magnitude of the problem faced by the modeller during the specification of a building is shown, focussing on the representation of thermal mass in building simulation. The focus is particularly on the simulation of ICF; a construction method which is not yet well-researched. To the authors' knowledge this is the first thorough investigation of the simulation of ICF and the first study that reflects on the effect of modelling decisions and modelling uncertainty on thermal mass simulation.

2 RESEARCH METHOD

The case study was a single-zone test building based on the one specified in the BESTEST methodology (Judkoff & Neymark, 1995). The rationale was to minimise building complexity and thus decrease the number of variables related to geometry and zoning in the input data. At the outset, all simulation models were validated using the BESTEST case 600 for low thermal mass and case 900 for high thermal mass. Then the construction details were changed in line with the specific study. All other input parameters remained identical to the BESTEST methodology. Three different construction methods: insulated concrete formwork, low thermal mass, and high thermal mass were simulated, as shown in Fig. 2. For ease of reference, these will be referred to as ICF, LTM and HTM from this point forward.

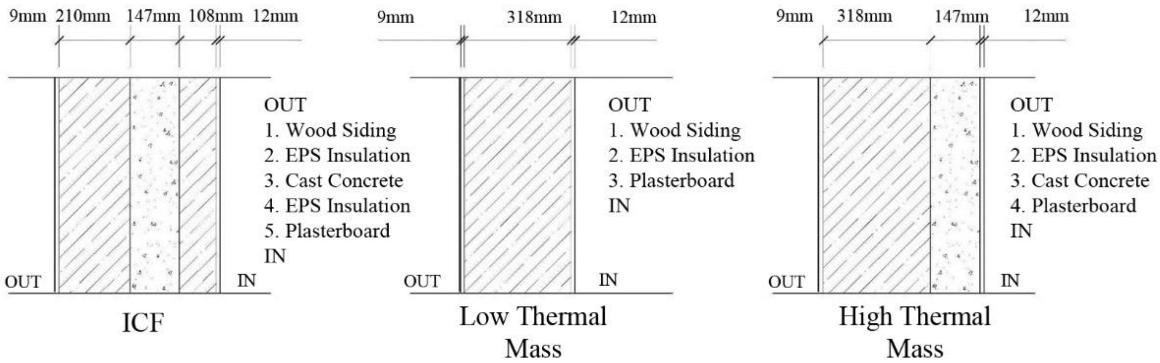


Fig. 2 *Cross-section of the three wall construction methods (ICF; LTM; and, HTM)*

The ICF option was based on real building construction details, and was used as a reference to specify U-Values for all other construction elements. In this way U-values were consistent for all three building models; hence, the main difference between the three construction methods was in the amount of thermal mass. Table A.1 (in the Appendix) describes the construction materials for all three options.

The simulation settings were identical in all three scenarios: each building model had the same internal footprint, window size and glazing properties, the same HVAC system, internal gains and infiltration rates, as summarised in Table 1. Energy was used for space conditioning and other equipment. No domestic hot water was used. The DRYCOLD weather file, downloaded from NREL , was used as a Typical Meteorological Year (TMY), i.e. a climate with cold clear winters and hot dry summers.

Table 1 *Input data used for the building model*

Building Model Details	
Internal Treated Floor Area	6m x 8m = 48m^2
Orientation	Principal axis running east west direction
Windows	Two double glazed windows, 2m x 3m each, on south façade, U-Value = 3.00 W/m^{2}K, g-Value = 0. 747
U-Values (W/m^{2}K)	Walls = 0.10
	Floor = 0.10
	Ceiling = 0.11
HVAC system	Ideal loads
HVAC Set points	20ºC Heating/ 27ºC Cooling
HVAC Schedule	24h (Continuously on)
Internal Gains	200W (other equipment)
Infiltration	0.5ACH (Constant)

Two freeware, validated and commonly used BPS tools were selected, as they showed the greatest overall consistency in setup and default settings (seven other tools were considered and discounted) (Mantesi et al., 2016). Importantly, both tools offered significant flexibility to the user, through changing the default settings, hence they presented the best opportunity to achieve the overall aim of the research. These will be referred to as tools A and B from this point onwards.

The research was undertaken in three main phases, as shown in Fig. 3.

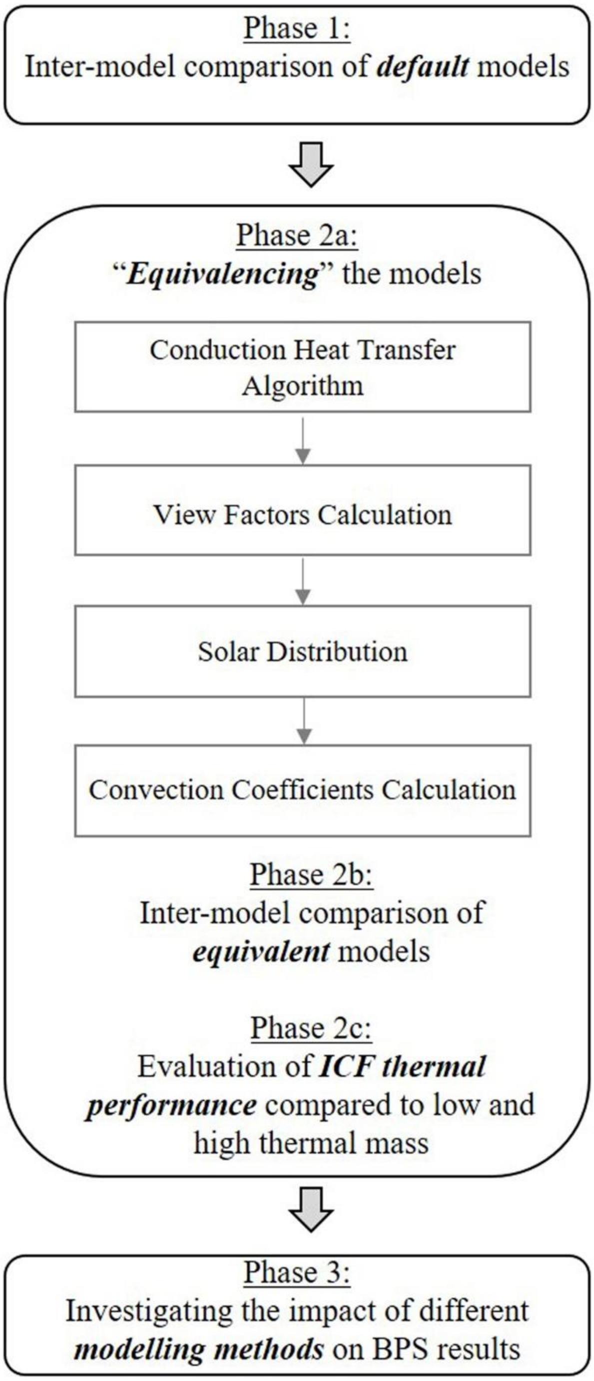


Fig. 3 *The three phases in the research method.*

Phase 1 compared simulation results provided by the two BPS tools when simulating all three construction methods (i.e. ICF, LTM, and HTM) using the tools' default algorithms. This was done to determine whether any discrepancies in the simulation predictions provided by the tools were significant (i.e. surface temperatures, heating or cooling demand), and whether this discrepancy was affected by the amount of thermal mass. Both annual and hourly results were included in the analysis:

1. Results for the annual energy consumption and the peak thermal loads were plotted monthly. Divergence in the simulation predictions was analysed using the Normalised Root Mean Square Error (NRMSE) (1). The NRMSE[20] is a non-dimensional form of the RMSE and was used to calculate absolute error in simulation results.

$$NRMSE\ (\%) = \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_{i,b} - x_{i,a})^2}{n}}}{\bar{x}} * 100 \quad (1)$$

$$\bar{x_i} = \frac{x_{i,a} + x_{i,b}}{2} \quad (2)$$

$$\bar{x} = \frac{\sum_{i=1}^{n} \bar{x}_i}{n} \quad (3)$$

Where,

$x_{i,a}$ and $x_{i,b}$ are the predictions provided by tools A and B respectively at each time step

$\bar{x}_i$ is the mean value of $x_{i,a}$ and $x_{i,b}$ for each time step

[20] The NRMSE when normalised to the mean of the observed data is also called CV(RMSE) for the resemblance with calculating the coefficient of variance.

$\bar{x}$ is the mean value of the predictions provided by both tools A and B

n is the size of the sample

2. Hourly results for the heating and cooling demand, along with surface temperatures of a wall element were plotted for two three-day periods, one in the heating and one in the cooling season. The days selected for the hourly results analysis were when the highest and lowest dry-bulb outdoor temperatures were recorded. The analysis focussed on the internal surface, intra-fabric and external surface temperature of the east wall. The east wall was selected for this step of the analysis because it would receive direct solar radiation both in its external and internal surfaces. However, a relatively similar divergence was observed in the results provided by the two BPS tools for all other walls in the simulation models.

Phase 2 focussed on the model "equivalencing" process. This was done to minimise any differences between the simulation models, making them equivalent for comparison, by selecting identical algorithms and consistent input settings (see Table A.2 in the Appendix). An extended literature review identified the main features, capabilities and default solution algorithms in the tools (Crawley et al., 2008; Zhu et al., 2012). An overview of the calculation and solution algorithms employed in both BPS tools is included in Table A.3 (Appendix). The "equivalencing" process was done on the annual simulation results, aiming to serve as a crude analysis on the impact of the different algorithms on the results discrepancy. Starting from a basecase scenario representing the default models, a step-by-step process was followed to make the models equivalent by changing to identical solution algorithms one step at a time. The impact of each step was investigated by calculating the NRMSE, for each of the three construction methods. The results were analysed sequentially to understand which algorithms had the greatest impact on each discrepancy, how the inconsistencies were affected based on the varying levels of thermal mass, and whether any divergence became more obvious (i.e. heating or cooling demand). Once the simulation models were "equivalent", the NRMSE of the annual and hourly results were compared against the initial NRMSE of the default models. The aim was to quantify the reduction in the results variation.

The thermal performance of the ICF, LTM and HTM models were compared before and after the model "equivalencing" process. The purpose was to investigate if the results would be different pre and post-"equivalencing", to reflect on the impact of the "modelling gap" and to highlight the significance of reducing uncertainties in building performance simulation.

Following the model "equivalencing" process, several modelling factors that were found to have a significant impact on the results were investigated further. Therefore, the third and final phase considered the differences in modelling methods employed by the two tools. This was done to highlight how the simulation outcome is affected by the different modelling methods, even when the input values are identical (in this instance the climate data).

3 RESULTS AND ANALYSIS

This section presents the results obtained from the three phases of the research. Annual and hourly simulation results obtained by the two BPS tools when the user relies on the default setting are presented first. Then, the simulation predictions of the equivalent models are analysed, followed by an account of the investigation of the different modelling methods available within the two BPS tools. The purpose of the section is to provide a detailed account of the outcomes of the analysis, in particular to consider the differences between tools A and B.

3.1 PHASE 1: IMPACT OF DEFAULT SETTINGS ON THE BPS RESULTS

3.1.1 Annual Simulation Results of Two Tools Using Default Settings

The following section analysed the annual simulation results for the heating and cooling demand provided by the two tools, when the user relies on the default settings and their variation. Fig. 4 shows the absolute difference and the NRMSE in the simulation results provided by tools A and B for each construction method, for the annual heating and cooling energy consumption and the peak heating and cooling loads. The divergence in the simulation results provided by the two tools for the default models was high. In terms of absolute difference in the annual and peak heating demand, the ICF building showed the highest difference in the simulation predictions provided by the two tools. In the annual and peak cooling demand, the highest absolute difference (in kWh and W) was observed in the LTM building, followed by the HTM building. In general the absolute differences were higher in the annual and peak cooling demand, reaching up to 300kWh in the annual cooling demand of the LTM and HTM buildings and up to 700W in the peak cooling demand of the LTM building.

Looking at the relative differences (i.e. NRMSE) in the predictions provided by the two BPS tools, highlighted the significance of these variations. The largest divergence was found in the annual heating energy consumption for ICF (NRMSE = 26.05%) and HTM (NRMSE = 16.20%). Furthermore, the HTM case showed a major difference in the annual cooling and peak cooling loads (NRMSE = 6.96% and NRMSE = 6.50% respectively). The LTM building showed overall good consistency in the simulation predictions for both annual energy consumption and peak loads, with the exception of peak cooling demand (NRMSE = 5.06%). Finally, there was good agreement between the two tools for the peak heating loads, regardless of the amount of thermal mass (NRMSE < 4%).

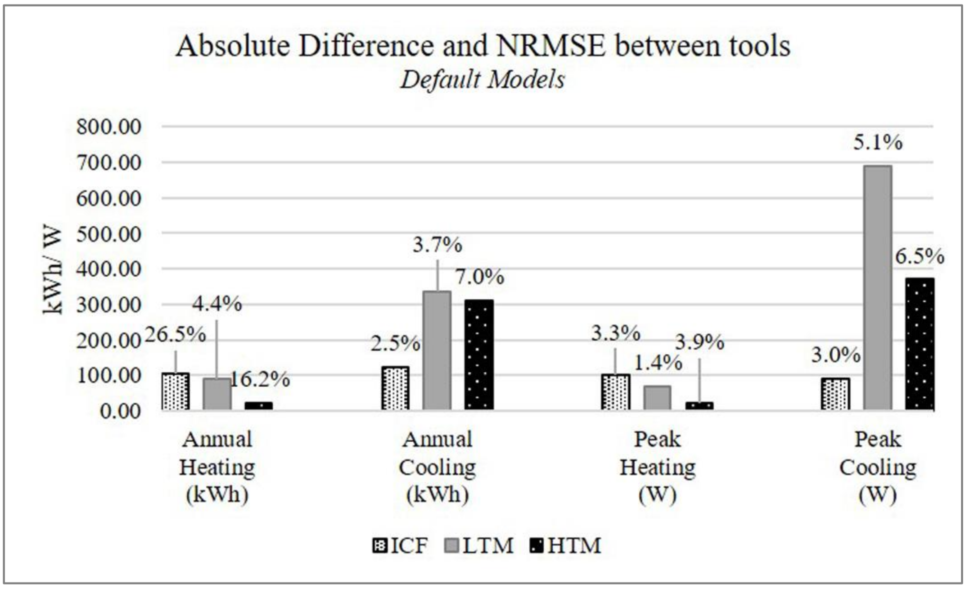


Fig. 4 *Absolute Difference and NRMSE between the simulation predictions provided by tools A and B for the three construction methods, when the user relies on the tools' default settings.*

The monthly breakdown of annual heating energy consumption for the default models, as illustrated in Fig.5, shows that the greatest divergence was found in results for the winter months (December, January and February); it was most significant in the ICF and the HTM buildings. In the monthly breakdown of the annual cooling energy consumption (Fig.5) the predictions for ICF showed good consistency. The most significant discrepancy was observed in LTM and HTM between January and April, and between November and December. Good agreement between the two BPS tools was achieved over the summer period. For peak heating loads (Fig.5), the divergence was negligible during the entire simulation period, for all three constructions. For peak cooling loads (Fig.5), the ICF case showed an insignificant variation between the two tools, whereas the other two construction methods (i.e. LTM and HTM), displayed a surprisingly high divergence in peak cooling loads during the heating period (January to May and October to December), yet there is a good consistency over the summer months.

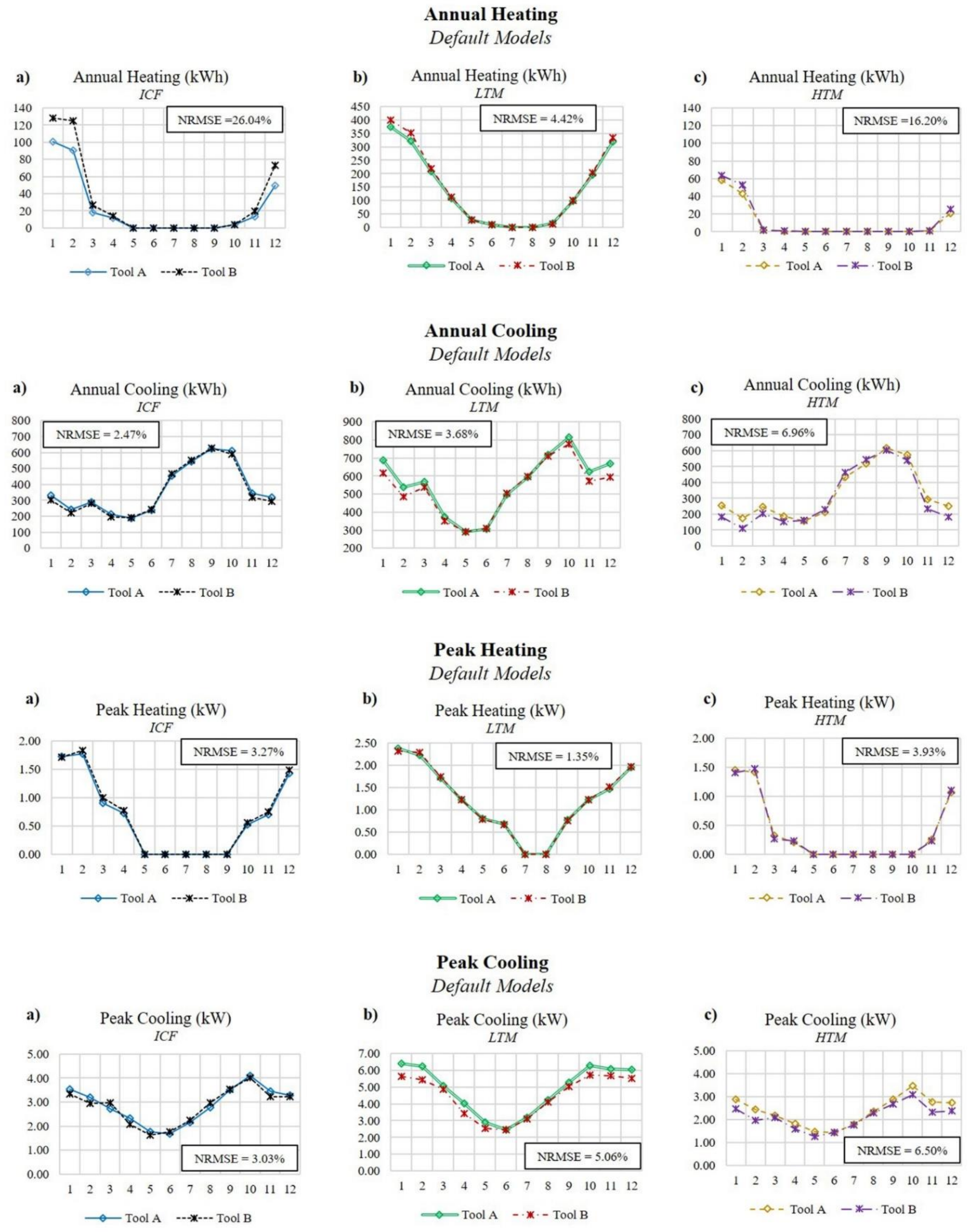


Fig. 5 *Monthly breakdown of annual heating and cooling energy consumption and peak heating and cooling loads. Simulation predictions provided by tool A and tool B for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the user relies on the tools' default settings.*

3.1.2 Hourly Simulation Results of the Two BPS Tools Relying on the Default Settings

Fig. 6 shows the discrepancy in the hourly simulation results provided by the two BPS tools for the internal surface, the intra-fabric[21] and the external surface temperatures of the east wall. The results are plotted for three consecutive days in the heating period, when the lowest outside dry-bulb temperature was predicted. The divergence in the predictions of the two tools was relatively low for the internal surface temperature in all three constructions, with a maximum of NRMSE[22] = 4.00% observed in the ICF building. The node temperature in the middle of the wall element showed that there was a more pronounced discrepancy in the LTM building (NRMSE = 29%), much lower compared to the other two construction methods, where the variation was NRMSE = 4.71% for the ICF and just NRMSE = 1.82% for the HTM building. With regards to the outside surface temperature, the same variation equal to NRMSE = 12% was observed in all three constructions.

Fig. 7 shows the discrepancy in the simulation predictions provided by the two BPS tools for the inside surface, intra-fabric and outside surface of the east wall for three consecutive days in the cooling season. The variation in the temperature of the internal surface was negligible in all three constructions (below NRMSE = 2%). There was an NRMSE = 5% discrepancy in the predictions of the intra-fabric temperature of the LTM wall. Finally, there was an NMRSE = 8.75% discrepancy in the simulation of the outside surface temperature, which was again found to be the same in all three construction methods.

[21] Tool A calculates by default the conduction heat transfer using the Conduction Transfer Function algorithm. CTF does not allow the calculation of temperature distribution within the element of the fabric. For the purposes of this analysis, the conduction heat transfer algorithm for the East wall was set to Conduction Finite Difference.

[22] The hourly temperature results are expressed in degree centigrade throughout the paper (°C). If expressed in Kelvin (K), then the RMSE values might have been different.

It is noteworthy that although the divergence in the simulation predictions provided by the two BPS tools was relatively low with regards to hourly temperature results, looking at the absolute divergence, there were instances that the maximum temperature difference was high. For example looking at the internal surface of the ICF building, as predicted by the two tools (Fig.6), the maximum absolute difference reached up to 5^{o}C. This finding could affect significantly the outcome of thermal comfort assessments and the selection of BPS tools could result in different conclusions regarding the thermal performance of the building.

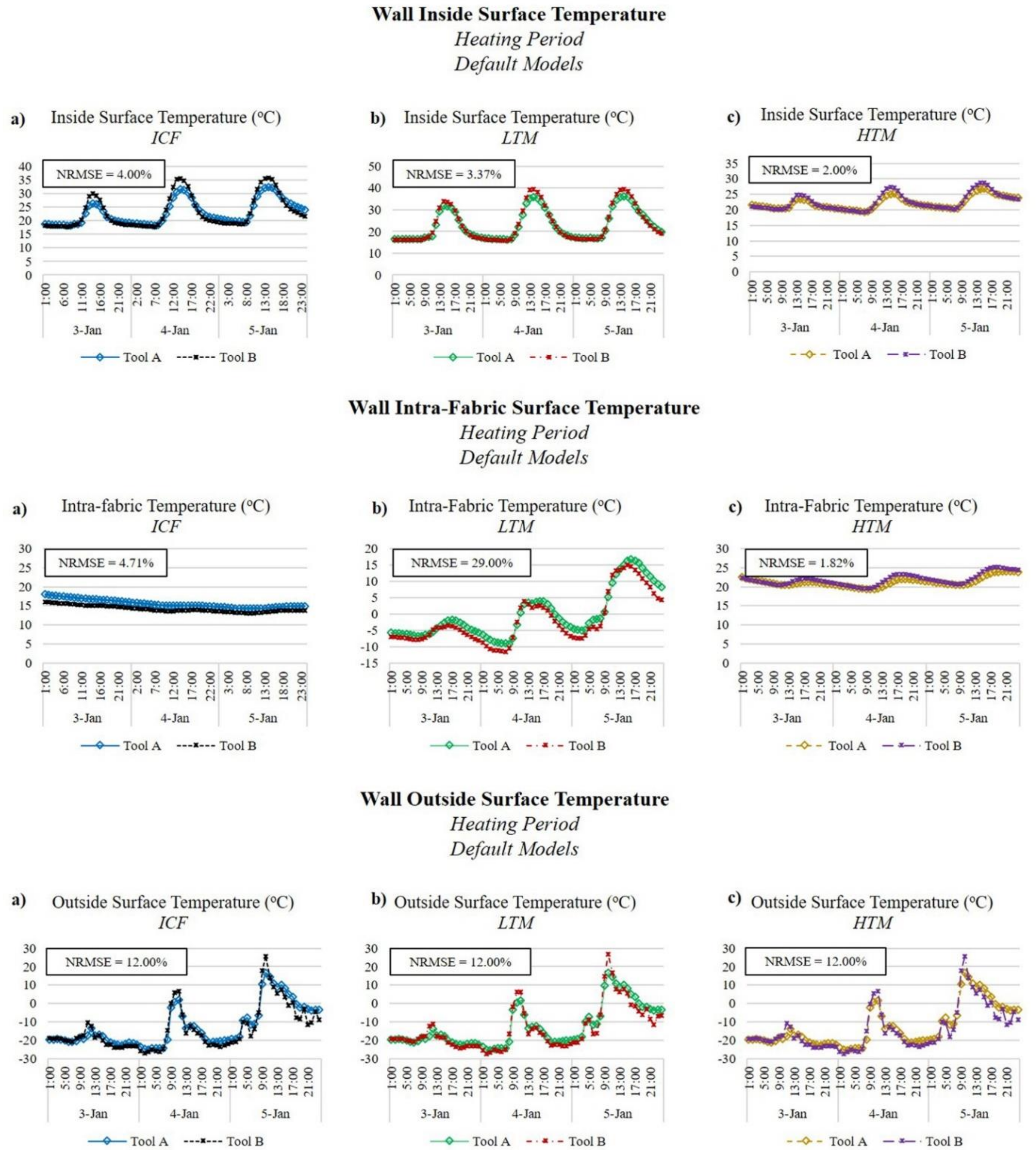


Fig. 6 *Hourly breakdown of the inside surface, intra-fabric and outside surface temperature of the east wall. Simulation predictions provided by tool A and B for three consecutive days in the heating season (03 – 05 January) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the user relies on the tools' default settings.*

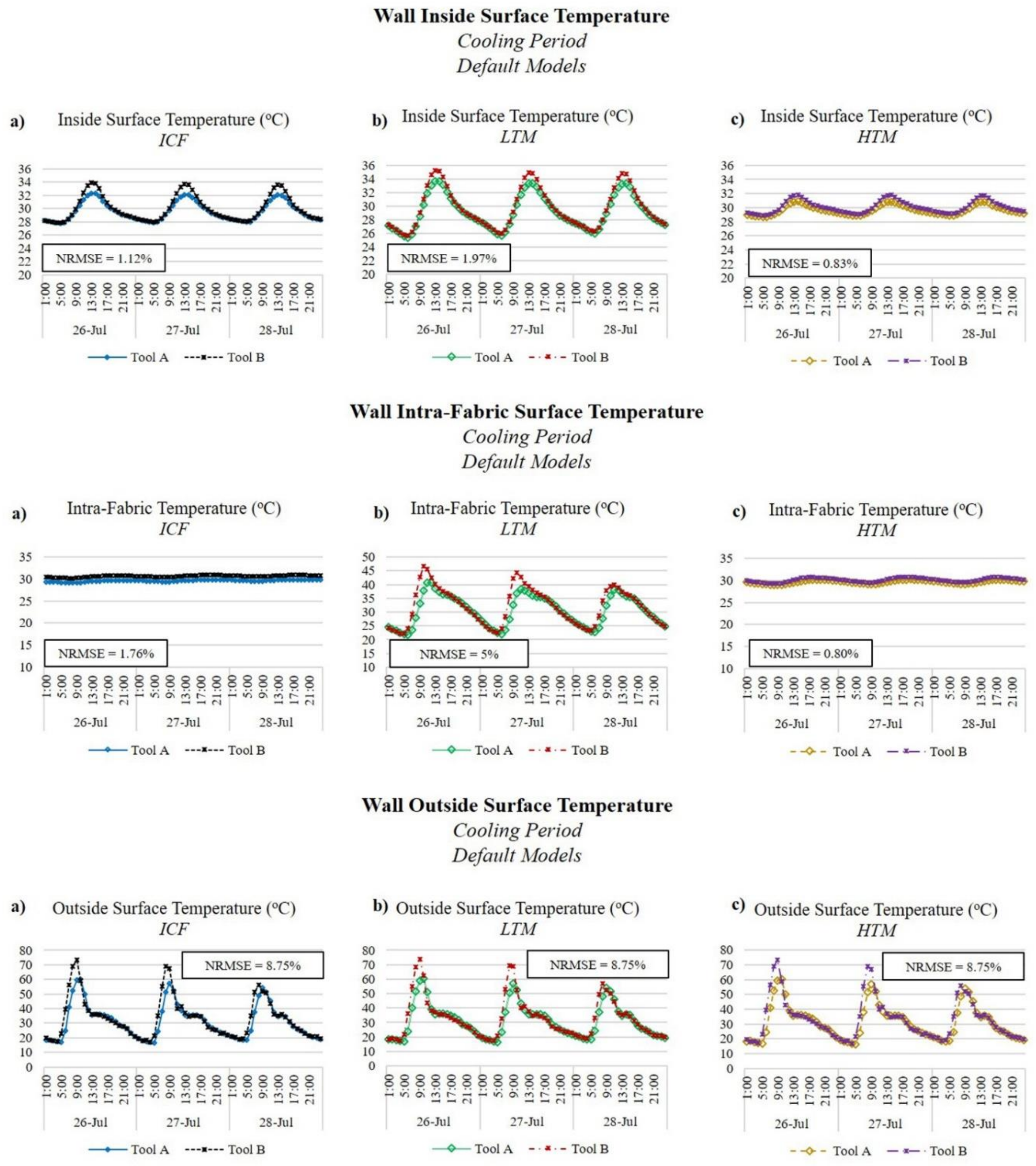


Fig. 7 *Hourly breakdown of the inside surface, intra-fabric and outside surface temperature of the east wall. Simulation predictions provided by tool A and B for three consecutive days in the cooling season (26 – 28 July) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the user relies on the tools' default settings.*

The discrepancy in the predictions of the east wall temperature evolution was relatively low in all three construction methods (apart from the intra-fabric temperature of the LTM wall in the heating season). In general, the discrepancy in the results for the wall temperature was found to be higher in the LTM building than the other two construction methods. As a result it would be expected that the variation in the heating demand predictions would also be higher in the LTM building. Surprisingly, the hourly breakdown of the heating demand, as indicated in Fig. 8, showed that there was an NRMSE = 13.43% for the ICF building, an NRMSE = 9.20% for the HTM building and the LTM building showed the lowest variation equal to NRMSE = 5.16%. The discrepancy in the simulation predictions for the hourly cooling demand in the three-day cooling period as shown in Fig.9 was relatively low for all three construction methods, even when the user relies on the default setting of the tools.

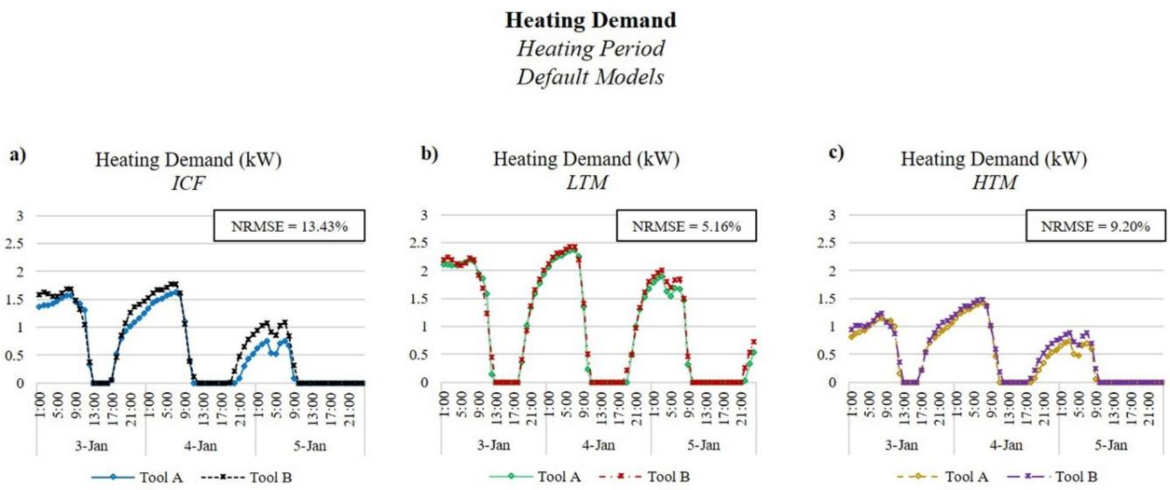


Fig. 8 *Hourly breakdown of heating demand. Simulation predictions provided by tool A and B for three consecutive days in the heating season (03 – 05 January) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the user relies on the tools' default settings.*

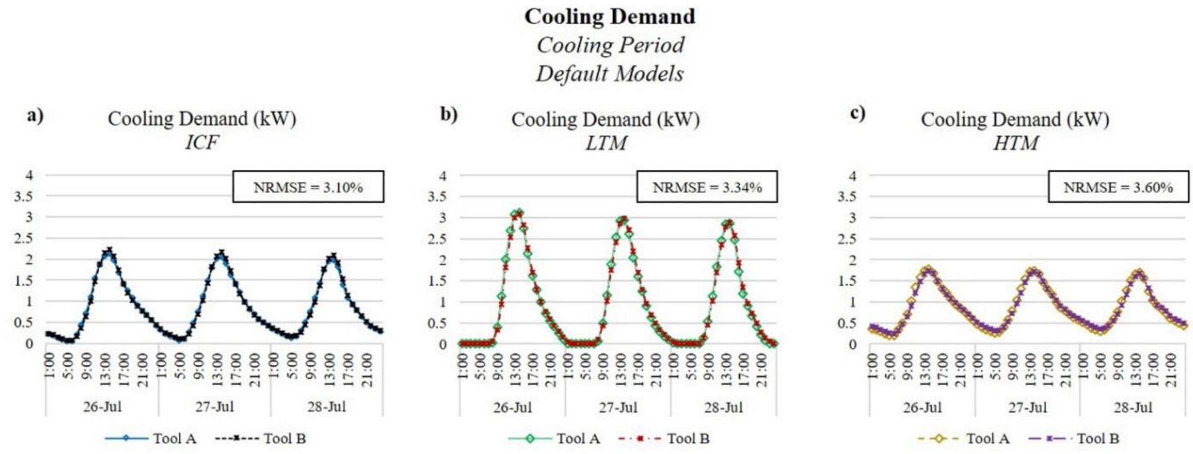


Fig. 9 *Hourly breakdown of cooling demand. Simulation predictions provided by tool A and B for three consecutive days in the cooling season (26 – 28 July) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the user relies on the tools' default settings.*

3.2 PHASE 2: SIMULATION RESULTS OF EQUIVALENT MODELS

3.2.1 "Equivalencing" the Models

Prior to analysing the various calculation algorithms and their impact on the results divergence, it was essential to minimise the differences in the two models, caused by other factors. As part of the "equivalencing" process, Fig. 10 to 13 show the various steps used to minimise the difference between the two tools, i.e. to make the models equivalent for comparison. Results are shown for all three construction methods (ICF, LTM, and HTM), for each tool, along with the NRMSE. Fig. 10 shows the process of making the models equivalent and its impact on the monthly breakdown of annual heating energy consumption. Fig. 11 shows the "equivalencing" progression for annual cooling energy consumption. Fig. 12 and 13 show "equivalencing" in the peak heating and peak cooling demands, respectively.

In every case the "equivalencing" process resulted in reasonably consistent simulation results provided by the two BPS tools for the equivalent models (Step 4 in Fig. 10 to 13). The largest discrepancy was observed in the annual heating and cooling demand of the HTM building. A step-by-step process was followed to make the models equivalent by changing to identical solution algorithms.

- In *Step 1* the conduction heat transfer algorithm in tool A was set to finite difference to match the conduction heat transfer calculation of tool B. This reduced the variation in the predictions for annual heating energy consumption in the LTM and HTM buildings, yet it increased the NRMSE in the ICF case (compared to the default models in Fig.9). The NRMSE was also increased in the predictions for the annual cooling demand for ICF and LTM, while it was reduced in the HTM building. Moreover, the discrepancy increased in predictions for the peak cooling loads for all three constructions.
- In *Step 2* the same view factors, used to calculate the radiant heat exchange between surfaces, were set in both models. This reduced the NRMSE in all cases, for all three constructions, apart from the peak heating loads, where it was slightly increased for LTM and HTM.
- In *Step 3* the direct solar distribution falling on each surface in the zone, including floor, walls and windows was calculated in both models by projecting the sun's rays through the exterior windows. This step significantly affected all the results. The NRMSE in the predictions was notably reduced in almost every case, particularly in the annual heating energy consumption. However, the NRMSE in the peak heating was increased in the HTM case.
- Finally, in *Step 4* the convection coefficients of the internal and external surfaces, used to calculate the convection heat transfer, were set to the same constant user-defined values. This, surprisingly, increased the variation for the annual cooling energy consumption and decreased the discrepancy in the annual heating and the peak loads for all three constructions. Furthermore, a general observation is that, by setting the surface convection coefficients to constant, the energy consumption predicted by both tools for

the annual and the peak heating demand for all three construction methods increased considerably, whereas the annual and peak cooling demand remained unaffected. Assuming constant values for the convection coefficients was a limitation of this study. In reality the building is always exposed to changes in the boundary conditions, resulting in time-varying convective transfer coefficients (Beasusoleil – Morrison, 2000). However, for the purpose of this analysis, where the aim was to minimise the differences between the two BPS tools as much as possible, constant convection coefficients were used in order to reduce the level of modelling uncertainty.

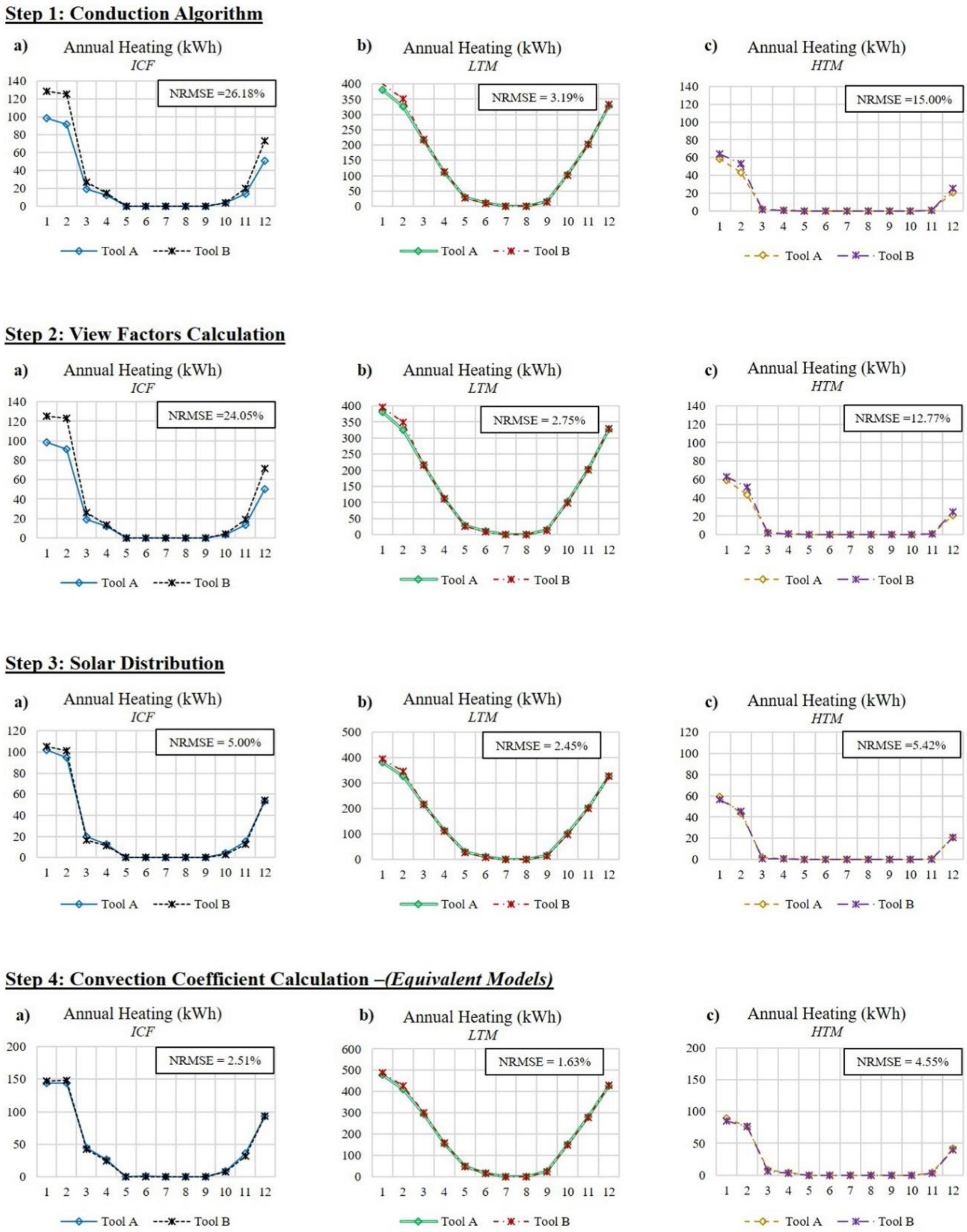


Fig. 10 *"Equivalencing" the models. Monthly breakdown of annual heating energy predictions provided by tool A and tool B for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM).*

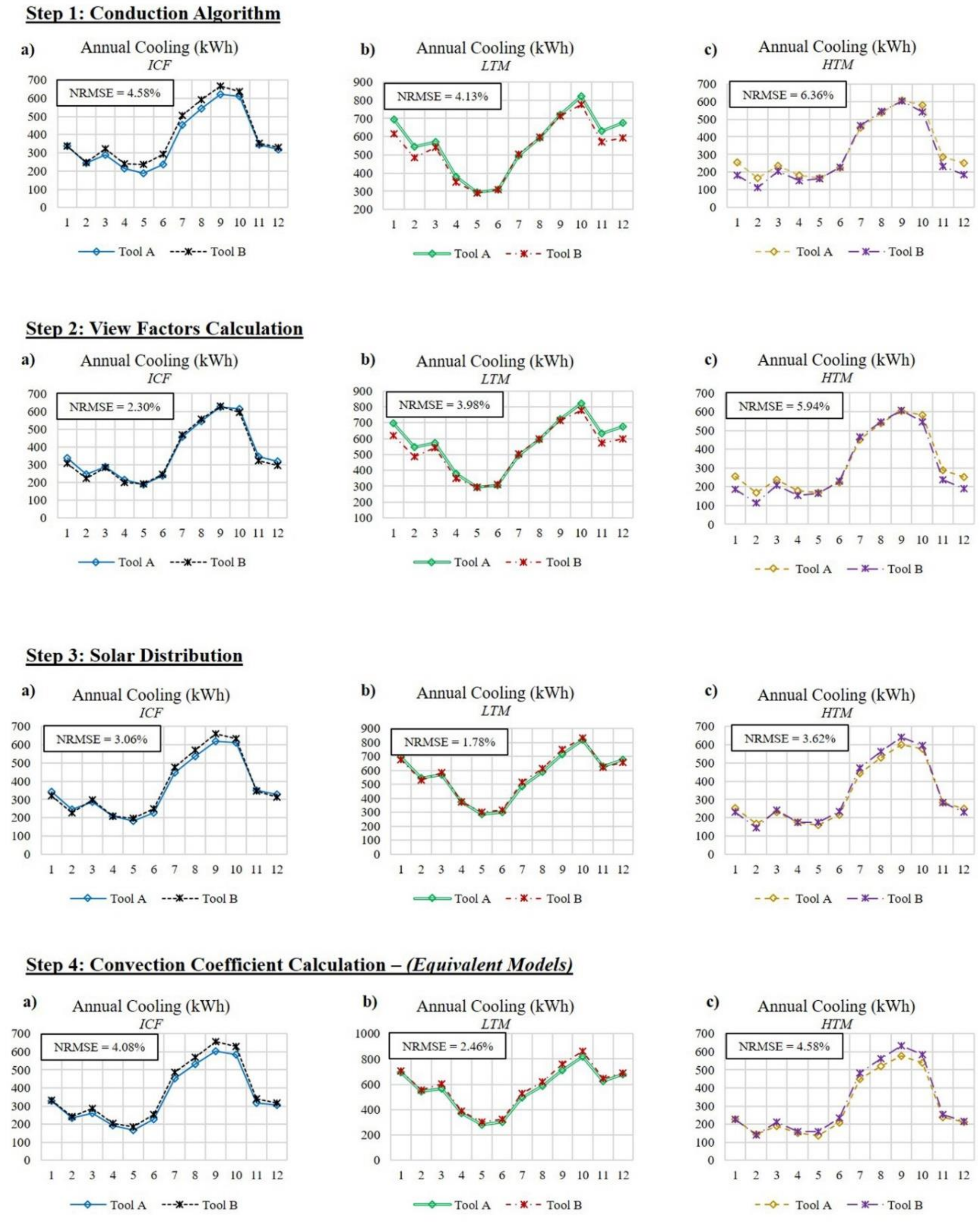


Fig. 11 *"Equivalencing" the models. Monthly break down of annual cooling energy predictions provided by tool A and tool B for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM).*

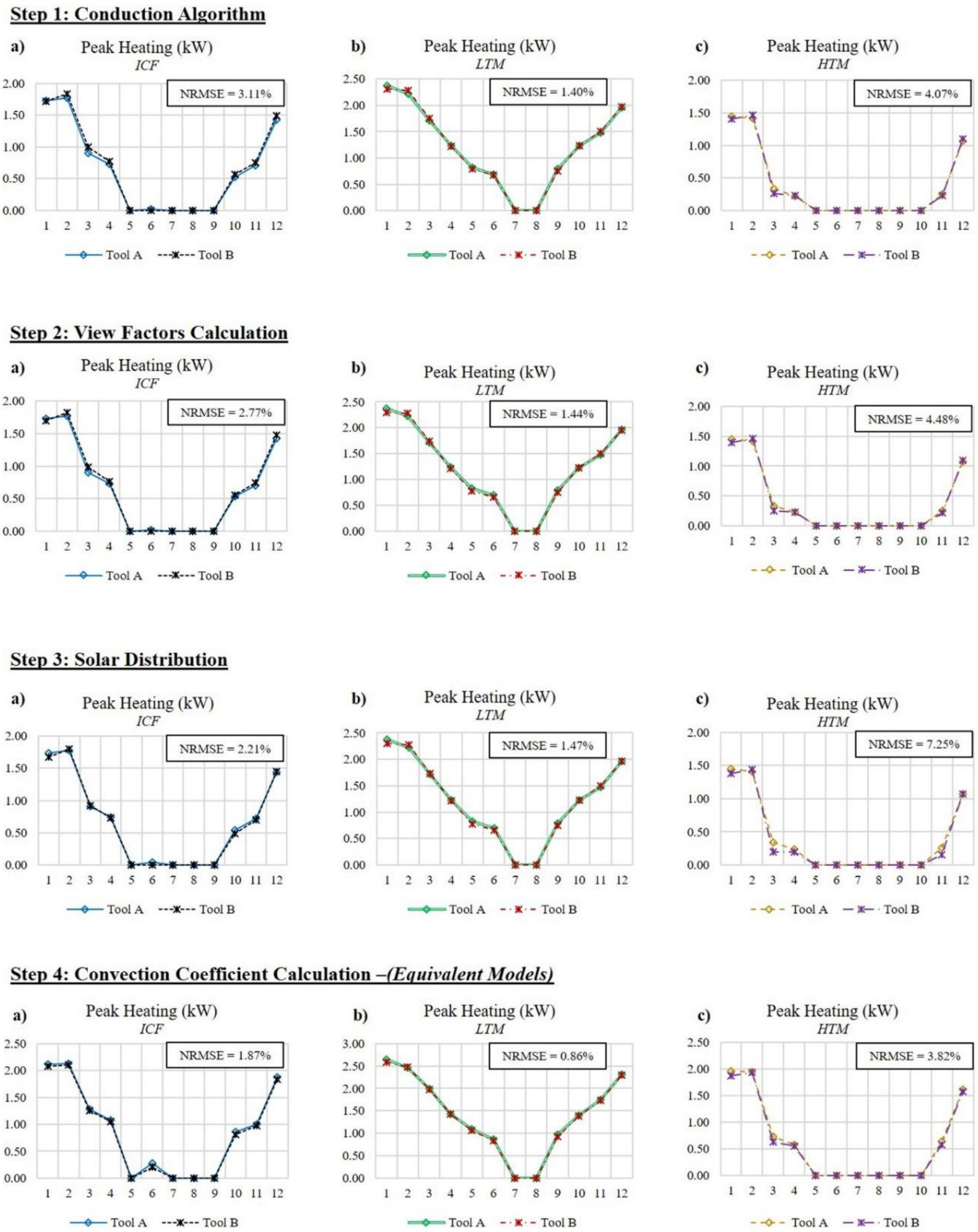


Fig. 12 *"Equivalencing" the models. Monthly break down of peak heating loads predictions provided by tool A and tool B for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM).*

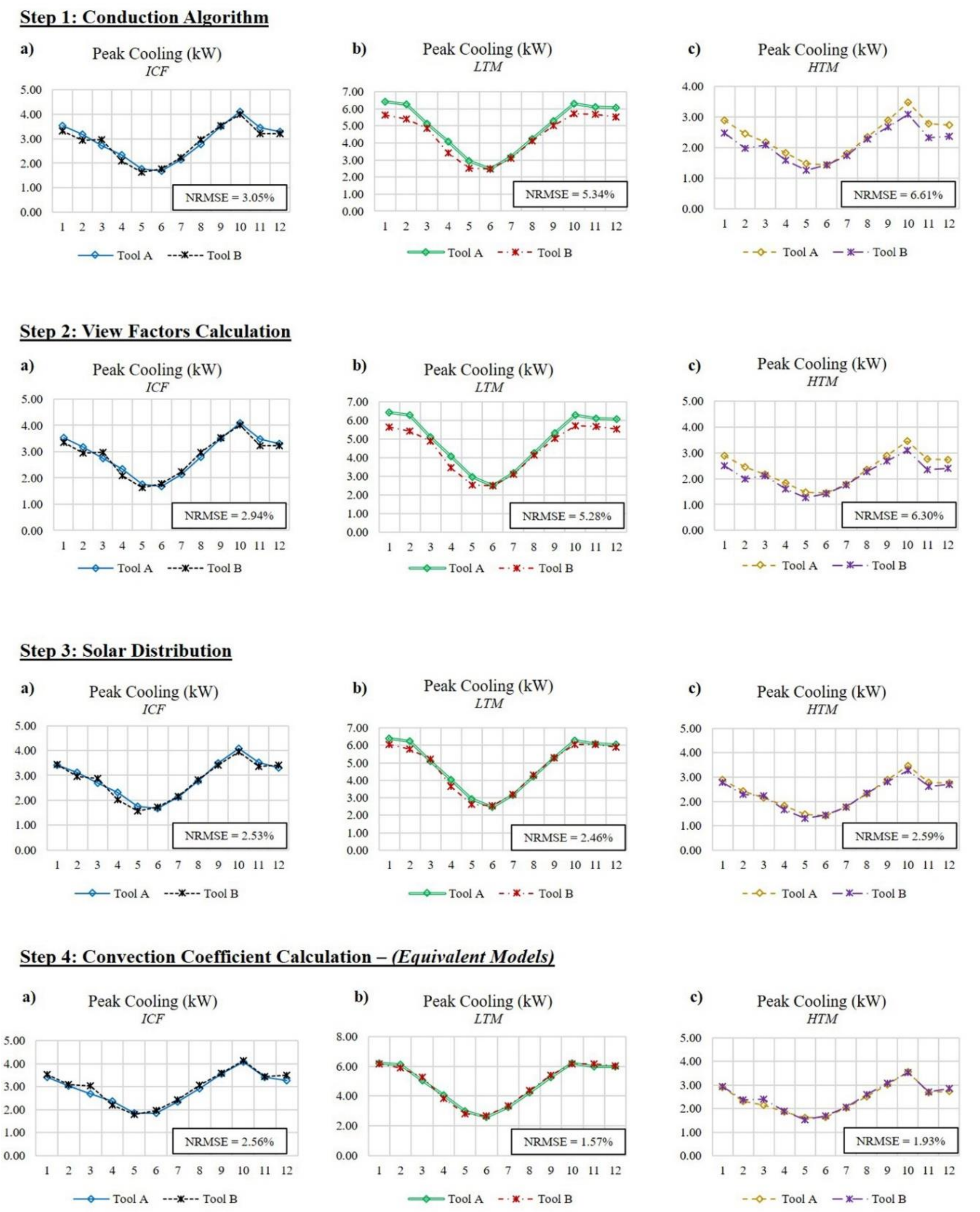


Fig. 13 *"Equivalencing" the models. Monthly break down of peak cooling loads predictions provided by tool A and tool B for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM).*

3.2.2 Annual Simulation Results of Equivalent Models

Following the model "equivalencing" process, the profiles of the monthly breakdown for the annual heating demand of the equivalent models (Step 4 in Fig.10) show that the most pronounced discrepancy was found again in the winter months (January to February), especially in the ICF building. In the annual cooling energy consumption however (Step 4 of Fig. 11), the greatest divergence in the equivalent models was observed between July and October in all three construction methods, and was more obvious in the ICF and HTM cases. Contrary to the default models, an overall good agreement was observed in the annual cooling results of the two BPS tools during the winter period. In the peak heating and peak cooling loads (Step 4 in Fig.12 and Fig.13) the NRMSE was insignificant and no substantial discrepancy was evident.

The divergence in the annual simulation results for the equivalent models was reduced compared to the default models (Fig.14) in both heating and cooling demand and for all construction methods. Fig. 14 shows the absolute difference and the NRMSE in the simulation predictions provided by tools A and B for annual heating and cooling energy consumption and peak heating and cooling loads for both the default and the equivalent models. The graph illustrates how the absolute difference and the NRMSE were reduced in the equivalent models for all three construction types, in instances up to 24% (i.e. annual heating of ICF). With regards to the absolute differences, the highest discrepancy in the prediction of the two tools was observed in the annual cooling demand, reaching up to 300kWh for all three construction methods. This value might be considered as high, yet when compared to the total calculated annual cooling demand (i.e. varies between 4000kWh for the HTM and to 7000kWh for the LTM buildings) it is of less significance. In the annual heating, peak heating and peak cooling demand the absolute differences were minimised for all three buildings. Looking at the relative differences in the predictions provided by the two BPS tools, the highest divergence was observed in the annual heating and cooling energy consumption of HTM and the annual cooling demand of the ICF building (NRMSE = 4.6% and NRMSE = 4.1%, respectively). In general, the simulation results provided by the equivalent models for all three construction methods were very consistent. However, the discrepancy in the prediction of the annual cooling demand remained high in all three constructions even after the models were "equivalenced". Particularly in the case of ICF, the divergence in the calculation of the annual cooling demand increased after the "equivalencing" process rather than decreasing.

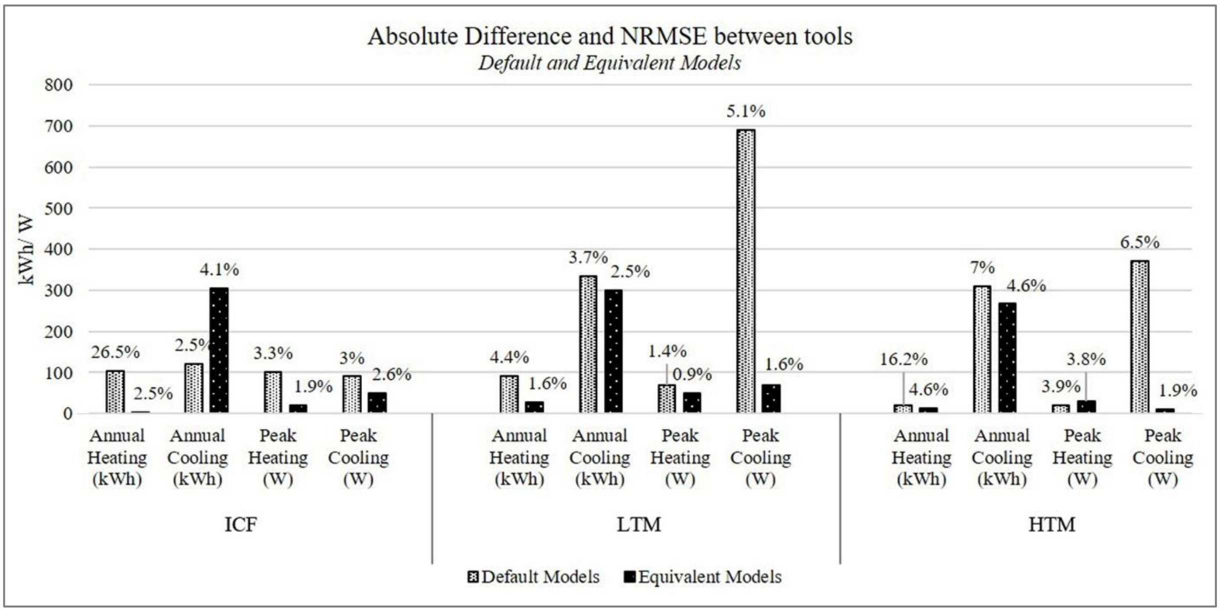


Fig. 14 *Absolute difference and NRMSE between the simulation predictions provided by tools A and B for the three construction methods, (i) ICF, (ii) low thermal mass (LTM) and (iii) high thermal mass(HTM), when the user relies on the tools' default settings and when the models are equivalent.*

3.2.3 Hourly Simulation Results of Equivalent Models

Fig. 15 and Fig.16 show the discrepancy in the hourly simulation results provided by the two BPS tools for the internal surface, the intra-fabric and the external surface temperatures of the east wall after the "equivalencing" process. Fig.15 shows the results for three consecutive days in the heating period. As can be seen from the graphs the variation in the predictions for all three constructions was very low for the temperatures of the three nodes (i.e. inside surface, intra-fabric and outside surface). A very good consistency was achieved in the results provided by the two BPS tools. The highest variation was found in the outside surface temperature, where the NRMSE = 3.00%, yet it was still relatively low.

An even better agreement between the two tools was achieved for the prediction of the surface temperatures in the cooling period (Fig. 16). The variation in the temperature of the nodes for all three case, inside surface, intra-fabric and outside surface was found to be negligible in all three constructions (below NRMSE = 2%).

The absolute differences in the internal, intra-fabric and external temperatures, as predicted by the two BPS tools, were also negligible for both periods under investigation and for all three construction methods.

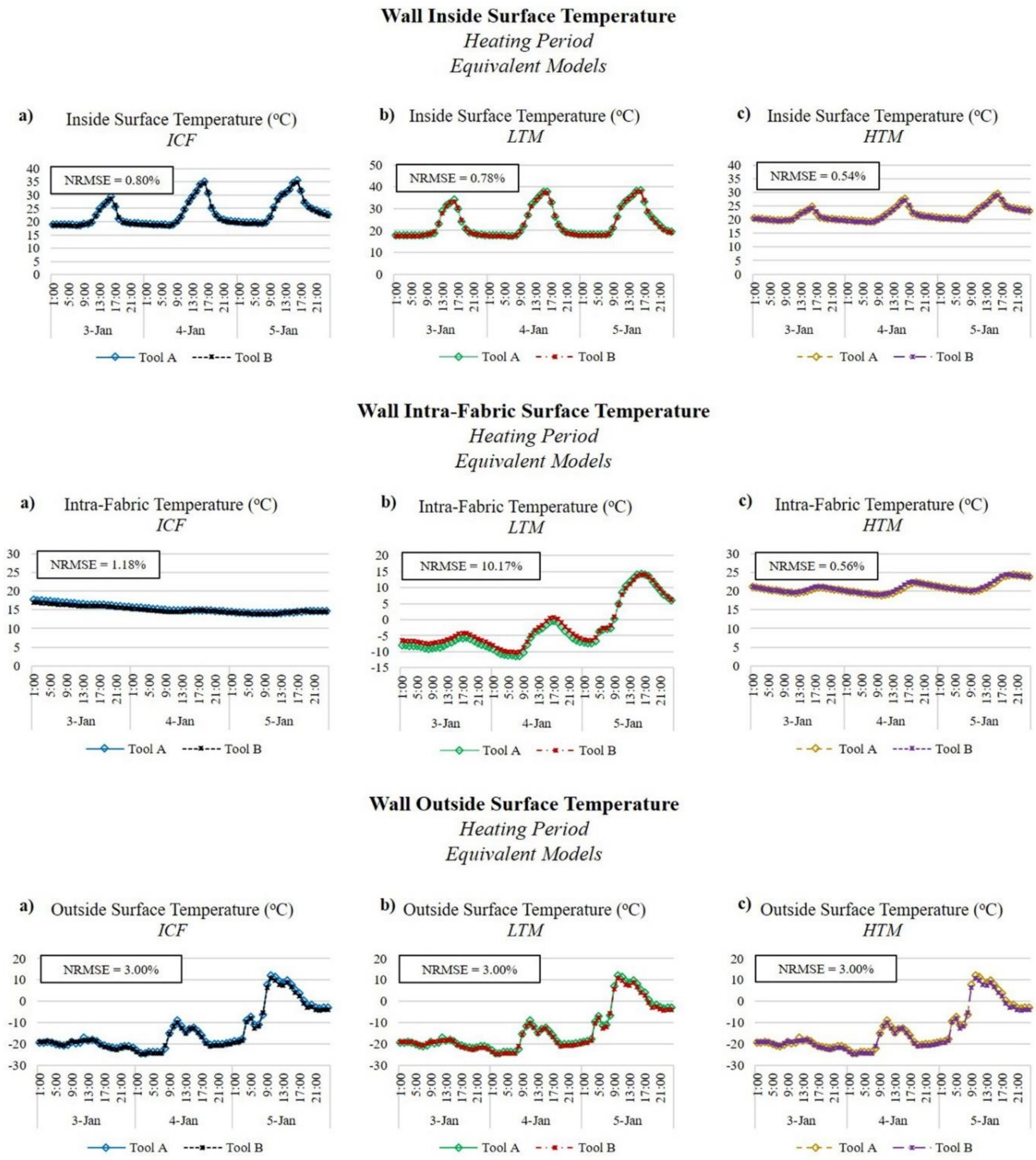


Fig. 15 *Hourly breakdown of the inside surface, intra-fabric and outside surface temperature of the east wall. Simulation predictions provided by tool A and B for three consecutive days in the heating season (03 – 05 January) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the models are equivalent.*

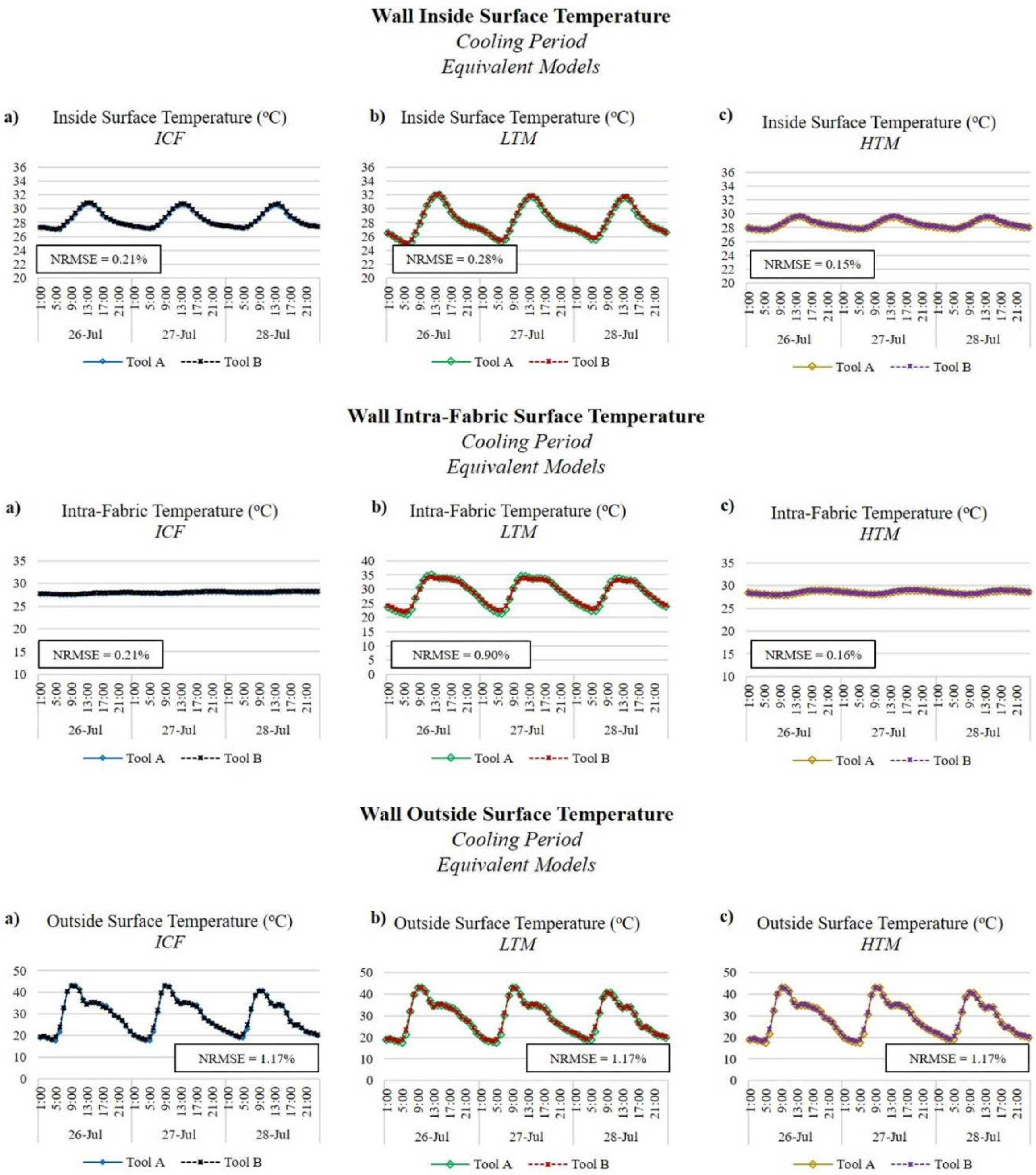


Fig. 16 *Hourly breakdown of the inside surface, intra-fabric and outside surface temperature of the east wall. Simulation predictions provided by tool A and B for three consecutive days in the cooling season (26 – 28 July) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the models are equivalent.*

With regards to the hourly breakdown of the heating and cooling demand, as illustrated in Fig. 17 and Fig.18, there was again a very good agreement in the predictions provided by the two BPS tools. For the heating demand (Fig.17) the discrepancy was found to be lower than NRMSE = 4.50% for all three construction methods. The variation in the cooling demand

(Fig.18) was found to be even lower and around NRMSE = 2.50% for all three buildings. The general observation is the after the model were equivalenced, there was a very good consistency in the hourly simulation predictions both for the surface temperatures, but also for the space heating and cooling needs.

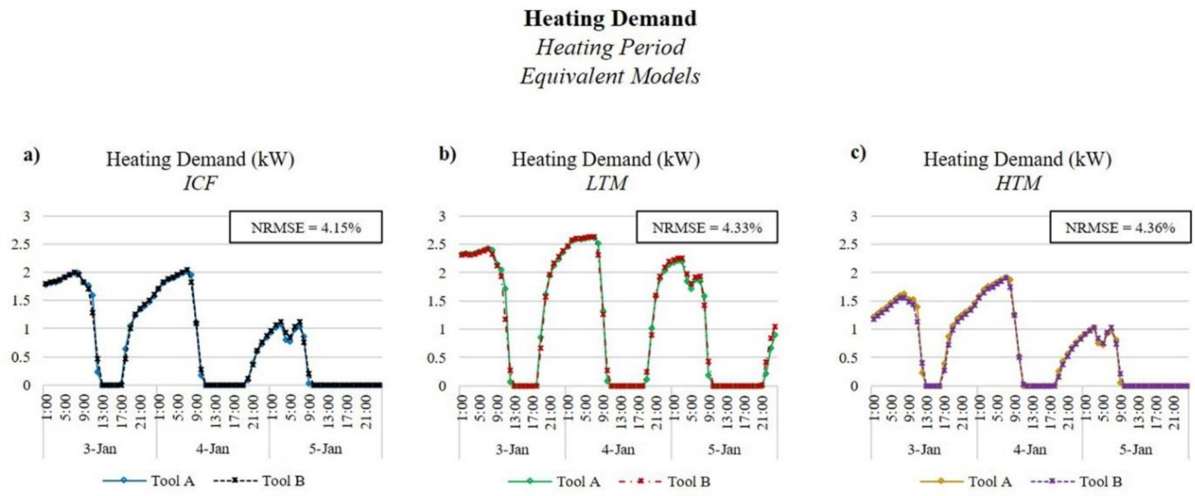


Fig. 17 *Hourly breakdown of heating demand. Simulation predictions provided by tool A and B for three consecutive days in the heating season (03 – 05 January) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the models are equivalent.*

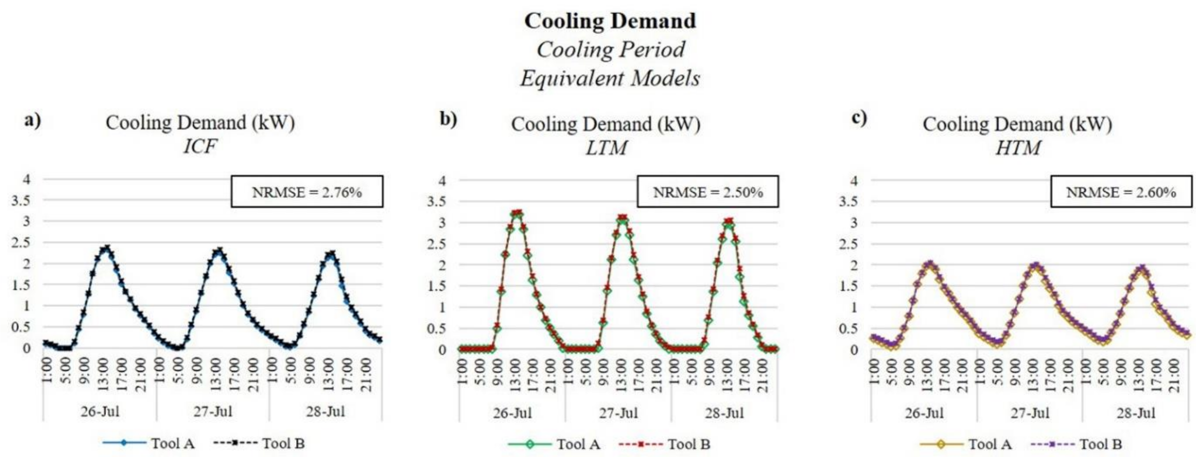


Fig. 18 *Hourly breakdown of cooling demand. Simulation predictions provided by tool A and B for three consecutive days in the cooling season (26 – 28 July) for all three constructions: (a) ICF, (b) low thermal mass (LTM) and (c) high thermal mass (HTM), when the models are equivalent.*

3.2.4 Comparison of Thermal Performance Between the Three Constructions

A comparison was performed on the annual thermal performance of ICF against the thermal performance of the LTM and the HTM building, before and after the model “equivalencing” process. The aim was to investigate whether the “modelling gap” would affect the conclusions on the comparative performance of ICF and to highlight the significance of reducing uncertainties in building performance simulation. The results illustrated in Fig. 19 and 20 show the average in the simulation predictions provided by the two BPS tools for the default and equivalent models, respectively. Tables 2 and 3 summarise the percentage difference in energy consumption of ICF compared to LTM and HTM, as predicted by each two BPS tools (along with their average).

Fig. 19 and Table 2 show the comparison between ICF, LTM and HTM buildings when the user relies on the default settings of the tools. Comparing the overall annual heating demand of ICF to the other two construction methods, the two BPS tools predicted that ICF would require on average 80.5% less annual heating energy than LTM and 60% more than HTM. In the annual cooling energy consumption, ICF showed 33.5% less cooling demand than the LTM building and 13.5% more than the HTM building. The peak heating loads of the ICF building were 25.5% less compared to the LTM building and 18% higher than the HTM. Finally, in the peak cooling loads ICF showed 33.5% reduced cooling demand than the LTM and 19% increase compared to the HTM building.

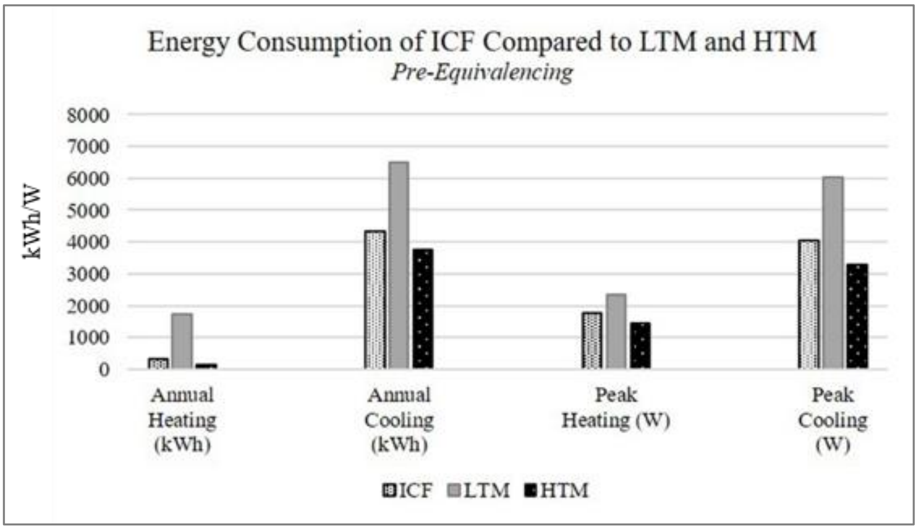


Fig. 19 *Comparison of ICF building energy consumption to LTM and HTM buildings, when the user relies on the tools' default settings, average of both tools.*

Table 2 *Percentage difference in energy consumption of ICF compared to LTM and HTM, when the user relies on the tools' default settings.*

ICF Energy Consumption						
	ICF vs. LTM			ICF vs. HTM		
	Tool A	Tool B	Average of both Tools	Tool A	Tool B	Average of both Tools
Annual Heating	-83%	-78%	-80.5%	+57%	+63%	+60%
Annual Cooling	-33%	-34%	-33.5%	+11%	+16%	+13.5%
Peak Heating Loads	-27%	-24%	-25.5%	+16%	+20%	+18%
Peak Cooling Loads	-36%	-31%	-33.5%	+15%	+23%	+19%

After the models "equivalencing" process the results, as shown in Fig. 20 and Table 3, indicate that ICF behaves closer to the HTM building than before. For instance, in the annual heating demand, the two BPS tools predicted that ICF would require on average 56% more energy than the HTM building. This figure remains high, yet it is lower than the initial estimations pre-equivalencing (Table 2). Accordingly, post-equivalencing the ICF building showed just 8% increased peak heating demand compared to the HTM building (Table 3). Pre-equivalencing this value was estimated to be 18% (Table 2). Similar findings apply to the peak cooling demand. The general remark both before and after the model "equivalencing" process is that the ICF building behaved much more similarly to HTM, with the exception of annual heating energy consumption. For annual heating demand, although the energy consumption of ICF was significantly reduced compared to LTM (78.5%), it still required higher amount of heating energy compared to HTM (56%). In the annual cooling demand and the peak heating and cooling loads ICF consumed slightly increased energy than the heavyweight structure. In the comparison of ICF to LTM, the former consumed significantly less energy for both annual heating and cooling.

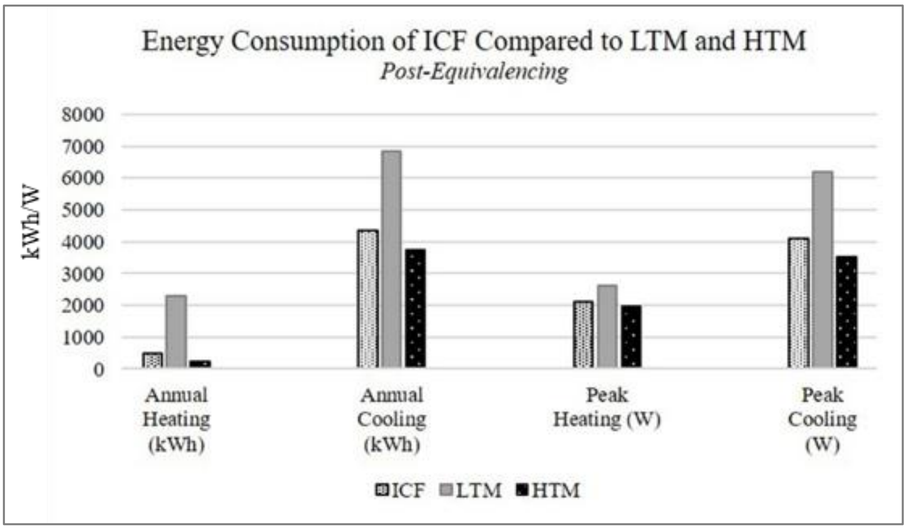


Fig. 20 *Comparison of ICF building energy consumption to LTM and HTM buildings, when the models are equivalent, average of both tools.*

Table 3 *Percentage difference in energy consumption of ICF compared to LTM and HTM, when the models are equivalent.*

ICF Energy Consumption						
	ICF vs. LTM			ICF vs. HTM		
	Tool A	Tool B	Average of both Tools	Tool A	Tool B	Average of both Tools
Annual Heating	-78%	-79%	-78.5%	+55%	+57%	+56%
Annual Cooling	-37%	-37%	-37%	+14%	+14%	+14%
Peak Heating Loads	-19%	-19%	-19%	+8%	+8%	+8%
Peak Cooling Loads	-34%	-33%	-33.5%	+13%	+15%	+14%

Looking at the monthly breakdown of the annual and peak, heating and cooling demand for the equivalent models (Step 4 of Fig. 10 to 13), the thermal performance and the energy consumption of ICF was compared to the other two options. For annual heating energy consumption (Step 4 in Fig. 10), the profiles of the monthly breakdown is similar for all three constructions, although the amount of heating demand varies significantly. More specifically, LTM requires a maximum of around 500kWh of heating during January, while ICF and HTM require approximately 150kWh and 80kWh respectively. Moreover, the LTM results indicated no heating demand for two months, July and August, and for ICF there was no heating demand for five months (i.e. May to September). For HTM, the heating demand was even smaller and the results predicted zero heating for seven months, between May and November.

In the annual cooling energy consumption (Step 4 of Fig.11), ICF and HTM followed very similar profiles in the monthly breakdown and require similar amounts of cooling. LTM indicated a different profile of annual cooling compared to the other two cases, throughout the year. In general, it required more cooling energy, with higher peaks, especially over the heating period (i.e. January to May, September to December).

In respect of peak heating loads (Step 4 of Fig.12), all three construction methods showed different monthly profiles. As with the annual heating demand, in the peak heating loads, LTM indicated no heating demand for two months, in July and August. The ICF building required no heating for almost five months (May to September), while HTM indicated no peak heating loads over a period of six months (May to October). LTM required a maximum peak heating of around 2.50kW in January, while for the other two methods the maximum demand (of around 2.00kW) occurred in February. In general LTM showed increased peak heating demand throughout the year compared to the other two buildings. ICF and HTM required relatively similar amounts of heating over winter and summer, with the main differences found to be over the intermediate periods (March to May and September to November).

For peak cooling loads (Step 4 of Fig.13), all three constructions showed a similar profile in the monthly breakdown, with the exception of November and December, when there was a significant drop in the peak cooling loads for ICF and HTM, yet for LTM the demand remained almost constant. The amount of peak cooling in LTM was higher compared to the other two cases, throughout the year.

Looking at the difference in predicted performance of ICF compared to the other two construction methods due to the use of different tools, before and after the model "equivalencing" process, as indicated in Tables 2 and 3, it is obvious that a very good consistency was achieved after the models were "equivalenced". More specifically, in the comparison of ICF to HTM construction method, pre-equivalencing the variation between the two tools was around 6% in the annual heating, 4% in the annual cooling and peak heating loads and up to 8% in the peak cooling loads. After the models were "equivalenced" the variations in the predicted performance provided by the two BPS tools were minimised to less than 2%. Similar findings apply to the comparative performance of ICF to LTM construction method. In general, the "equivalencing" process resulted in more consistent conclusions regarding the energy consumption of ICF compared to the other two construction methods.

3.3 PHASE 3: INVESTIGATING THE IMPACT OF DIFFERENT MODELLING METHODS ON BPS RESULTS

During the "equivalencing" process, several observations were made in respect of the different modelling methods employed by the two BPS tools – this section provides an overview of some important points.

The first was the solar timing that was used in the calculation of the solar data. In both tools the solar values in the weather file were average values over the hour. When the simulation timestep was greater than 1 (sub-hourly simulation), interpolated values were used. Tool A calculated by default the average values based on the midpoint of each hour, whereas tool B offered a user-selectable option to treat solar irradiance included in the climate files, based on the half hour or the top of each hour. As a consequence, the selection of the solar timing calculation affected the simulation results provided by tool B. Fig. 21, shows the comparison of the simulation predictions provided by tool B when the solar timing was set to the midpoint or the top of the hour, for annual and peak heating demand (Fig.21a) and annual and peak cooling demand (Fig. 21b). The hatched bars show the results when solar timing is taken at the midpoint of the hour and the solid-coloured bars show the results when solar timing is taken at the top of each hour. For all three construction methods, the annual and the peak heating demand was always reduced when the solar timing was set to the midpoint of the hour, but the annual and peak cooling was slightly increased. Fig. 21a shows some very clear differences in the predicted annual heating demand due to solar timing calculations for all three construction methods. The maximum difference, as indicated in Table 4, was in the annual heating energy consumption of the HTM and the ICF buildings (-7.48% and -6.23% respectively). In general there were insignificant differences in the annual and peak cooling demand; hence the solar timing had only a minor impact on the cooling predictions.

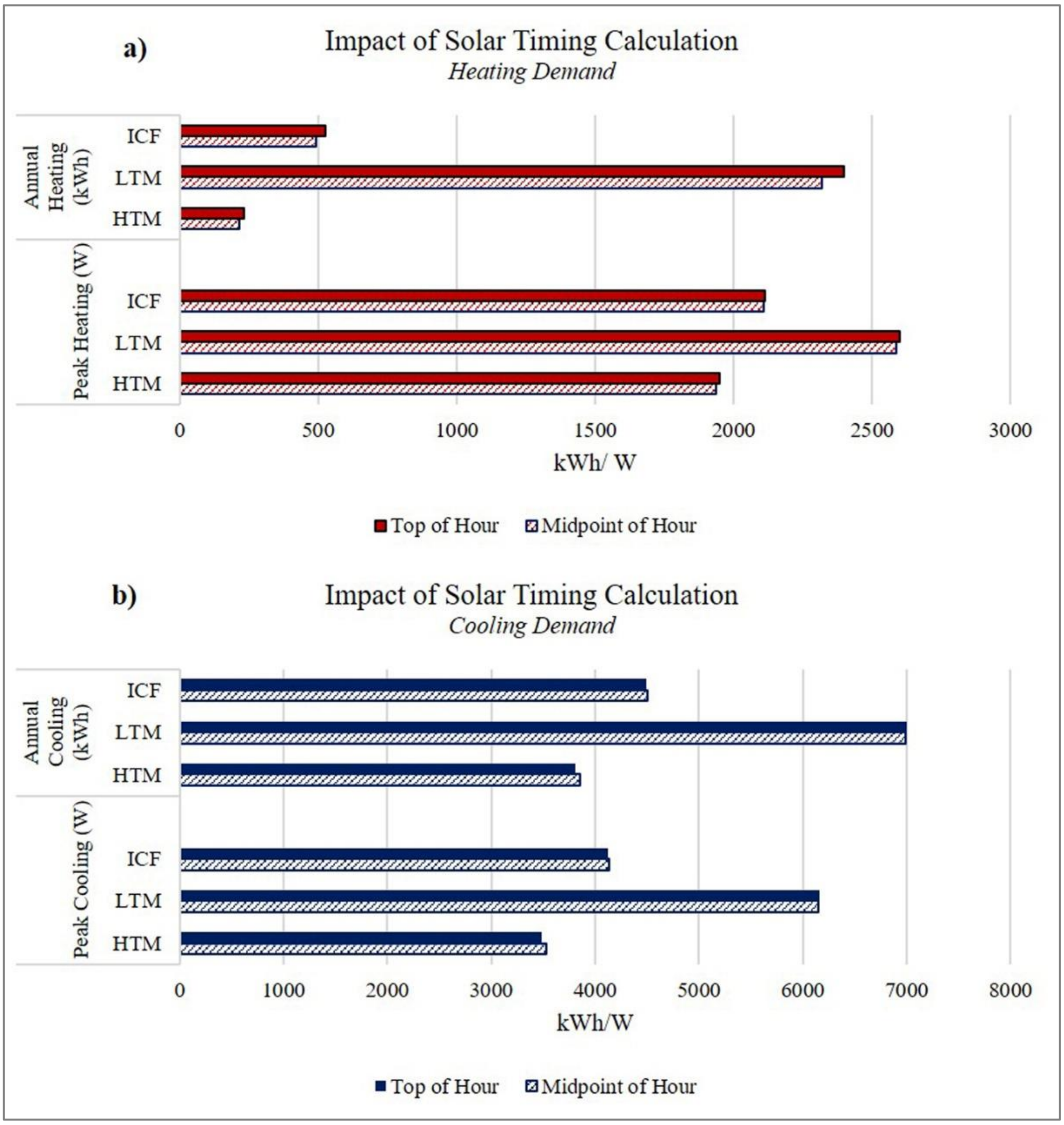


Fig. 21 *Absolute difference in the predictions provided by tool B when solar timing is set to the midpoint or the top of the hour. (a) Annual and peak heating demand, (b) Annual and peak cooling demand.*

Table 4 *Relative difference in the predictions provided by tool B when solar timing is set to the midpoint or the top of the hour.*

	Solar Timing Calculation Relative Difference			
	Annual Heating	Peak Heating	Annual Cooling	Peak Cooling
ICF	-6.23%	-0.32%	+0.30%	+0.05%
LTM	-3.27%	-0.41%	+0.14%	+0.13%
HTM	-7.48%	-0.62%	+1.18%	+1.10%

Another factor that was investigated as part of the "equivalencing" process was the impact of assumptions for the calculation of the external surface convection coefficients; more specifically, the impact of variations in wind speed on the simulation results provided by the two BPS tools. When the external convection coefficient of the surfaces was set to constant (user-defined), the variations in the wind speed (i.e. taken from the climate file), had no impact on the simulation results, as anticipated. In other words, assuming a constant exterior convective coefficient, could be interpreted as setting a constant value for the wind velocity throughout the simulation period. However, when the convection coefficients were calculated based on the default algorithms, the impact of wind speed differed between the two tools and varied according to the construction method. The reason was that both tools consider the wind speed in their external surface convection coefficient calculation regime, yet they use different equations to do so. Tool A included surface roughness within the external convection coefficient calculation, whereas tool B relied solely on the wind speed. To investigate this issue further, the default algorithms for the calculation of convective heat transfer coefficients were selected in both tools and the simulations were performed twice; once when the wind speed was taken from the climate file and once when the wind speed in the climate file was set to 0m/s throughout the whole year.

Fig. 22 shows the impact of the assumptions for convective heat transfer coefficients on the results provided by tool A and tool B, for annual and peak heating demand and annual and peak cooling demand. The graphs illustrate the absolute difference in kWh (annual demand) and in W (peak loads) when the wind speed is taken from the climate file and when the wind speed is set to 0m/s throughout the simulation period. The solid-coloured bars show the reduction (or increase) in the results due to the lack of wind for tool A and the hatched bars show the reduction (or increase) for tool B. Here, annual and peak heating demand was reduced in the absence of wind, whereas the annual and peak cooling demand increased, for both tools and for all construction methods. The assumptions for the convective heat transfer coefficients had the most significant impact in the calculation of the annual heating and cooling energy consumption (Table 5). Their impact was also obvious in the peak heating loads, whereas, the differences in the simulation of the peak cooling loads with and without wind were negligible. In every case, with the exception of the peak cooling loads, the impact of assumptions related with the calculation of convection coefficients was more profound for the ICF and HTM, for both tools. For annual heating demand, the impact of wind speed variations had a more significant effect within tool B than tool A. In all other cases (i.e. peak heating and annual and peak cooling), the impact was similar for both tools.

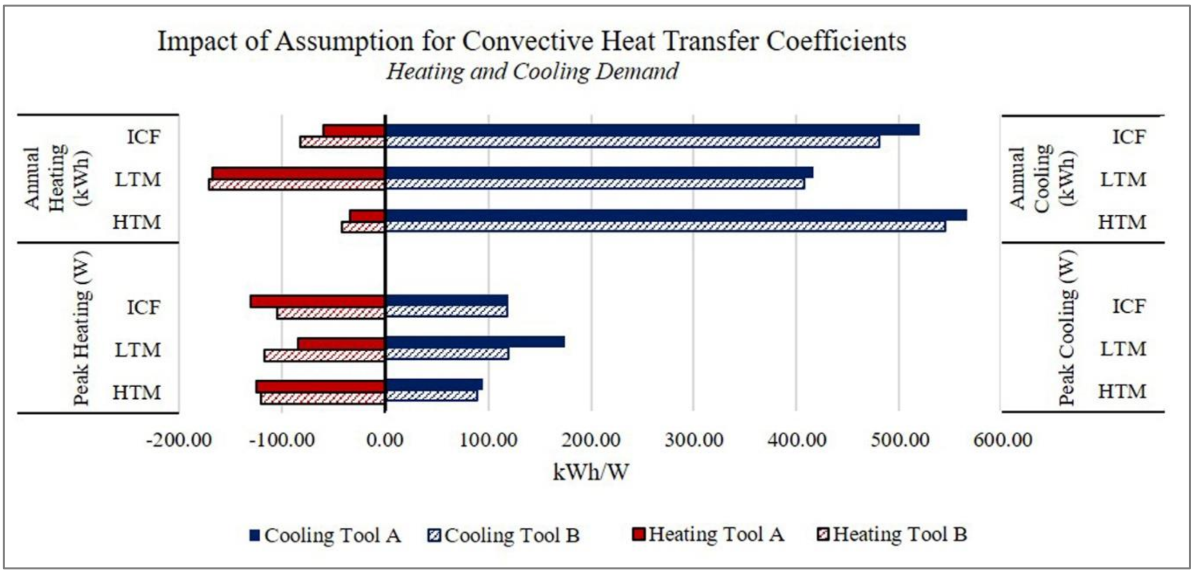


Fig. 22 *Absolute difference in kWh and W between results provided by tool A and tool B, when simulations are performed with and without wind. Annual and peak heating demand, annual and peak cooling demand.*

Table 5 *Relative difference in the predictions provided by tool A and tool B, when simulations are performed with and without wind.*

Impact of Assumption for Convective Heat Transfer Coefficients Relative Difference								
	Annual Heating		Peak Heating		Annual Cooling		Peak Cooling	
	Tool A	Tool B	Tool A	Tool B	Tool A	Tool B	Tool A	Tool B
ICF	-18%	-24%	-7%	-6%	+12%	+11%	+3%	+3%
LTM	-10%	-10%	-4%	-5%	+6%	+6%	+3%	+2%
HTM	-25%	-31%	-9%	-8%	+15%	+14%	+4%	+3%

4 DISCUSSION

The following section includes a discussion of the academic implications of this research, in respect of key literature in the area and contribution to knowledge. ICF is mostly perceived as an insulated panel, because of the internal layer of insulation, which is expected to act as a thermal barrier, isolating the thermal mass of the concrete from the internal space. Even though there is evidence from previous studies (Kosny et al., 2001; Maref et al., 2010) supporting its thermal storage capacity, when compared to a light-weight timber-frame panel with equal levels of insulation, there is still a gap in knowledge in quantifying its thermal mass.

There is a difference between the thermal mass of the fabric and the effective thermal mass. The term effective thermal mass is used to define the part of the structural mass of the construction which participates in the dynamic heat transfer (Slee et al., 2014; BS EN ISO 13786, 2017). There are several simplified, usually simple dynamic, quasi-steady state or steady state methods used for the calculation of energy use in buildings, such as the BS EN ISO 13790 (2008) and the UK Government's standard assessment procedure for energy rating of dwellings (SAP2012) (BRE, 2012). In such approaches the effective thermal mass is usually accounted for with simplified calculations, relying on the thermal capacity of the zone's construction elements. Taking SAP as an example, in order to calculate the thermal mass parameter of an element, one needs to calculate the heat capacity of all its layers. However, it is specifically stated that starting from the internal surface, the calculations should stop when one of the following conditions occurs:

- an insulation layer (thermal conductivity <= 0.08 W/m·K) is reached;
- total thickness of 100 mm is reached.
- half way through the element;

In other words, according to SAP the storage capacity of ICF concrete core is completely disregarded. Similarly, in the ISO 13790: 2008 the internal heat capacity of the building is calculated by summing up the heat capacities of all the building elements for a maximum effective thickness of 100mm. This highlights the significance of using reliable dynamic whole building simulation in order to evaluate accurately the thermal performance of specific buildings and non-conventional construction methods.

On the other hand, it is widely accepted that large discrepancies in simulation results can exist between different BPS tools (Irving, 1982; Zhu et al., 2012; Mantesi et al., 2016). Kalema et al. (2008) compared three different BPS tools with regards to their ability in calculating the effect of thermal mass in energy demand reduction. The authors contrasted the simulation results provided by the three BPS tools and analysed their divergence. However, they did not reflect on the impact that the different calculation methods employed by the tools had on the results discrepancy. When creating a simulation model, the users are asked to make several important decisions; which BPS tool to use, how to specify the building, which input values are appropriate, which modelling methods and simulation algorithms to select. Several studies analysed the influence of modelling decisions and user input data in the simulation predictions (Guyon, 1997; Berkeley et al., 2014; Strachan et al., 2015). In the work conducted by Beausoleil-Morrison and Hopfe (2016) a post-simulation autopsy was performed on the results provided by nine different model users for the BESTEST building. The analysis highlighted the influence of default setting and decision-making during the specification of a simulation model. In a similar context the work presented in this paper investigated the effects of default settings, different modelling methods and calculation algorithms on the "modelling gap". However to the authors' knowledge this is the first time that such an analysis was done focussing on the representation of different types of thermal mass in whole BPS. Furthermore, this is the first detailed analysis on the simulation of ICF, a construction type that has not previously been studied.

The analysis showed that there is indeed a large divergence in the simulation results provided by the two tools for the default models in terms of both the absolute and relative differences. It is important to look both at the relative differences in terms of inter-modelling divergence, but also to appreciate the real meaning of values. For instance, the absolute difference in the calculation of annual and peak heating and cooling loads (Fig.4) showed that the maximum value was observed in the peak cooling loads of the LTM building (i.e. 700W). That might be considered as a high number, however comparing it to the total predicted peak cooling loads for the LTM building (which was calculated on average around 6000W by both tools), it becomes clear that it is not such a substantial difference. In contrast, the absolute difference in the predictions of the two tools for the annual heating demand of the ICF was 100kWh. Given that the average total annual heating demand calculated by both tools was around 400kWh, it is clear that the discrepancy in this case is much more significant. Another example is the calculation of internal surface temperature as illustrated in Fig.6. The predictions provided by the two tools for the ICF building showed a variation of NRMSE = 4%. Nevertheless, looking at the actual numbers, it can be seen that the temperature difference was at times, as much as 5^{o}C. Although there is seemingly a good consistency in the simulation predictions provided by the two tools, an absolute temperature difference of 5^{o}C is substantial. This practically means that very different interpretations could be drawn regarding the thermal comfort assessment of the ICF building based on the selection of BPS tool.

In general, the results of the default models showed that in the ICF and HTM buildings the variation in the annual heating demand was up to 26% and 16%, respectively. Furthermore, the greatest inconsistency was observed over the winter months. The discrepancy was evident in all three construction methods, for both annual and peak, heating and cooling demand. A better agreement was found in the simulation results for the summer period. The results indicated that further investigation was required to minimise the differences in the way the two BPS tools simulate solar gains.

Prior to analysing the various calculation algorithms and their impact on the results divergence, it was essential to minimise the differences in the two models, caused by other factors. A process of making the models equivalent was followed, where identical algorithms and input values were specified in both BPS tools. The results of the equivalent models showed very good agreement for all three construction methods (Fig.14). The HTM case remained the one where the greatest inconsistencies were observed, even after the models were "equivalenced" (NRMSE = 4.6% in the annual heating and cooling demand). Moreover, the discrepancy in the prediction of the annual cooling demand remained relatively high in terms of both absolute and relative difference for all three constructions. More specifically, in the case of ICF building, the "equivalencing" process increased the discrepancy in the simulation results, resulting in an NRMSE=4.1%. This finding indicates that there is a level of modelling uncertainty allied to ICF simulation that requires further investigation through measurements and empirical validation.

The "equivalencing" process showed that the two most influential parameters in the results' divergence was the distribution of direct solar radiation and the specification of the surface convection coefficients. The assumption of a default insolation distribution, rather than a time-varying calculated insolation distribution, could be considered to be a modelling decision, rather than a modelling uncertainty. In this case, the user may be justifiably deploying a simplified approach to save time and computational effort, in the knowledge that there will be a loss of accuracy. Similarly, the incorrect specification of solar timing can be considered to be a user error, not a modelling uncertainty. In the context of this paper however, we addressed the impact of default settings under the umbrella of modelling uncertainties, in addition to parameters such as convection coefficients and sky temperature calculations.

Another interesting finding of the study was when the thermal performance of ICF was compared to the other two construction methods. This was done both before and after the model "equivalencing" process. The ICF building was found to perform closer to the HTM building, both pre- and post-equivalencing. However the predictions regarding the comparative performance of ICF in relation to the other two construction methods differed, based on the selection of the BPS tool pre-equivalencing. It was noteworthy that after the model "equivalencing" process a very good agreement was observed in that respect by both tools. This finding highlighted the importance of minimising the "modelling gap" and showed that relying on the default settings of the BPS tools could potentially be misinterpreted. Nevertheless, due to the lack of real monitoring data the accuracy of simulation predictions cannot be empirically validated and does not permit robust conclusions to be drawn on the actual performance of ICF (or the other two construction methods). This and all the other limitations of the study are thoroughly discussed in the following sections.

5 RESEARCH LIMITATIONS

There are several constraints and limitations in the study presented in this paper. One of the most important is the absence of an absolute truth. In other words, it is impossible to say what is correct and what is wrong, whether one tool performs closer to reality than the other or even if ICF indeed performs closer to reality after the "equivalencing" process.

To achieve a direct comparison between the two BPS tools and to minimise the level of uncertainty in the input data several decisions were made during the "equivalencing" process. An example is the use of constant values for the surface convection coefficients. In fact, the building is always exposed to changes in the boundary conditions, both internally and externally. This practically means that the convection coefficients of the surface would vary over time (Beausoleil- Morrison, 2000). For the purpose of this study it was decided to use constant user-specified values in order to minimise the difference between the two BPS tools as much as possible. This decision may help to reduce the "modelling gap", however it introduces an understandable prediction error in the approximation of reality.

Moreover, the case study selected for the study prevented several important factors related to thermal mass simulation from being analysed, such as the impact of variable internal gains and air flows, the impact of intermittent occupation, the risk of overheating and others. The case study set up was selected in order to reduce the specification and scenario uncertainties as much as possible. The specification uncertainties are associated with incomplete or inaccurate specification of building input parameters. The scenario uncertainties are all the external conditions imposed on the building due to weather conditions, occupants' behaviour and others (De Wit & Augenbroe, 2002). In the study of Hopfe and Hensen (2011) the specification uncertainties associated with physical properties of the materials contributed to 36% increase in the annual heating demand and up to 90% increase in the annual cooling demand. Gaetani et al. (2015) found that the scenario uncertainties imposed on the building due to occupants' behaviour could contribute up to 170% increase in the simulation of annual heating energy consumption. From that perspective, the case study selection served well the purpose of analysing the "modelling gap". Certainly, it was difficult to derive solid conclusions about the actual thermal performance of either of the three construction methods in such a simplified simulation scenario. Comparing the relative performance of the ICF building against the other two construction methods showed that, in the specific case study, the former behaves closer to the HTM building, a finding that was further enhanced after the two models were equivalenced. However, a more realistic case study, where the three construction methods would be compared in a more representative environment and where real data could be used as a reference point to the actual ICF performance, could improve the reliability of this outcome.

The analysis was performed using the NRMSE. The RMSE is a helpful metric used for comparisons between data sets. However, when normalised to the mean of the observed data (i.e. NRMSE) it becomes unitless. This may facilitate the comparison of results that are in different units, yet it makes it difficult to put things in context. One example is the energy consumption of the HTM building. In general, the HTM building showed a reduced energy demand compared to the other two construction methods. This translates into a higher NRMSE value in the HTM building even if the absolute difference in the predictions provided by the two BPS tools is the same for the other two construction methods. There might be cases where the result of this magnification could be misinterpreted by the reader. It is considered rather important to look at both the absolute and relative difference in order to appreciate the significance of the results' variations.

Finally, the main aim of the study was to perform a crude comparative analysis between the two BPS tools and reflect on the impact that the different algorithms and default settings have on the representation of thermal mass in whole building performance simulation. From that point of view, the analysis was mostly focussed on monthly and annual simulation results provided by the two BPS tools for the heating and cooling demand. Hourly predictions on the space heating and cooling loads and the surface temperatures were presented for two representative periods before and after the model "equivalencing" process, showing that there is indeed a level of uncertainty in the way the charging and discharging of the mass is simulated in the two BPS tools. However, further investigation is necessary to analyse how the specific heat transfer mechanisms that occur in and out of the building affect the transient performance of the thermal mass, how these are simulated in different BPS tools and to give a better insight on how to tackle the "modelling gap".

6 CONCLUSION

To be able to support the commercial proposition of new materials and innovative building technologies it is important to predict and communicate their thermal behaviour and energy performance accurately. Faced with a lack of empirical data, computer simulation can be used to provide quantitative data, supporting the decision-making process. The study presented in this paper investigated the "modelling gap", the implications of default input parameters and the impact of different modelling methods on the representation of thermal mass in BPS. Three different construction methods were analysed, considering different levels of thermal mass in the building fabric; ICF, LTM and HTM. This study is the first detailed analysis on the simulation of ICF and the first study to reflect on the influence of modelling decisions on thermal mass simulation.

Large discrepancies can occur when modelling an identical building using different BPS tools. These inconsistencies are usually referred to as modelling uncertainties (Hopfe & Hensen, 2011) and can lead to a lack of confidence in building simulation. In this research, modelling uncertainties account for up to 26% of the variation in the simulation predictions. Their impact might not be as high compared for example to uncertainties related to occupancy [up to 170% in (Gaetani et al., 2015)], however it is significant. The level of thermal mass in the fabric was found to have a considerable impact on the inconsistencies in the results; hence the highest variation was mostly observed in the ICF and the HTM buildings. Particularly in the case of

ICF, of which there is currently little research on modelling and evaluation of its performance, the selection of BPS tool could cause ICF construction to look less desirable to designers and hence impact market penetration. This practically means that when evaluating simulation predictions for decision-making, the impact of choosing a particular BPS tool or method should be acknowledged by modellers.

There are many BPS tools currently on the market, each serving a different purpose. To make BPS tools more "user-friendly", software companies often provide a default value for most of the required input parameters. It is common for users to rely on default settings without fully appreciating the implications on their decision and without fully understanding the sensitivity of the model to several important parameters. The outcome of this study highlighted the need for BPS tools to be transparent about their methods of calculation and for modellers to make informed decisions about the specification of a model. Only then can the quantification of energy savings through simulation be seen in the correct context by designers and regulators.

The research was undertaken in three phases. In Phase 1, the divergence in the simulation results provided by the tools when the model user relies on the default input settings was found to be relatively high, particularly in the annual heating energy consumption. The most significant discrepancy was observed over the winter period, when the solar angle is small. Better consistency was observed over the summer months.

In Phase 2, after the "equivalencing" process, identical calculation algorithms and input values were specified in both simulation models. The results showed a very good agreement. The discrepancy in the annual heating and cooling demand of the HTM building and the annual cooling energy consumption of the ICF building remained the highest between all three construction methods, indicating that there is a level of modelling uncertainty in the representation of thermal mass in BPS, which requires further investigation.

Lastly, in Phase 3 of this research, two different modelling factors (i.e. solar timing and wind speed) were analysed to show how the different modelling methods employed by the tools affect the results' discrepancy, even when the input values are the same (in this case the climate data). The analysis showed that the variation observed in the simulation predictions was higher for the heating demand and increased according to the level of the thermal mass in the fabric; hence the most profound inconsistencies were observed once again in the simulation of the ICF and HTM buildings.

The relative performance of ICF compared to the other two construction methods was analysed before and after the model "equivalencing" process. This research demonstrated that, for the specific case study, ICF behaved in a broadly similar way to HTM. A finding which was further enhanced after the models were equivalenced. This is a potentially significant finding, indicating that ICF could be a viable alternative for energy efficient construction. Nevertheless, validation through further computational analysis, empirical testing, and building monitoring will be required to validate the results and clarify future directions for research.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Engineering and Physical Sciences Research Council and the Centre for Innovative and Collaborative Construction Engineering at Loughborough University for the provision of a grant (number EPG037272) to undertake this research project in collaboration with Aggregate Industries UK Ltd. Furthermore they would like to thank Dr Drury Crawley, Dr Jon Hand, Dr Rob McLeod, Dr Chris Goodier and Ms Maria del Carmen Bocanegra-Yanez for their help and advice.

REFERENCES

Adekunle, T.O. & Nikolopoulou, M., 2016. Thermal comfort, summertime temperatures and overheating in prefabricated timber housing. *Building and Environment*, 103, pp.21–35. doi.org/10.1016/j.buildenv.2016.04.001.

Al-Sanea, S. A., Zedan, M.F. & Al-Hussain, S.N., 2012. Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. *Applied Energy*, 89(1), pp.430–442.

Armstrong, M.M., Maref, W., Saber, H.H., Rousseau, M.Z., Ganapathy, G. & Swinton, M.C., 2011. *The impact of the thermal mass on field energy performance of insulating concrete form (ICF) wall*, Canada: National Research Council.

Beausoleil-Morrison, I., 2000. *The adaptive coupling of heat and air flow modelling within dynamic whole-building simulation*. PhD Thesis, University of Strathclyde.

Beausoleil-Morrison, I. & Hopfe, C.J., 2016. Teaching Building Performance Simulation: Ever Done an Autopsy? In *3rd Building Simulation and Optimization Conference BSO2016. Newcastle, UK, 12-14 September 2016, Conference Proceedings*.

Becker, K. & Parker, J.R., 2009. A Simulation Primer. In *Digital Simulations for Improving Education: learning through artificial teaching environments*. Hershey, PA: IGI Global, pp. 1–24.

Berkeley, P., Haves, P. & Kolderup, E., 2014. Impact of Modeler Decisions on Simulation Results. In *2014 ASHRAE/IBPSA-USA Building Simulation Conference Atlanta, GA September 10-12, 2014, Conference Proceedings*.

BRE, 2012. *SAP 2012 The Government ' s Standard Assessment Procedure for Energy Rating of Dwellings*, London.

BS EN ISO 13786, 2017. *Thermal performance of building components - Dynamic thermal characteristics - Calculation methods*, Geneva.

BS EN ISO 13790, 2008. *Energy performance of buildings - Calculation of energy use for space heating and cooling*, Geneva.

Burman, E., Rigamonti, D., Kimpain, J. & Mumovic, D., 2012. Performance gap and thermal modelling: A comparison of simulation results and actual energy performance for an academy in North West England. In *1st Building Simulation and Optimization Conference, BSO2012, Loughborough, UK, 10-11 September 2012, Conference Proceedings*.

Clarke, J. A., 2001. *Energy Simulation in Building Design* 2r.e. ed., London: Oxford, Butterworth-Heinemann.

Corgnati, S.P. & Kindinis, A., 2007. Thermal mass activation by hollow core slab coupled with night ventilation to reduce summer cooling loads. *Building and Environment*, 42(9), pp.3285–3297.

Crawley, D.B., Hand, J.W., Kummert, M. & Griffith, B.T., 2008. Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, 43, pp.661–673.

Csaky, I. & Kalmar, F., 2015. Effects of thermal mass, ventilation, and glazing orientation on indoor air temperature in buildings. *Journal of Building Physics*, 39(2), pp.189–204.

Dincer, I. & Rosen, M., 2011. Thermal Energy Storage Systems and Applications, 2nd ed., Chichester: John Wiley and Sons, Ltd.

Dodoo, A., Gustavsson, L. & Sathre, R., 2012. Effect of thermal mass on life cycle primary energy balances of a concrete- and a wood-frame building. *Applied Energy*, 92, pp.462–472.

European Parliament and Council, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. *Official Journal of the European Union*, pp.13–35.

Foucquier, A., Robert, S., Suard, F., Stephan, L. & Jay, A., 2013. State of the art in building modelling and energy performances prediction: A review. *Renewable and Sustainable Energy Reviews*, 23, pp.272–288.

Gaetani, I., Hoes, P.J. & Hensen, J.L.M., 2015. Occupant behavior in building energy simulation: Towards a fit-for-purpose modeling strategy. *Energy and Buildings*, 121, pp.188–204. doi.org/10.1016/j.enbuild.2016.03.038.

Gaetani, I., Hoes, P.J. & Hensen, J.L.M., 2016. On the sensitivity to different aspects of occupant behaviour for selecting the appropriate modelling complexity in building performance predictions. *Journal of Building Performance Simulation*, 1493(November), pp.1–11. doi.org/10.1080/19401493.2016.1260159.

Givoni, B., 1979. Passive cooling of buildings by natural energies. *Energy and Buildings*, 2(4), pp.279–285.

Guglielmini, G., Magrini, U. & Nannei, E., 1981. The influence of the thermal inertia of building structures on comfort and energy consumption. *Journal of Building Physics*, 5(October), pp.59–72.

Guyon, G., 1997. Role of the model user in results obtained from simulation software program. In *5th Conference of International Building Performance Simulation Association (IBPSA), Building Simulation, BS2017, Prague, Czech Republic, 8-10 September 1997, Conference Proceedings.*

Hacker, J.N., DeSaulles, 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(3), pp.375–384.

Hart, R., Mendon, V. & Taylor, T., 2014. *Residential Wall Type Energy Impact Analysis*, Florida Masonry Apprentices & Education Foundation.

Hill, D. & Monsour, R., 2007. Monitored Performance of an Insulating Concrete Form Multi-Unit Residential Building, Canada.

Hoes, P. & Hensen, J.L.M., 2016. The potential of lightweight low-energy houses with hybrid adaptable thermal storage: Comparing the performance of promising concepts. *Energy and Buildings*, 110, pp.79–93.

Hopfe, C. & Hensen, J.L.M., 2011. Uncertainty analysis in building performance simulation for design support. , 43(10), pp.2798–2805. doi.org/10.1016/j.enbuild.2011.06.034.

Irving, A.D., 1988. Validation of dynamic thermal models. *Energy and Buildings*, 10(3), pp.213–220.

Irving, S.J., 1982. Energy program validation: conclusions of IEA Annex I. *Computer-Aided Design*, 14(I), pp.33–38.

Judkoff, R. & Neymark, J., 1995. International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method, Colorado.

Kalema, T., Johannesson, G., Pylsy, P. & Hagengran, P., 2008. Accuracy of Energy Analysis of Buildings: A Comparison of a Monthly Energy Balance Method and Simulation Methods in Calculating the Energy Consumption and the Effect of Thermal Mass. *Journal of Building Physics*, 32(2), pp.101–130.

Kendrick, C., Ogden, P., 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, pp.40–49.

Kokogiannakis, G., Strachan, P. & Clarke, J., 2008. Comparison of the simplified methods of the ISO 13790 standard and detailed modelling programs in a regulatory context. *Journal of Building Performance Simulation*, 1(4), pp.209–219.

Kolokotsa, D., Rovas, D., Kosmatopoulos, E. & Kalaitzakis, K., 2011. A roadmap towards intelligent net zero- and positive-energy buildings. *Solar Energy*, 85(12), pp.3067–3084. doi.org/10.1016/j.solener.2010.09.001.

Kosny, J., Petrie, T., Desjarlais, A., Atchley, J.A., Childs, P., Ternes, M & Christian, J., 2001. *How Insulating Concrete Form vs . Conventional Construction of Exterior Walls Affects Whole Building Energy Consumption : Results from a Field Study and Simulation of Side-by-Side Houses*, USA: Oak Ridge National Laboratory.

Kumar, S., Tewari, P., Mathur, S. & Mathur, J., 2017. Development of mathematical correlations for indoor temperature from field observations of the performance of high thermal mass buildings in India. *Building and Environment*, 122, pp.324–342. doi.org/10.1016/j.buildenv.2017.06.030.

Loonen, R.C.G.M., Singaravel, S., Trcka, M., Costola, D. & Hensen, J.L.M., 2014. Simulation-based support for product development of innovative building envelope components. *Automation in Construction*, 45, pp.86–95.

Macdonald, I. A. & Strachan, P., 2001. Practical application of uncertainty analysis. *Energy and Buildings*, 33(3), pp.219–227.

Mantesi, E., Hopfe, C.J., Glass, J. & Cook, M.J., 2015. Assessment of ICF Energy Saving Potential in Whole Building Performance Simulation Tools. In *14th Conference of*

International Building Performance Simulation Association (IBPSA), Building Simulation, BS 2015, Hyderabad, India, 7-9 December 2015, Conference Proceedings.

Mantesi, E., Hopfe, C. J., Glass, J., Cook, M. J., 2016. Investigating the Impact of Modelling Uncertainty on the Simulation of ICF for Buildings, In *3rd Building Simulation and Optimization Conference BSO2016. Newcastle, UK, 12-14 September 2016, Conference Proceedings.*

Mantesi, E., Cook, M.J., Glass, J. & Hopfe, C.J., 2015. Review of the Assessment of Thermal Mass in Whole Building Performance Simulation Tools. In *14th Conference of International Building Performance Simulation Association (IBPSA), Building Simulation, BS 2015, Hyderabad, India, 7-9 December 2015, Conference Proceedings.*

Maref, W., Armstrong, M.M., Saber, H., Swinton, M.C., Ganapathy, G. & Rousseau, M., 2010. Field Energy Performance of an Insulating Concrete Form (ICF) Wall, Canada: National Research Council.

McLeod, R.S. & Hopfe, C.J., 2013. Hygrothermal implications of low and zero energy standards for building envelope performance in the UK. *Journal of Building Performance Simulation*, 6(January 2015), pp.367–384.

McLeod, R.S., Hopfe, C.J. & Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment*, 70, pp.189–209.

Mirsadeghi, M., Costola, D., Blocken, B. & Hensen, J.L.M., 2013. Review of external convective heat transfer coefficient models in building energy simulation programs: Implementation and uncertainty. *Applied Thermal Engineering*, 56(1–2), pp.134–151. doi.org/10.1016/j.applthermaleng.2013.03.003.

Mourkos, K., Mantesi, E., Hopfe, C. J., Cook, M., Glass, J., Goodier, C., 2017. The Role of Fabric Performance in the Seasonal Overheating of Dwellings. In *15th International Building Performance Association, Building Simulation Conference, San Francisco, USA, 07-09 August 2017, Conference Proceedings*.

Navarro, L., DeGracia, A., Niall, D., castell, A., Browne, M., McCormack, S.J., Griffiths, P. & Cabeza, L.F., 2016. Thermal energy storage in building integrated thermal systems: A review. Part 2. Integration as passive system. *Renewable Energy*, 85, pp.1334–1356.

Omrany, H., GhaffarianHoseini, A., GhaffarianHoseini, A., Raahemifar, K. & Tookey, J., 2016. Application of passive wall systems for improving the energy effciency in buildings: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 62, pp.1252–1269.

Prada, A., Cappelletti, F., Baggio, P. & Gasparella, A., 2014. On the effect of material uncertainties in envelope heat transfer simulations. *Energy and Buildings*, 71, pp.53–60.

Rajagopalan, N., Bilec, M.M. & Landis, A.E., 2009. Comparative life cycle assessment of insulating concrete forms with traditional residential wall sections. In *2009 IEEE International Symposium on Sustainable Systems and Technology, ISSST ’09 in*

Cooperation with 2009 IEEE International Symposium on Technology and Society, ISTAS, Conference Proceedings.

Reilly, A. & Kinnane, O., 2017. The impact of thermal mass on building energy consumption. *Applied Energy*, 198, pp.108–121. doi.org/10.1016/j.apenergy.2017.04.024.

Roberz, F., Loonen, R.C.G.M., Hoes, P. & Hensen, J.L.M., 2017. Ultra-lightweight concrete: Energy and comfort performance evaluation in relation to buildings with low and high thermal mass. *Energy and Buildings*, 138, pp.432–442.

Rodrigues, L.T., 2010. *An investigation into the use of thermal mass to improve comfort in British housing*. PhD Thesis, University of Nottingham.

Saber, H.H, Maref, W., Armstrong, M.M., Swinton, M.C., Rousseau, M.Z. & Gnanamurugan, G., 2011. Numerical Simulations to Predict the Thermal Response of Insulating Concrete Form (ICF) Wall in Cold Climate, Canada: National Research Council.

Sadineni, S.B., Madala, S. & Boehm, R.F., 2011. Passive building energy savings: A review of building envelope components. *Renewable and Sustainable Energy Reviews*, 15(8), pp.3617–3631. doi.org/10.1016/j.rser.2011.07.014.

Silva, A.S. & Ghisi, E., 2014. Uncertainty analysis of the computer model in building performance simulation. *Energy and Buildings*, 76, pp.258–269. doi.org/10.1016/j.enbuild.2014.02.070.

Slee, B., Parkinson, T. & Hyde, R., 2014. Quantifying useful thermal mass: How much thermal mass do you need? *Architectural Science Review*, 57(4), pp.271–285. doi.org/10.1080/00038628.2014.951312.

Strachan, P., Svehla, K., Heusler, I., Kersken, M., 2015. Whole model empirical validation on a full-scale building. *Journal of Building Performance Simulation*, 1493(January 2016), pp.1–20.

Wang, H. & Zhai, Z. (John), 2016. Advances in building simulation and computational techniques: A review between 1987 and 2014. *Energy and Buildings*, 128, pp.319–335. doi.org/10.1016/j.enbuild.2016.06.080.

De Wit, S. & Augenbroe, G., 2002. Analysis of uncertainty in building design evaluations and its implications. *Energy and Buildings*, 34(9), pp.951–958.

Zhu, D., Hong, T., Yan, D. & Wang, C., 2012. *Comparison of Building Energy Modeling Programs: Building Loads*, USA: Ernest Orlando Lawrence Berkeley National Laboratory.

Zhu, L., Hurt, R., Correia, D. & Boehm, R., 2009. Detailed energy saving performance analyses on thermal mass walls demonstrated in a zero energy house. *Energy and Buildings*, 41(3), pp.303–310.

APPENDIX

Table A.1 *Building fabric construction details*

Construction Details						
Element (Outside – Inside)		K (W/mK)	Thickness (mm)	Density (kg/m^3)	Cp (J/kgK)	U-Value (W/m^{2}K)
Insulated Roof Panel System	Roof Decking EPS Insulation Plasterboard	0.14 0.035 0.16	25 300 13	530 25 950	900 1400 840	
	Total					0.11
ICF & High Thermal Mass Floor	Hardcore Gravel Blinding Membrane EPS Insulation Concrete Slab	1.8020 1.73 0.19 0.035 1.13	300 50 5 350 150	2243 2243 1121 25 1400	837 837 1674 1400 1000	
	Total					0.10
Low Thermal Mass Floor	Stone Bed Wet Lean Membrane EPS Insulation Timber Flooring	1.8020 1.73 0.19 0.035 0.14	300 50 5 350 25	2243 2243 1121 25 650	837 837 1674 1400 1200	
	Total					0.10
ICF Wall Assembly	Wood Siding EPS Insulation Cast Concrete EPS Insulation Plasterboard	0.14 0.035 1.13 0.035 0.16	9 210 147 108 12	530 25 1400 25 950	900 1400 1000 1400 840	
	Total					0.11
Low Thermal Mass Wall	Wood Siding EPS Insulation EPS Insulation Plasterboard	0.14 0.035 0.035 0.16	9 210 108 12	530 25 25 950	900 1400 1400 840	
	Total					0.11
High Thermal Mass Wall	Wood Siding EPS Insulation EPS Insulation Cast Concrete Plasterboards	0.14 0.035 0.035 1.13 0.16	9 210 108 147 12	530 25 25 1400 950	900 1400 1400 1000 840	
	Total					0.11

Table A.2 *Algorithms and input values used in equivalent models*

Simulation Solution (Loads, Plant, System Calculations):	Simultaneous Calculations
Time Step:	6/h (10mins)
Warming up:	25 days
Heat Balance Solution Algorithms:	Surface and Air Heat Balance Equations
Conduction Solution Method:	Finite Difference Solution
Internal Convection Coefficient:	Fixed, User-defined value (hi=3.16)
External Convection Coefficient:	Fixed, User-defined value (he=24.67)
Interior Surface Long-Wave Radiation Exchange:	Calculated view factors (same values used in both programs)
Exterior Surface Long-Wave Radiation Exchange:	Surface, Air, ground and Sky Temperature dependent
Direct Solar Internal Distribution:	Calculated by the programme
Solar Timing for solar data calculation:	Midpoint of the hour

Table A.3 *Calculation methods and default solution algorithms used in the BPS tools.*

	Tool A	**Tool B**
Simulation Solution (Loads, Plant, System Calculations):	*Simultaneous calculations*	*Simultaneous calculations*
Time Step Resolution:	*Sub-hourly*	*Sub-hourly*
Heat Balance Solution Algorithms;	*Surface and air heat balance*	*Surface and air heat balance*
Conduction Solution Method;	*1-dimensional*	*1-dimensional*
	Conduction Transfer Functions	*Finite Difference Solution*
Internal Convection Coefficient Calculation:	*TARP*	*Alamdari & Hammond correlations*
External Convection Coefficient Calculation:	*DOE-2*	*McAdams correlations*
Interior Surface Long-Wave Radiation Exchange:	*Script F (exchange coefficients between pairs of surfaces)*	*Long-wave radiation exchange between all zone surfaces*
Exterior Surface Radiation Exchange:	*Surface, Air, Ground and Sky Temperature Dependent*	*Surface, Air, Ground and Sky Temperature Dependent*
Direct Solar Radiation:	*Weather File*	*Weather File*
Diffuse Sky Model;	*Anisotropic*	*Anisotropic*
Solar Beam Distribution:	*Falling entirely on the floor*	*Diffusely distributed within the zone*
Time Point for solar data:	*Solar timing at the midpoint of each hour*	*Solar timing at the top of each hour*

APPENDIX C PAPER 3: THE ROLE OF FABRIC PERFORMANCE IN THE SEASONAL OVERHEATING OF DWELLINGS

Full Reference

Mourkos, K., Mantesi, E., Hopfe, C. J., Cook, M., Glass, J., Goodier, C., 2017. The Role of Fabric Performance in the Seasonal Overheating of Dwellings, In *15th International Building Performance Association, Building Simulation Conference, San Francisco, USA, 07-09 August 2017, Conference Proceedings.* URI: https://dspace.lboro.ac.uk/2134/25188.

Abstract

Airtightness and thermal conductance of the fabric play a key role in constructing low-energy buildings. These two factors might minimise the building's heating demand in winter but contribute to its overheating in summer. This study focused on a building using Insulated Concrete Formwork (ICF), a site-based Modern Methods of Construction (MMC). ICF walls consist of cast in situ concrete poured between two layers of Expanded Polystyrene (EPS) insulation. The walls can achieve very low U-values and high levels of airtightness. The overall aim was to investigate the resilience or vulnerability of the ICF to overheating. A whole building monitoring study was used to empirically investigate the impact of the ICF fabric performance and to validate the accuracy of Building Performance Simulation (BPS) predictions provided by two tools. The results indicate that the building was able to provide a stable internal environment. In addition, both tools were able to predict indoor temperatures in a consistent way. However, the outcome of the analysis highlighted the significance of selecting appropriate data in terms of weather, internal gains and occupant behaviour when assessing overheating and the importance of developing a methodology for model calibration against indoor air temperatures for overheating assessment.

Key Words

Insulating Concrete Formwork; Thermal Comfort; Thermal Mass; Building Performance Simulation; Empirical Validation; Overheating

Paper Type – Conference Paper

1 INTRODUCTION

Climate change has been in the focus of scientific research recently. In Europe, the built environment accounts for 40% of the total energy use and 36% of the total CO_2 emissions (Foucquier et al.; 2013, McLeod et al., 2013). Residential buildings alone use about 60% of the total energy consumption attributed to the building sector (Foucquier et al., 2013). Governments have set targets to reduce buildings' energy consumption and mitigate environmental impacts by focusing on reduction of fabric heat losses (reduced infiltration, better insulation etc.). Highly insulated, low carbon buildings are sensitive to overheating (Jones et al., 2016; NHBC, 2012). There is strong evidence that a significant portion of domestic housing will overheat, not only in the future, but also under current weather conditions (Committee on Climate Change, 2014).

1.1 OVERHEATING IN DWELLINGS

The issue of overheating has received increased attention by both academics and industry. According to Lomas and Porritt (2017), the following factors can have an impact on overheating: Climate change; Urbanisation; Ageing population; Increased energy efficiency of new homes; Modern construction methods leading to dwellings with less thermal mass; and, Lack of shading devices and shutters for aesthetic reasons.

Predicting overheating is a task which consists of: (1) predicting indoor air temperatures, and (2) selecting temperature thresholds against which the predicted temperatures will be compared (CIBSE, 2013). As far as the first stage is concerned, there are two options: Firstly, to employ either static or adaptive temperature thresholds. For instance, according to CIBSE Guide A (2006), the living areas and bedrooms of a dwelling would be characterised as overheated if more than 1% of the annual occupied hours exceeded an operative temperature of 28°C and 26°C, respectively. Similarly, according to the PassivHaus Planning Package (PHPP) (Hopfe

& McLeod, 2015) when an operative temperature equal to 25°C is exceeded, the outcome of the overheating assessment (i.e. the occupied hours that exceed the above threshold) is classified as follows: > 15% as catastrophic; 10-15% as poor; 2-5% as good; and, 0-2% as excellent.

Secondly, adaptive criteria take into account the fact that people have an inherent inclination to adapt to different conditions (e.g. changes in the air temperature) (Nicol & Humphreys, 2002). Hence, the comfort temperature is associated with the prevailing outdoor air temperatures. As far as the second stage is concerned, there are assessment methods like the Standard Assessment Procedure (SAP) (BRE, 2012) and the PHPP tool that employ steady state equations to estimate monthly mean temperatures. Nevertheless, internal temperatures are very sensitive to the ratio of heat gains to losses in homes that fulfil high standards in terms of insulation and airtightness (Dengel & Swainson, 2012). Such a dynamic phenomenon is unlikely to be captured by static calculations. Hence, in order to deal with the overheating issue in more depth and to be able to predict it with more confidence, the employment of a dynamic simulation tool may be necessary (Hopfe & McLeod, 2015). Furthermore, since overheating is an issue that is under investigation in recent years, no knowledge has been acquired yet in relation to the effectiveness of different measures/strategies needed to be adopted in order to tackle it. Hence, dynamic simulations can be employed to bridge this gap (Dengel et al., 2016).

1.2 PERFORMANCE OF ICF

The thermal mass of the fabric can be used to prevent buildings from overheating (Csaky & Kalmar, 2015; Al Sanea et al., 2011). The term ‘thermal mass’ is used to define all elements in the building fabric that are able to store energy during time of surplus and release this energy back into the space at time of scarcity (Ghattas et al., 2013). The principal benefit of heavyweight (high thermal mass) structures is their ability to dampen fluctuations in interior conditions when significant fluctuations occur in the outside environment (Al Sanea & Zedan, 2011; Kosny et al., 2001).

The analysis presented in this paper focuses on Insulating Concrete Formwork (ICF), a Modern Method of Construction (MMC) solution provided by the heavyweight construction industry. In recent years, the UK housing industry has shown a trend towards off-site MMC (DCLG, 2008). MMC are mostly lightweight, off-site, innovative technologies of house building. The drivers and barriers to MMC have been analysed in previous work (Pan et al., 2007; Kempton & Syms, 2009) and are outside the scope of this research. Even though ICF is not a lightweight, factory-made construction method, it is a site-based MMC, mainly due to its increased speed of construction. It consists of modular prefabricated Expanded Polystyrene (EPS) hollow blocks assembled on site and cast in situ concrete. Once the concrete has cured, the insulating formwork remains permanently in place resulting in a typical reinforced concrete wall with continuous internal and external insulation (Chant, 2012).

Figure 1 *Prefabricated Expanded Polystyrene (EPS) hollow block of ICF, before the concrete is poured.*

The ICF walling system can provide high levels of airtightness (Kosny, et al., 2001) very low U-values and can reduce the existence of thermal bridging. Due to the internal layer of insulation, ICF acts as an insulated panel, acting thermally as a lightweight structure. Research associated with ICF in the UK mainly uses computational analysis (Mantesi et al., 2015; Mantesi et al., 2016). Previous computational, numerical and field studies conducted elsewhere indicated that in cold climates the thermal capacity of its concrete core shows evidence of heat storage effects, resulting ultimately in reduced energy consumption when compared to a lightweight conventional timber-framed wall with equal levels of insulation (Hart et al., 2014; Armstrong, 2011).

1.3 EMPIRICAL VALIDATION OF BPS TOOLS

When trying to assess the energy, environmental and thermal performance of high thermal mass buildings, the use of reliable dynamic BPS is essential (Davies, 2004). Since all models represent a simplification of reality, it is generally acknowledged that there is a high level of uncertainty and sensitivity associated to current BPS methods and tools (Hopfe & Hensen, 2011). Empirical validation is a common practice to ensure that the results from simulation programs are reliable (Ryan & Sanquist, 2012; Fumo, 2014). To reduce the inaccuracies of BPS, the building models need to be updated when new information becomes available (Monari & Strachan, 2014).

1.4 RESEARCH AIM AND OBJECTIVES

The analysis presented in this paper focuses on the passive cooling performance of ICF. The aim is to investigate the resilience or vulnerability of ICF to overheating. Whole building monitoring was used to empirically investigate the impact of ICF fabric performance, and to validate the accuracy of two BPS tools predictions when modelling ICF. To the authors' knowledge, this study is one of the first empirical investigations into the impact of ICF fabric performance on overheating in the domestic sector. The objectives are:

1. To understand the relationship between ICF fabric performance and propensity of a building to overheat.

2. To investigate the impact of occupancy on the dwelling's tendency to overheat, or not; and,
3. To empirically evaluate the accuracy of current state-of-the-art BPS tools when modelling ICF, especially their ability to estimate overheating.

2 METHODOLOGY

This study is a computational and empirical evaluation on the passive cooling performance of ICF. Monitoring data were gathered from an ICF low-energy dwelling, designed to achieve near to Passivhaus levels. The case study is a two storey, three-bedroom house of approximately 250m^2, located in the wider area of Guildford, in a rural settlement called Gomshall, in Surrey, UK. The building envelope uses ICF walls, an insulated foundation raft, a prefabricated concrete hollow-core slab, and prefabricated EPS roof panels. The recorded data included information on the:

- On-site weather data
- Internal air temperatures
- CO_2 levels
- Energy consumption (at the main board)
- Windows opening and closing
- Mechanical Ventilation and Heat Recovery (MVHR) system operation (on summer bypass)

Table 1*Thermal properties of materials (data obtained from the contractor)*

1: Opaque Elements						
Element (from Outside to Inside)		**Thickness (mm)**	**Conductivity (W/mK)**	**Density (kg/m³)**	**Specific Heat (J/kgK)**	**U-Value (W/m²K)**
ICF Wall	Cement Screed	3	0.8	2100	650	
	Cement Plaster	3	0.72	1760	840	
	EPS Insulation	210	0.037	25	1400	**0.113**
	Cast Concrete	147	2	2300	1000	
	EPS Insulation	108	0.037	25	1400	
	Plasterboard	13	0.21	950	840	
Roof	Slate Tiles	5	1.13	1400	1000	
	Air Gap	25	R=0.15 m²K/W	-	-	
	Rood Decking	25	0.14	530	900	**0.115**
	EPS Insulation	300	0.037	25	1400	
	Plasterboard	20	0.21	950	840	
Ground Floor*	Stone Bed	300	1.802	2243	837	
	Blinding Layer	50	1.73	2243	837	
	Membrane	5	0.19	1121	1647	
	EPS Insulation	350	0.037	25	1400	**0.101**
	Concrete Slab	150	2	2300	1000	
	Ceramic Tiles	8	0.8	1700	850	
First Floor	Plasterboard	20	0.21	950	840	
	Air Gap	150	R=0.15 m²K/W	-	-	
	Hollow Core Concrete	250	1.70	2300	840	**1.312**
	Air Gap	115	R=0.15 m²K/W	-	-	
	Ceramic Tiles	8	0.8	1700	850	
Partitions	Plasterboard	15	0.21	950	840	
	Air Gap	70	R=0.15 m²K/W	-	-	**2.16**
	Plasterboard	15	0.21	950	840	
2: Transparent Elements						
	Glass U-Value (W/m²K)	**Glass g value**	**Glass Visible Transmittance**	**Frame Conductance (W/m²K)**		
Windows	0.61	0.52	0.67	1.72		

*in the living room and the bedrooms ceramic tiles are replaced with carpet (thickness = 8mm, conductivity = 0.06 W/mK, density = 200 kg/m³and specific heat = 1300 J/kgK

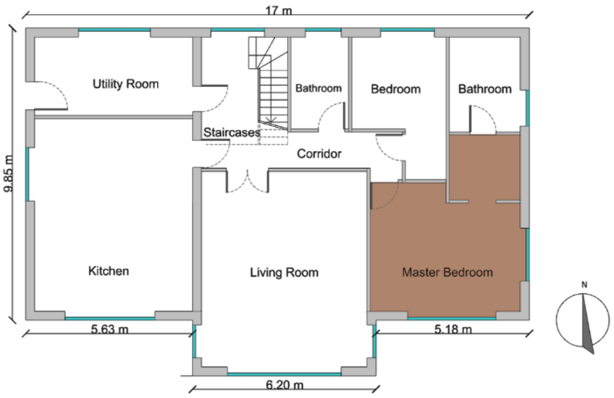


Figure 2 *Plan of ground floor*

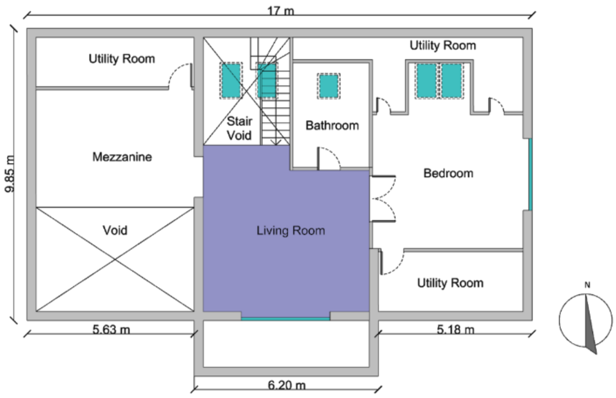


Figure 3 *Plan of first floor*

To address the three objectives, the research consisted of the following three stages. The first part of the study analysed the monitoring data regarding internal air temperatures for two of the main living areas, the ground floor master bedroom and the first floor living room as shown in Figures 2 and 3. The building was analysed under a transient state in an unoccupied (07/07 to 13/07) and an occupied (24/07 to 30/07) period. The response of the fabric was compared against fluctuations at the boundary conditions (i.e. ambient temperatures, solar radiation, internal conditions - changes in internal gains and occupancy patterns). The aim was to investigate the effects of the thermal mass in the fabric and to evaluate the resilience or vulnerability of the specific construction method to overheating. Two different weeks within July were analysed and compared, one unoccupied and one occupied (to evaluate the impact of occupancy on the building's tendency to overheat).

Figure 4 *South-West view of the building case study*

The second part of the analysis was focused on BPS. The recorded data on the actual thermal performance of the ICF case study were compared against the respective design assumption (i.e. weather conditions, internal gains, ventilation rates etc.). Benchmarks regarding the building's operation and occupancy schedules were used from the National Calculation Method[23] (NCM) (i.e. Figures 5 and 6 depict internal gains for the rooms under investigation, while the ventilation rate was equal to 10 l/s/person) along with the Typical Meteorological Year (TMY) climate file from the nearest weather station (Gatwick Airport). The discrepancy between simulation outputs and actual monitoring data was evaluated (to investigate the gap between simulation predictions and reality).

[23] NCM is a procedure for demonstrating compliance with Building Regulations. Available at http://www.uk-ncm.org.uk/ [last visited: 12/12/16].

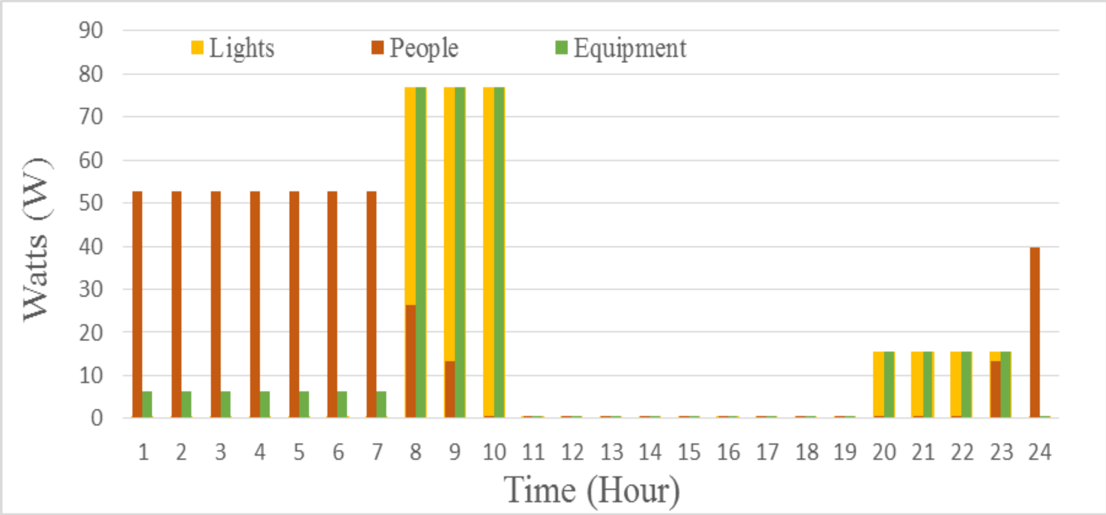


Figure 5 *Occupant, lighting and equipment gains from the NCM for the* ***bedroom in the ground floor***

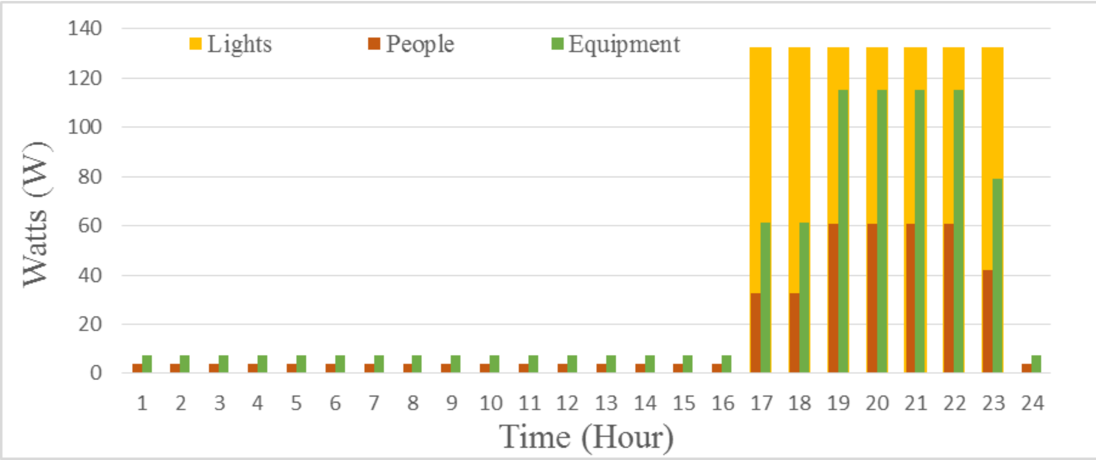


Figure 6 *Occupant, lighting and equipment gains from the NCM for the* ***living room in the first floor***

As far as the creation of the thermal models concerns, two detailed models were constructed in two different research, open-source BPS tools, EnergyPlus[24] and ESP-r[25]. In these tools, each

[24] EnergyPlus™ is a whole building energy simulation program developed in the Department of Energy (DOE) in USA. Available at: https://energyplus.net/ [last visited: 12/12/16].

[25] ESP-r is a whole building energy simulation program developed at Department of Mechanical Engineering at the University of Strathclyde in UK. Available at: http://www.esru.strath.ac.uk/Programs/ESP-r.htm [last visited: 12/12/16].

room of the building was modelled as a thermal zone (i.e. the models consist of 16 thermal zones).

Infiltration rates were predicted utilising data from the leakage test that was conducted; according to this test, the effective leakage area (ELA) @ 4 Pa was found to be equal to 0.39 cm^2/m^2. This was used as an input to the simulations by multiplying this value with the exposed area of each thermal zone.

The third and final stage of the analysis was the empirical validation of the simulation results provided by the two BPS tools. Information from the monitoring study was used as input in the post-occupancy simulation models. Outputs for the absolute air temperatures were compared with recorded data. The aim was to evaluate the discrepancy between the two BPS tools and the gap between simulation predictions and reality.

Occupancy schedules were derived from the CO_2 levels recorded at room level. Then, occupant gains were estimated based on the information that the building was occupied by two persons and obtaining values for the metabolic rates from the NCM (e.g. 90 and 110 W/person for the bedroom and the living room respectively). Gains from lights and equipment were estimated based on the derived occupancy schedules and measurements of electrical consumption at building level. Finally, ventilation rates (Table 2) were predicted based on information provided by the occupants regarding the operation of the MVHR unit.

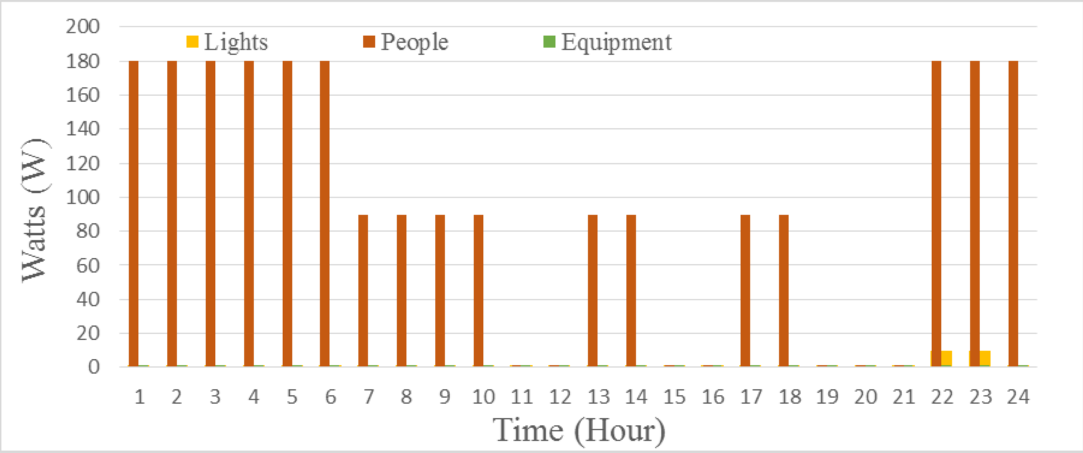


Figure 7 *Internal gains obtained from the monitored data for the* ***bedroom in the ground floor***

It is important to recall that this study focuses on the ability of BPS tools to predict indoor air temperatures irrespective of the temperature thresholds chosen for the overheating assessment. Therefore, no specific overheating criteria were considered.

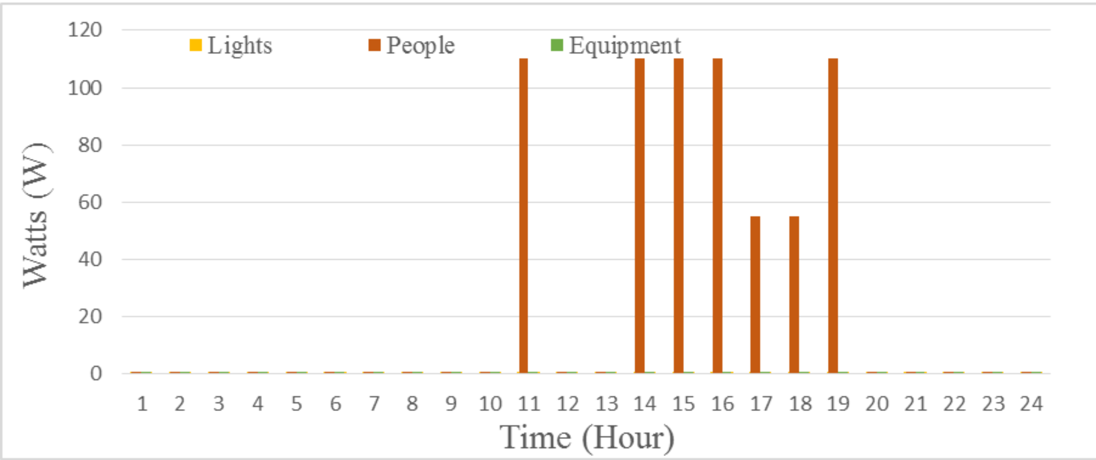


Figure 8 *Internal gains obtained from the monitored data for the* ***living room in the first floor***

Table 2 *Ventilation rates for both rooms under investigation*

	Schedule	**Flow/Zone (l/s)**
Unoccupied week	00:00–24:00	1.58
Occupied week	00:00-06:30	8.32
	06:30-11:30	48.58
	11:30-13:30	73.61
	13:30-21:00	48.58
	21:00-24:00	8.32

Finally, to date, there is no standard methodology available regarding how to calibrate a model in terms of indoor air temperatures. The International Performance Measurement and Verification Protocol (IPMVP) (U.S. Department of Energy, 2002) and the ASHRAE Guideline 14 (ASHRAE, 2002) provide some criteria for determining whether a model is calibrated but these are applicable only in the case that energy use is assessed. Nevertheless, since the Root Mean Squared Error (RMSE[26]) is employed as a means to measure the declination between actual data and simulations, this statistical measure will be used in this study as well.

3 RESULTS

3.1 INDOOR AIR TEMPERATURE PREDICTIONS UTILISING TYPICAL WEATHER DATA AND INPUTS FROM NCM

Comparing recorded air temperatures with predictions made by EnergyPlus and ESP-r utilising typical weather data and inputs from the NCM for the bedroom on the ground floor illustrates the significance of choosing appropriate data for weather, internal gains and ventilation rates as shown in Figure 9. From this graph, two observations can be made. Firstly, that the air temperatures predicted by the two BPS tools are much higher than the recorded air temperatures. More specifically, the average monitored daily temperature ranges from 22.9°C to 24.6°C while the average temperature predicted by EnergyPlus and ESP-r ranges from 35.1°C to 36.6°C. Secondly, that the diurnal temperature profile arising from the monitored data is much more stable than those predicted by the two BPS tools as stated previously. Daily fluctuations between the highest and lowest temperatures range from 0.8°C to 2.1°C for the recorded data, while for the data from EnergyPlus and ESP-r the fluctuations range from 2.8°C

[26] The RMSE is a measure of the difference between two sets of values; lower values indicate better agreement between these two sets.

to 5.1°C and 2.4°C to 6.1°C respectively. As far as the inter-model comparison is concerned, there is good agreement between the two tools with a RMSE equal to 0.66°C.

The temperature predictions for the living room on the first floor are similar (Figure 10). The average monitored daily temperature ranges from 24.0°C to 25.1°C while the average temperature predicted by EnergyPlus and ESP-r ranges from 35.8°C to 37.8°C and 36.3°C to 38.1°C respectively. Similarly, daily differences between the highest and lowest temperatures range from 1.0°C to 2.4°C for the recorded data, while for the data from Energy Plus and ESP-r the differences range from 1.6°C to 6.2°C and 2.1°C to 7.0°C respectively. Again, the agreement between the predictions of the two tools is high with a RMSE equal to 0.62°C.

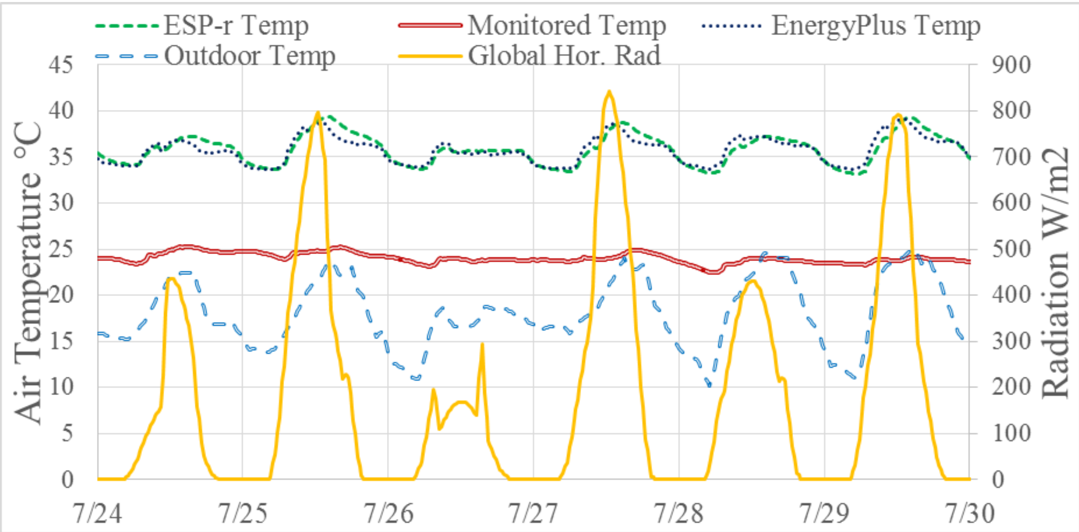


Figure 9 *Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the* ***occupied bedroom in the ground floor*** *between 24/07 to 30/07*

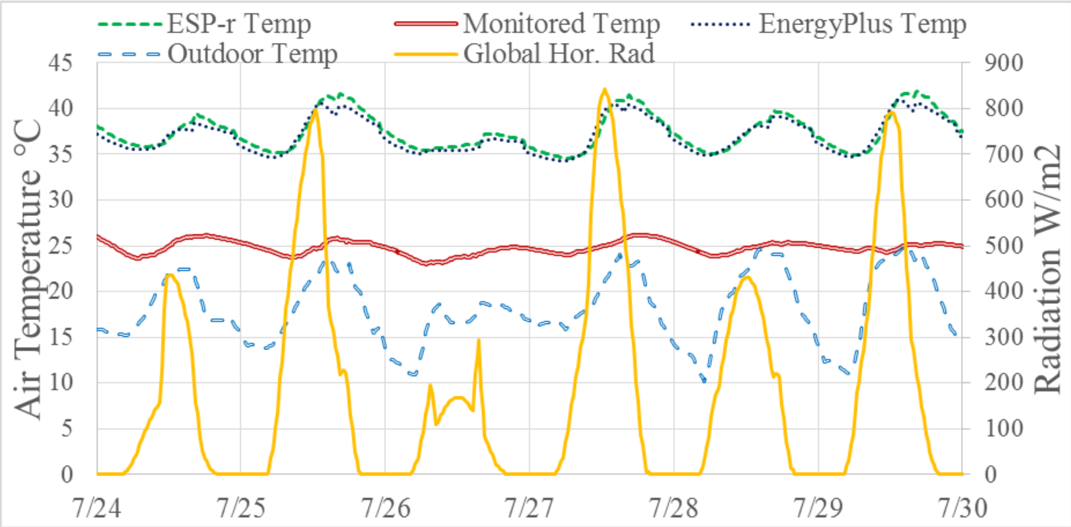


Figure 10 *Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the* ***occupied living room in the first floor*** *between 24/07 to 30/07*

3.2 INDOOR AIR TEMPERATURE PREDICTIONS UTILISING MONITORED DATA FOR THE UNOCCUPIED WEEK

Indoor air temperatures estimated by EnergyPlus and ESP-r were compared against actual temperatures in the bedroom in the ground floor and the living room in the first floor. The simulations were conducted utilising monitored weather data and internal gains. The analysis period was from the 07/07 to 13/07, a period that the building was unoccupied. This resulted in the removal of a great amount of uncertainty associated with occupants' varying behaviour (e.g. in terms of opening/closing windows and internal heat gains in rooms).

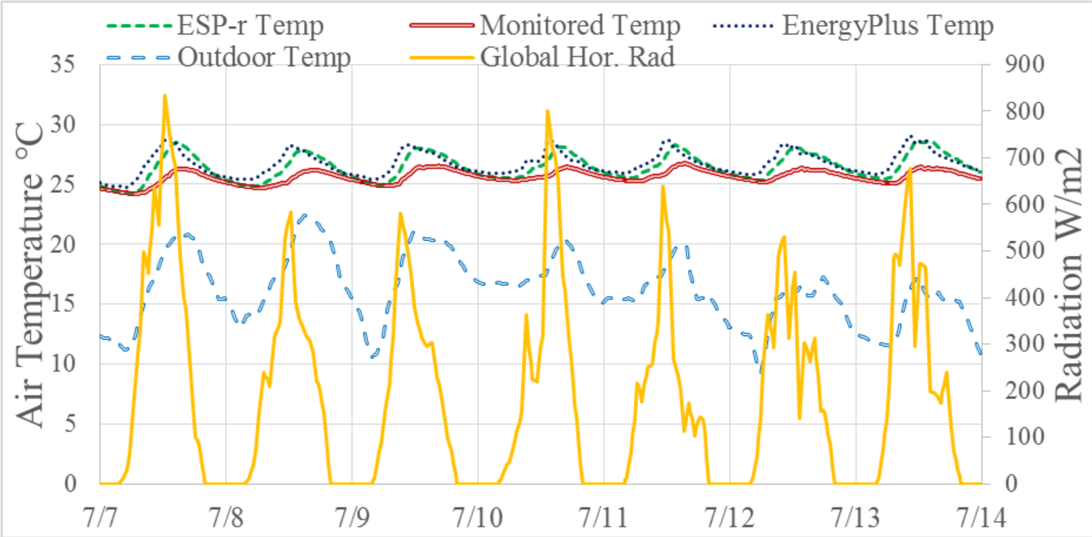


Figure 11 *Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the* ***unoccupied bedroom in the ground*** *floor between 07/07 to 13/07*

From the graph in Figure 11, it is apparent that both BPS tools predict indoor temperatures in a consistent way. In addition, both tools seem to overestimate peak temperatures while a time lag is also observed indicating that solar gains are not accounted for realistically. More specifically, daily fluctuations between highest and lowest temperatures range from 24.2°C to 26.8°C for the recorded data, while for the data from EnergyPlus and ESP-r the fluctuations range from 24.8°C to 29°C and 24.2°C to 28.6°C respectively. The RMSE is equal to 1.04°C for the ESP-r, 1.34°C for the EnergyPlus and for the inter-model comparison is equal to 0.62°C. When the sum of hours exceeding 26°C and 28°C is considered, a significant difference is observed between the predictions and actual measurements as Figure 12 indicates.

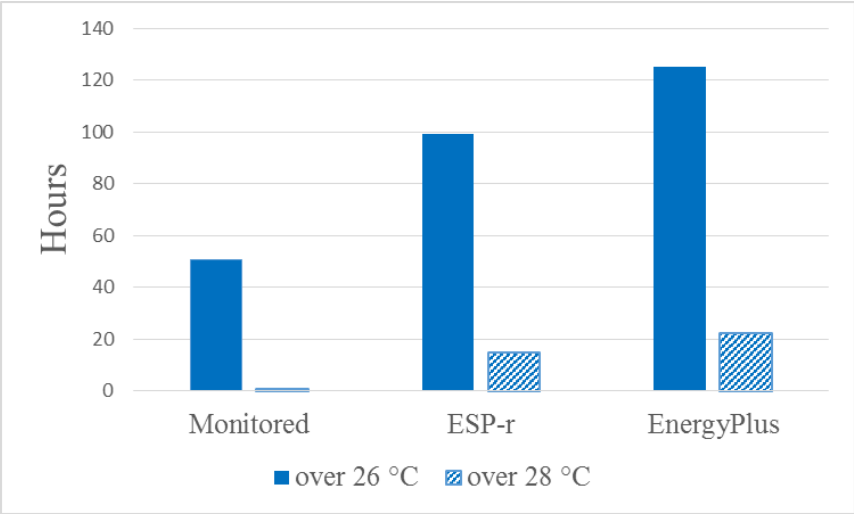


Figure 12 *Sum of total hours exceeding 26°C and 28°C for the* ***unoccupied bedroom in the ground floor*** *between 07/07 to 13/07*

The analysis for the living room indicates similar findings. The RMSE is approximately equal to 1.0°C (1.0°C for the ESP-r and 1.11°C for the EnergyPlus) while the error associated with the inter-model comparison is less than 1.0°C (0.67°C). As shown in Figure 13, a time lag and an overestimation of peak temperatures is observed here too.

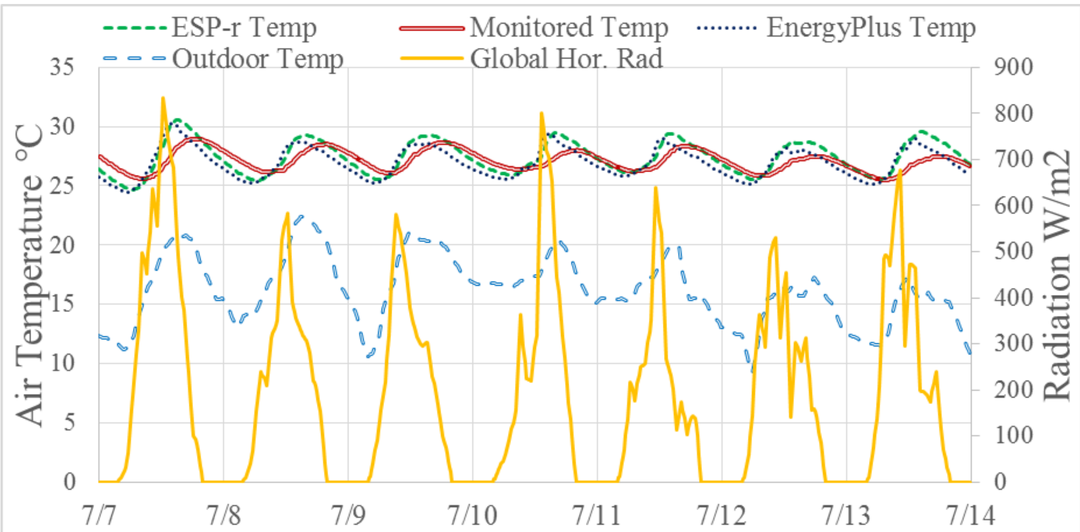


Figure 13 *Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the* ***unoccupied living room in the first floor*** *between 07/07 to 13/07*

When examining actual hours of exceedance of the temperature thresholds considered, it is apparent that the difference between monitored temperatures and predictions is substantial as Figure 14 suggests.

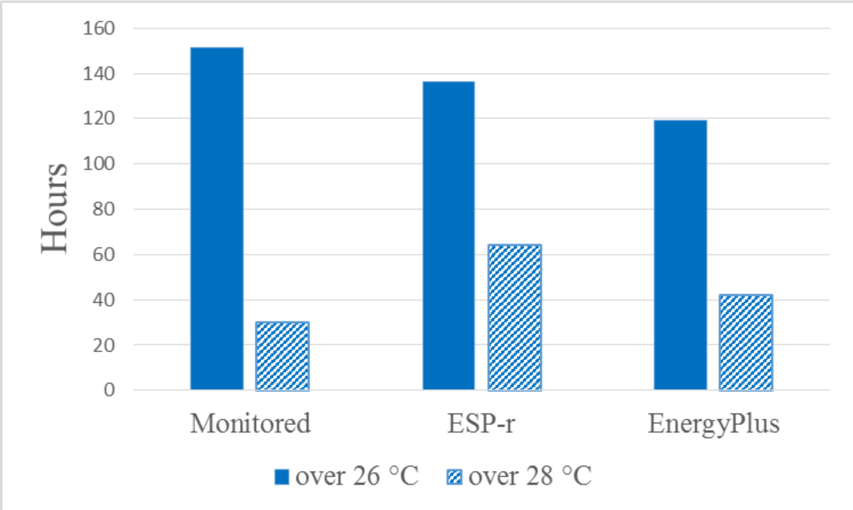


Figure 14 *Sum of total hours exceeding 26°C and 28°C for the* ***unoccupied living room in the first floor***

3.3 INDOOR AIR TEMPERATURE PREDICTIONS UTILISING MONITORED DATA FOR THE OCCUPIED WEEK

Figure 15 displays estimates from the BPS tools, as well as measured air temperatures for the period between 24/07- 30/07 for the bedroom on the ground floor. What is interesting in the graph is that the occupants have no influence on the results. The RMSE is less than 1.0°C (0.99°C for the ESP-r and 0.94°C for the EnergyPlus) while as far as the inter-model comparison concerns, the respective error is equal to 0.82°C. As in the previous analyses, spikes are observed too. However, the trend observed in the previous graphs (i.e. the BPS tools overestimate systematically air temperatures) is not evident in this graph. For this analysis, no difference is observed in relation to the sum of hours exceeding 26°C and 28°C. The installed sensors did not record temperatures greater than the above thresholds, which is depicted by both tools.

The analysis for the living room in the first floor suggests a greater inconsistency between measurements and predictions than the analysis for the bedroom. The RMSE is equal to 2.21°C for the ESP-r and 1.31°C for the EnergyPlus. At the same time, the declination between the two tools is larger as well (1.26°C).

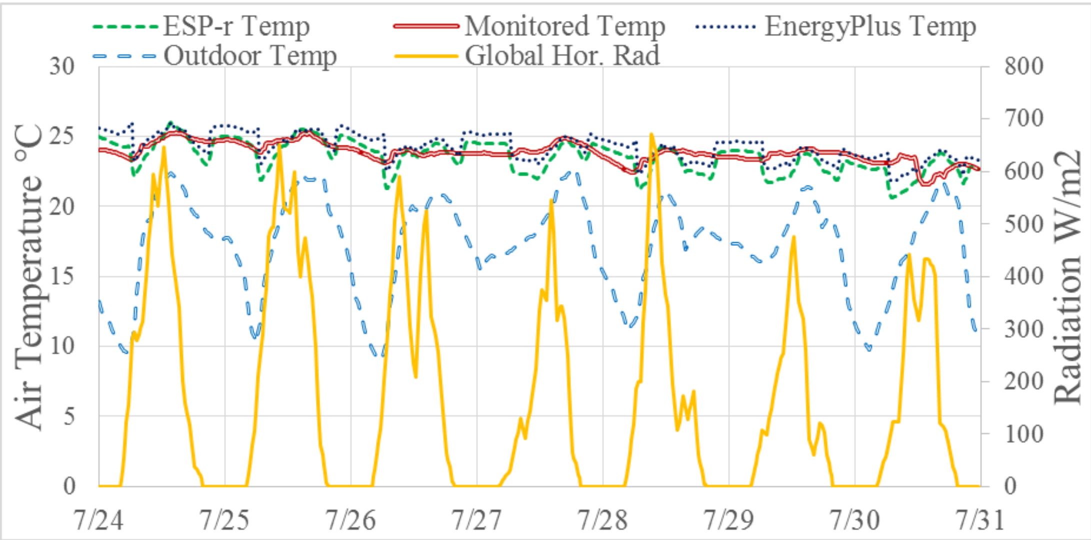


Figure 15 *Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the* ***occupied bedroom in the ground floor*** *between 24/07 to 30/07*

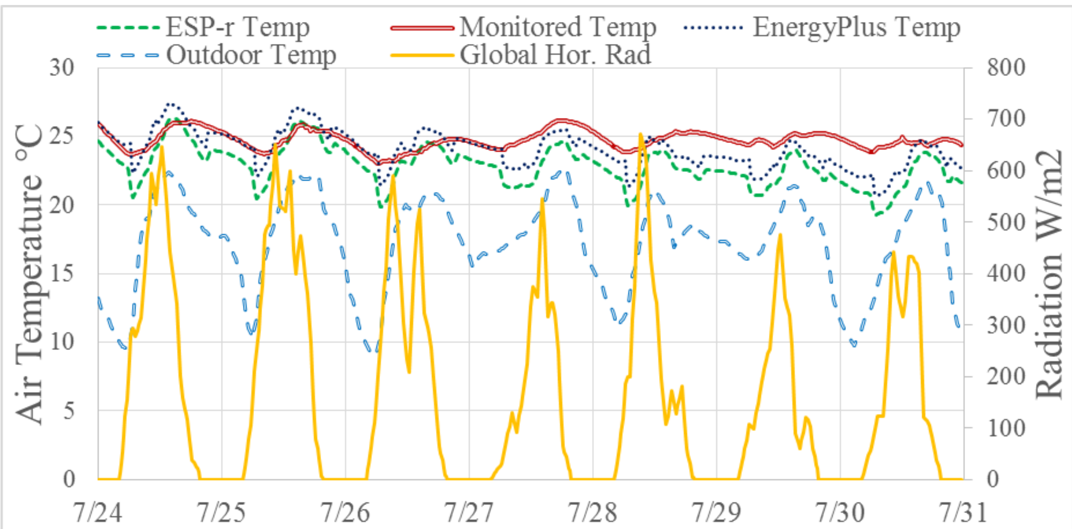


Figure 16 *Outdoor Air Temperature, Global horizontal Radiation, and Air Temperatures predicted by EnergyPlus and ESP-r for the* ***occupied living room in the first floor*** *between 24/07 to 30/07*

From the graph in Figure 16, it is apparent that for the majority of the analysis period both tools underestimate air temperatures (with the exception of EnergyPlus for short time periods which predict higher temperatures than the measured values). Finally, the sum of the total hours exceeding 26°C was less than 10 hours, something that was depicted by both tools while both measured and predicted temperatures never exceeded 28°C as shown in figure 17.

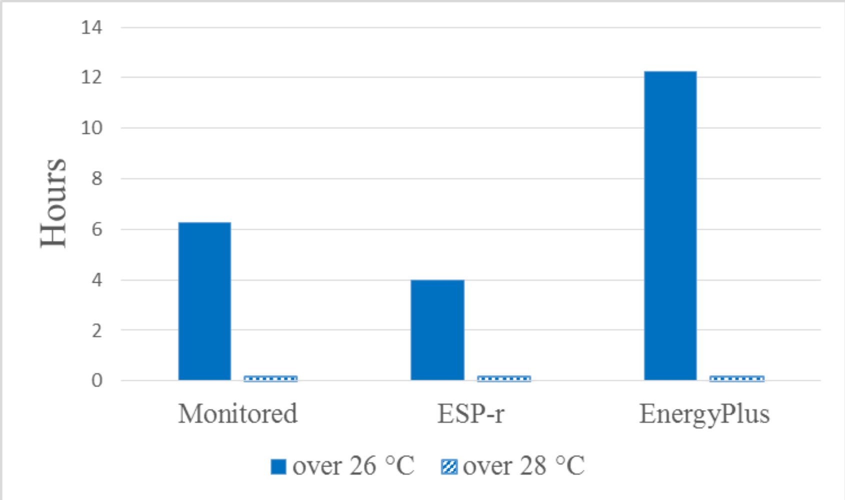


Figure 17 *Sum of total hours exceeding 26°C and 28°C for the* ***occupied living room in the first floor*** *between 24/07 to 30/07*

3.4 ANALYSIS OF THE FABRIC RESPONSE TO FLUCTUATIONS IN THE BOUNDARY CONDITIONS

From the monitoring results, it can be seen that the indoor air temperatures in both rooms under investigation (i.e. ground floor master bedroom and first floor living room) are relatively stable. For the occupied week, the diurnal temperature variation is between 2.5°C for the master bedroom (Figure 9) and 3.2°C for the living room (Figure 10), while the ambient air temperature fluctuation is up to 15°C. For the unoccupied week, the diurnal temperatures fluctuation is in the range of 2.5°C in the bedroom (Figure 11) and in the range of maximum 5°C for the first-floor living room (Figure 13), while the ambient air temperature fluctuates up to 12°C. These findings show that the fabric of the building is able to dampen internal air temperature swings, providing a stable internal environment. This is partly attributed to the thermal mass of the fabric and the space (i.e. ICF walls, concrete slab and internal furnishing), but also to the ventilation regime (continuous mechanical ventilation, operating in conjunction with the thermal mass). Moreover, it is interesting to notice that when comparing the two weeks (occupied and unoccupied), the effect of the occupants show minimal impact on the internal air temperature swings. In both weeks, the internal air temperatures, although stable, are significantly higher than the ambient air temperatures. Nonetheless, for the occupied week, when we are mostly concerned about overheating, indoor temperatures remain below 26°C for both spaces under investigation. Finally, in the unoccupied week, the first floor living room shows a slightly increased air temperatures and higher diurnal temperature variation in comparison to the ground floor bedroom (Figures 11 and 13).

4 DISCUSSIONS

4.1 THERMAL PERFORMANCE OF ICF

The findings of the analysis regarding the thermal response of the fabric to changes in boundary conditions indicate that the thermal mass of the structure is able to dampen diurnal indoor temperature variations. The monitoring results confirm the findings of previous studies (Csaky & Kalmar, 2015; Al-Sanea et al., 2011; Kosny et al., 2001) showing that the fabric with increased levels of thermal mass results in a relatively stable internal environment. For the occupied period, internal air temperatures were below 26^{o}C. The internal temperatures were found to be relatively higher for the unoccupied week, yet the diurnal temperature swings were again significantly reduced in comparison to the ambient temperature fluctuations. This is attributed to the thermal mass of the fabric, the added thermal mass due to furniture but also on the operation of the mechanical ventilation system. The latter was operating with constant airflow rates, even during the unoccupied week, purging the excess heat from the thermal mass, avoiding a possible heat build-up.

4.2 IMPACT OF SELECTION OF INPUT DATA IN SIMULATION RESULTS

In the analysis of indoor air temperatures, when utilising typical weather data and inputs from the NCM, the findings confirmed the results of previous studies (De Wilde, 2014; Coakley et al., 2014; Fumo, 2014); the selection of appropriate input data has a significant impact on the accuracy of the simulations. More specifically, Figures 5-8 show that the internal gains predicted by the NCM database are higher than the actual ones (with the exception of occupant gains where the NCM underestimates them). In addition, it was observed that the differences between the two data sets regarding ventilation rates had a more profound impact on the results. The actual ventilation rates (Table 2) were much higher than those from the NCM (for instance, for the living room according to the NCM the living room has ½ of an occupant during the evening, resulting in 5.5 l/s).

The simulation data provided by both BPS tools showed very good agreement. However, they both predicted significantly higher internal air temperatures, greater diurnal temperature variations, and also severe overheating. The analysis highlighted the significance of calibration, and it showed the importance of updating post occupancy simulation models with real input data, if available.

4.3 EMPIRICAL VALIDATION OF BPS TOOLS

The empirical validation of the BPS predictions showed that there was an overall good agreement between the simulation results provided by the two BPS tools, but also between simulation predictions and reality. Both tools showed a tendency to overestimate peak temperatures in both rooms during the unoccupied period. This may also be a result of the optical properties assigned to the windows. Both tools require inputs such as transmittance and reflectance for each window layer, data that were not available. Such properties were assumed for both BPS models based on the description of the window (in terms of number of layers and presence of coatings) and ensuring that the overall properties of the windows (U-values and g-values) match those provided by the manufacturer. However, it is not certain that solar gains were modelled accurately since different combinations of optical properties can result in the same overall provided U-values and g-values. The most significant inconsistencies were observed in the simulation of indoor air temperatures in the first floor living room. Both BPS tools predicted temperatures below those recorded. This may be due to the fact that the living room is in contact with the staircases where no physical boundary exists. However, in terms of modelling this zone a boundary had to be introduced: in this case a single layer of glazing was chosen, with a very large U-value in order to allow solar gains from the windows located in the staircases to enter the living room. Nevertheless, this highlights the importance that zoning can have. It would be interesting to investigate further the inconsistency, or otherwise, if a more sophisticated method (i.e. CFD analysis) was employed for the simulation of the inter-zonal air movement. A slight time lag was observed in the simulation results. This implies that the way the two tools calculate the availability of solar radiation is different. Moreover, a time lag on the peak internal temperatures was also observed between simulation predictions and actual recorded data. The inconsistency was observed when the peak internal temperature occurs. Both tools predicted peak internal temperatures a few hours earlier than in reality. This indicates that solar gains are not accounted for realistically in the simulation. Part of the aforementioned time lag is also attributed to the thermal mass in the fabric and the internal space. A limitation of both simulation models is that they did not include internal mass due to furniture. Previous studies have shown that the furniture could have a significant influence on the distribution of energy received by room and the surfaces temperature (Soelami & Ballinger, 1992; Hand, 2016).

The general observation is that although there was a good consistency between the simulation predictions of both BPS tools and between simulation and reality, when estimating hours of exceedance of the temperatures thresholds, a significant divergence was observed. The latter raises concerns on the ability of simulation tools to accurately estimate number of hours that indoor air temperatures exceed a certain threshold.

In the comparison between the occupied and the unoccupied periods, the uncertainty introduced by the occupants had an insignificant influence on the simulation results. During the calibration of the post-occupancy simulation models, the most considerable sensitivity was observed on the simulation of the mechanical ventilation regime. This can be attributed to the fact that infiltration rates for each room were estimated utilising the ELA as determined in the building leakage test. However, during the test the MVHR unit was not in operation. Under actual conditions, when the MVHR unit is on, the infiltration rates may be different (Emmerich & Persily, 2014). Finally, significant sensitivity was also observed on the specification of the pre-conditioning period.

5 RESEARCH LIMITATIONS

Although monitored data were available for windows operation, these were not utilised for two reasons. First, the set of data was incomplete and second, other critical information such as opening factors were not available. Taking into account the parameters needed to be included in a BPS tool for modelling windows operation (e.g. pressure coefficients of exterior surfaces, operation schedule of interior doors etc.) it was decided to omit them due to the high amount of uncertainty introduced in the thermal models. In addition, the interaction between the MVHR unit and the airtightness of the building was not considered. For this reason, the ventilation flow rate was used as a variable in the calibration process.

6 CONCLUSIONS

This study set out to investigate whether an ICF building can buffer temperature changes and hence reduce the likelihood of overheating. This study was also designed to investigate the contribution of occupant behaviour in overheating. Although the current research draws on data from a single case study, the findings suggest that an ICF building can help moderate temperature changes; the diurnal temperature profile for both rooms considered was more stable than the respective outdoor profile. Furthermore, the analysis from the occupied period showed that occupants did not increase the propensity of the home to overheat at all. However, no wider conclusions can be drawn, given that the results come from one single case study and the period of analysis is quite short. Also, this analysis has shown through simulations the significance of selecting appropriate data when assessing overheating. Utilising inputs from the NCM database resulted in a large discrepancy between simulation predictions and actual for the indoor temperatures. Nevertheless, both software tools were able to predict indoor temperatures in a consistent way when an inter-model comparison was performed and after inputs from the NCM were replaced with actual data, the respective gap was reduced substantially. Finally, a discrepancy was observed in relation to the ability of the BPS tools to predict indoor temperatures depending on the criterion used for assessing their adequacy. More specifically, although the RMSE was relatively low for most simulations (around 1.0°C), there was a great discrepancy between recorded data and predictions when hours of exceedance of specific temperature thresholds were considered. This highlights the importance of developing a methodology with specific criteria for calibrating a thermal model for overheating assessment.

7 FUTURE WORK

Future work will focus on investigating the impact of various design interventions such as different types and sizes of shading devices, different types of glazing etc. in this case study.

The impact of these measures on the indoor environment will be assessed with both models (i.e. the model utilising input data from the NCM and the model utilising monitored data).

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Engineering and Physical Sciences Research Council UK (EPSRC), the Centre for Innovative and Collaborative Engineering (CICE) at Loughborough University, Aggregate Industries UK Ltd, the Building Research Establishment (BRE), and Mr Ronny and Ms Barbara Karlsson for their support.

REFERENCES

Al-Sanea, S. A., Zedan, M. F. & Al-Hussain, S. N., 2011. Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. Applied Energy, 88(9), pp. 3113–3124.

Armstrong, M. M., Maref, W., Saber, H. H., Swinton, M. C., G, G., & Z, R. M., 2011. The Impact of Thermal Mass on Field Energy Performance of an Insulating Concrete Form (ICF) Wall. Canada: National Research Council Canada.

BRE, 2012. SAP2012.The Government's Standard Assessment Procedure for Energy Rating of Dwellings.

Chant, M. H., 2012. Insulating Concrete Formwork (ICF) and Concrete: An Alternative Construction Approach For Sustainable and Resilient Residential Architecture. MArch Thesis. University of Auckland.

CIBSE, 2006. CIBSE Guide A: Environmental design. London.

CIBSE, 2013. The limits of thermal comfort : avoiding overheating in European buildings. London.

Clarke, J. A., & Hensen, J. L. M., 2015. Integrated building performance simulation: Progress, prospects and requirements. *Building and Environment*, 91, pp. 294–306

Coakley, D., Raftery, P., & Keane, M., 2014. A review of methods to match building energy simulation models to measured data. *Renewable and Sustainable Energy Reviews*, 37, pp. 123–141.

Committee on Climate Change, 2014. *Managing Climate Risks to Well-Being and the Economy*, London: Adaptation Sub-Committee, Progress Report.

Csaky, I., & Kalmar, F., 2015. Effects of thermal mass, ventilation, and glazing orientation on indoor air temperature in buildings. *Journal of Building Physics*, 39(2), pp. 189–204.

Davies, M. G., 2004. *Building Heat Transfer*. Sussex: Wiley and Sons, Ltd.

DCLG, 2008. English Housing Survey. London: HMSO

Dengel, A. and Swainson, M., 2012. *Overheating in new homes; A review of the evidence, Research Review*, Zero Carbon Hub.

Dengel, A., Swainson, M., Ormandy, D., and Ezratty, V., 2016. *Overheating in dwellings*. Zero Carbon Hub.

De Wilde, P., 2014. The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction*, 41, pp. 40–49.

Foucquier, A., Robert, S., Suard, F., Stéphan, L., & Jay, A., 2013. State of the art in building modelling and energy performances prediction: A review. *Renewable and Sustainable Energy Reviews*, 23, pp. 272–288

Fumo, N., 2014. A review on the basics of building energy estimation. *Renewable and Sustainable Energy Reviews*, 31, pp. 53–60.

Ghattas, R., Ulm, F. J., & Ledwith, A., 2013. *Mapping Thermal Mass Benefit*. USA: Concrete Sustainability Hub.

Hand, J., 2016. Performance Implications of Fully Participating Furniture and Fittings in Simulation Models. In *3rd Building Simulation and Optimization Conference BSO2016. Newcastle, UK, 12-14 September 2016, Conference Proceedings.*

Hart, R., Mendon, V., & Taylor, T., 2014. *Residential Wall Type Energy Impact Analysis*. Florida: Florida Masonry Apprentices & Educational Foundation.

Hopfe, C. J., & Hensen, J. L. M., 2011. Uncertainty analysis in building performance simulation for design support. *Energy and Buildings*, 43(10), pp. 2798–2805.

Hopfe, C.J. and McLeod, R.S., 2015. *The Passivhaus Designer's Manual: a technical guide to low and zero energy buildings*. 1st ed. New York: Routledge.

Jones, R. V., Goodhew, S., & De Wilde, P., 2016. Measured Indoor Temperatures, Thermal Comfort and Overheating Risk: Post-occupancy Evaluation of Low Energy Houses in the UK. *Energy Procedia*, 88(6), pp. 714–720.

Kempton, J., & Syms, P., 2009. Modern methods of construction: Implications for housing asset management in the RSL sector. *Structural Survey* 27(1), pp. 36–45

Kosny, J., Petrie, T., Desjarlais, A., Atchley, J., Childs, P.W., Ternes, M.P. and Christian, J., 2001. *How Insulating Concrete Form vs. Conventional Construction of Exterior Walls Affects Whole Building Energy Consumption: Results from a Field Study and Simulation of Side-by-Side Houses*. USA: Oak Ridge National Laboratory.

Lomas, K.J. and Porritt, S.M., 2017. Overheating in buildings: lessons from research. *Building Research & Information*. 45 (1-2), pp. 1–18.

Mantesi, E., Hopfe, C. J., Glass, J. and Cook, M. J., 2015. Assessment of ICF Energy Saving Potential in Whole Building Performance Simulation Tools. In *14th International Building Performance Association, Building Simulation Conference, BS2015, Hyderabad, India, 07-09 December 2015, Conference Proceedings.*

Mantesi, E., Hopfe, C. J, Cook, M. J., Glass, J., 2016. Investigating the impact of modelling uncertainty on the simulation of ICF for buildings. In *3rd Building Simulation and Optimization Conference BSO2016. Newcastle, UK, 12-14 September 2016, Conference Proceedings.*

McLeod, R. S., Hopfe, C. J., & Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment*, 70, pp. 189–209

Monari, F., & Strachan, P., 2014. Coupling stochastic methods and detailed dynamic simulation programs for model calibration: two preliminary case studies. In *2nd Building Simulation and Optimisation Conference, BSO2014. London, UK, 23-24 June 2014, Conference Proceedings.*

Emmerich, S.J., and Persily, A.K., 2014. An improved method of modelling infiltration in commercial building energy models [online]. NIST Technical Note 1829. Available from: http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1829.pdf.

NHBC Foundation, 2012. Overheating in new homes: A review of the evidence. London: Andy Dengel and Michael Swainson.

Nicol, J.F. and Humphreys, M. a., 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*. 34 (6), pp. 563–572.

Pan, W., Gibb, A.G.F. and Dainty, A.R.J., 2007. Perspectives of UK housebuilders on the use of offsite modern methods of construction. *Construction Management and Economics* 25(2), pp. 183-194

Porritt, S.M., Cropper, P.C., Shao, L., and Goodier, C.I., 2012. Ranking of interventions to reduce dwelling overheating during heat waves. *Energy and Buildings* 55, pp. 16–27.

Ryan, E. M., & Sanquist, T. F., 2012. Validation of building energy modeling tools under idealized and realistic conditions. *Energy and Buildings*, 47, pp. 375–382.

Soelami, F. X. N., & Ballinger, J. A., 1992. A Study of the Influence of Furniture on the Thermal Behaviour of Interior Thermal Mass. *Architectural Science Review*, 35(3), pp. 101–105.

Zero Carbon Hub, 2015. *Assessing Overheating Risk*, Zero Carbon Hub, London

APPENDIX D PAPER 4: EMPIRICAL AND COMPUTATIONAL EVIDENCE FOR THERMAL MASS ASSESSMENT: THE EXAMPLE OF INSULATING CONCRETE FORMWORK

Full Reference

Mantesi, E., Hopfe, C. J., Mourkos, K., Glass[27], J., Cook, M. J. 2019. Empirical and Computational Evidence for Thermal Mass Assessment: The Example of Insulating Concrete Formwork, *Energy and Buildings,* 188-198, 314-332, doi: doi.org/10.1016/j.enbuild.2019.02.021.

Abstract

Insulated Concrete Formwork (ICF) is a site-based Modern Method of Construction (MMC). As a MMC, ICF has several advantages; increased speed of construction, cost and defect reduction, safety, among others. Moreover, the ICF wall construction method has similar benefits to any other heavyweight structure (such as strength, durability, noise attenuation). However, its thermal performance is not yet well-researched and understood. Using computational analysis and empirical evaluation, the aim of this research was to analyse the thermal performance of an existing ICF building; and to develop evidence about its transient thermal behaviour and how the latter is affected by the inherent thermal inertia of the concrete core. The results demonstrated that the ICF fabric showed a slow response to changes in boundary conditions, providing a stable internal environment. The concrete core of ICF was found to act as a buffer to the heat flow, reducing the transmission losses by 37%, compared to a lightweight wall with equivalent insulation. The analysis showed that although ICF is mostly

[27] Present address: The Bartlett School of Construction & Project Management, UCL, London, WC1E 7HB, UK.

considered as an insulated panel, the element's thermal mass is not as decoupled from the internal space, as has been thought the case.

Key Words

Thermal Monitoring; Empirical Validation; Calibrated Simulation; Dynamic Heat Transmission; Sensitivity Analysis; Benchmarking; Internal Air Temperature; Transient Energy Ratio

Paper Type – Journal Paper

1 INTRODUCTION

Improved building fabric performance (reduced infiltration, better insulation and optimal use of solar gains) is a primary consideration to reduce energy consumption in the built environment (McLeod & Hopfe, 2013). The thermal mass of a building's fabric can be used as a passive design strategy to reduce energy use for space conditioning (Reilly & Kinnane, 2017; Al-Sanea & Zedan, 2011; Navarro et al., 2016; Kumar et al., 2017; Kendrick et al., 2012). The term thermal mass defines the ability of a material to store sensible thermal energy by changing its temperature. The amount of thermal energy storage is proportional to the difference between a material's final and initial temperatures, its density, and its specific heat capacity (Dincer & Rosen, 2011). In simple terms the thermal mass (or thermal storage capacity) of the building fabric is its ability to capture and store casual and solar heat gains during time of surplus, disseminating the stored heat at time of scarcity (Reilly & Kinnane, 2017). In this way the building fabric helps to moderate internal temperature swings and shifts (delays) the time that the peak load occurs, resulting ultimately in reduced energy use for space conditioning (Hopfe & McLeod, 2015; Al-Sanea & Zedan, 2011; Balaras, 1996). All building construction methods can broadly be categorised as lightweight, medium weight and heavyweight, according to the level of thermal mass in the building fabric (Hopfe & McLeod. 2015).

1.1 INSULATING CONCRETE FORMWORK AS A HEAVYWEIGHT MODERN METHOD OF CONSTRUCTION

The UK housing construction industry has been characterised as conservative with very little changes noticed in the building design, construction and layout over the past 100 years (Rodrigues, 2009; Pan et al., 2007). However, a recent industry survey conducted by the National House Building Council (NHBC) (NHBC_Foundation, 2016) indicated that there is a noticeable turn toward lightweight and other off-site Modern Methods of Construction (MMC) due to their advantages in reducing cost, time, and defects. ICF is categorised as one of the site-based MMC (Rodrigues, 2009). The ICF wall component consists of modular prefabricated Expanded Polystyrene Insulation (EPS) hollow blocks and cast in situ concrete. The hollow blocks are assembled on site and the concrete is poured into the void. Once the concrete has cured, the insulating formwork stays in place permanently. The resulting construction structurally resembles a conventional reinforced concrete wall. The ICF wall system has several advantages; it shows an increased speed of construction, a significant structural strength and durability, and better noise attenuation. With regards to its thermal performance, ICF can provide complete external and internal wall insulation, minimising thermal bridging, providing very low U-values and high levels of air-tightness, if installed correctly (Rajagopalan, 2009).

ICF is often thought of as an insulated panel, acting thermally as a lightweight structure. There is a view that the internal layer of insulation isolates the thermal mass (say, of the concrete) from the internal space and interferes with thermal interaction. Despite evidence supporting ICF's thermal storage capacity (compared to a lightweight timber-frame panel with equivalent insulation), there remains an important shortcoming in knowledge of how ICF operates thermally, in this case, there is a generally poor level of understanding of how to quantify the effect of the thermal mass within ICF.

Several field and computational studies have been conducted in the past, mainly in the USA and Canada, aiming to investigate the benefits of the inherent thermal mass located at the core of ICF. The National Association of Home Builders (NAHB) Research Centre conducted a field study in Maryland, USA to evaluate the energy consumption of three side-by-side houses, two ICF houses and one built with timber-frame walls (NAHB, 1999). The houses were identical (apart from the external wall construction) unoccupied and built for the purposes of the study. The results showed that the two ICF houses performed much better than the timber-frame building, requiring on average 20% less energy for space conditioning. However, the authors suggested that this difference was mostly attributed to the different thermal resistance (R-value) of the walls and that the contribution of the ICF thermal mass was negligible. Similar conclusions were drawn by Hill and Monsour (Hill & Monsour, 2007), who performed a monitoring project to characterise the thermal performance of ICF and its airtightness in a residential building located in Ontario, Canada. By placing temperature sensors and taking heat flux measurements, the aim was to record the transient temperature behaviour of the ICF wall. Subsequently, a computational comparative analysis was performed (using eQUEST) and the as-built scenario was compared to a theoretical model without thermal mass (resembling a timber-frame structure). The authors concluded that there were insignificant improvements in terms of energy consumption between the ICF and timber-frame buildings. Armstrong et al. (2001) conducted a field monitoring study on the dynamic heat transmission through an ICF wall in Canada. In contrast to the previous two studies, the authors concluded that during transient conditions, the concrete core of ICF played a significant role in tempering heat losses to the exterior. The thermal mass of the concrete has been shown to reduce the peak heat flux through the assembly during cold weather.

Gajda and VanGeem (2000) conducted a computational analysis using DOE2.6 simulation program to compare the energy use in a typical house for five different locations across the USA, and for three different wall configurations; a conventional timber-frame wall, an ICF wall and a non-mass "ICF" wall (according to the minimum energy code requirements). The results indicated that in all locations the ICF wall showed higher energy savings compared to the other two walls. In the comparison of ICF to timber-frame the savings reached up to 9%. However, a limitation of this study was that the two different walls under investigation had different thermal resistances (R-values), hence a direct comparison could not provide feedback on the contribution of the ICF's thermal mass solely on the aforementioned energy savings. Kosny et al. (2001) performed a comparative computational analysis (using DOE-2) on the energy performance of lightweight and massive walls (including ICF) and calculated the potential energy savings for 10 different locations in USA climates. They concluded that among the high thermal mass configurations, the thermal performance of ICF was in between the thermal performance of the externally insulated and the internally insulated concrete wall and performed worse than a sandwich panel, where the insulation would be located at the middle of the wall. In the comparison of ICF to conventional timber-frame wall, the results showed that ICF can provide between 6% and 8% energy savings. However, similarly to the previous study, the R-values of the two walls were not equal. As a result, it is not possible to distinguish exactly which part of the energy savings are attributed to the thermal mass and which part is because of the enhanced fabric resistance of the ICF wall. Saber et al. (2011) investigated (using numerical analysis) the contribution of ICF thermal mass due to the concrete layer compared to a theoretical "ICF" wall without concrete and equal R-value for the cold climate of Ottawa, Canada. The results showed that the thermal mass of the concrete core can lead to up 6% savings in heating loads, compared to the same wall without the concrete layer. Hart et al. (2014) used simulation (EnergyPlus) to analyse the variation in energy end-use for a set of different wall types across different climate zones in the USA. The study compared externally and internally insulated concrete walls, ICF and timber-frame walls. With regards to ICF, the analysis showed that the energy use of ICF falls between the energy consumptions of externally and internally insulated concrete walls and always performs better than a timber-frame wall with equal levels of insulation. Rajagopalan et al. (2009) performed a comparative life cycle assessment (LCA) of wall sections comprised of ICF and timber-frame for the whole life cycle phases of a buildings, from raw materials to manufacturing, construction, use and end of life phases. They concluded that ICF has a higher embodied carbon than traditional timber-frame wall during manufacturing phase. Yet, the ICF showed reduced energy consumption during the use phase of the buildings, meaning that the overall environmental footprint of the ICF building could be outweighed by benefits achieved in terms of energy savings during the operational phase of the building.

Very few studies have considered the accuracy of ICF simulation in current building performance simulation (BPS) tools and software (Kosny & Kossecka, 2002; Mantesi et al., 2015; Mantesi et al., 2016; Mourkos et al., 2017; Mantesi et al., 2018). Kosny and Kossecka (2002) investigated the limitations associated to one-dimensional heat transfer analysis adopted in many of current simulation programs and proposed a method of implementing three-dimensional heat transfer modelling within whole building simulation tools. They proposed the concept of "equivalent wall", expressing the role of storage effects in heat flow through an element and tested the accuracy of this method against one-dimensional heat transfer and accurate three-dimensional model (using finite difference modelling). They found that for simple low thermal mass wall assemblies (such as timber-frame walls) the difference between one-dimensional and 3-dimensional heat transfer modelling was below 2%. However, for complex wall assemblies (such as ICF), the difference was in instances up to 27%. Mantesi et al. (2018) investigated the "modelling gap", namely the impact of default settings and the implications of the various calculation algorithms on the results divergence in thermal mass simulation using different tools. Three different construction methods were included in their analysis; ICF, low thermal mass (timber-frame) and high thermal mass (concrete wall). The results indicated that the modelling uncertainties accounted for up to 26% variation in the simulation predictions (annual heating of the ICF building), if the user relies on the default settings of the tools.

All of the previous studies presented in this section analysed the thermal performance of ICF, using either simulation or field measurements of test rigs. Fewer studies have combined simulation and monitoring results, and these have focused on the transient performance of the ICF wall assembly, measuring solely surface temperatures and heat flux of the ICF fabric. None of the aforementioned studies has considered internal thermal conditions and the energy consumption of an existing occupied ICF building.

1.2 AIM OF THIS RESEARCH

To the authors' knowledge this is the first whole building monitoring study conducted in a real ICF occupied detached building in Europe (namely in the UK), which combines computational analysis and empirical data. Although ICF dates back in Europe to the late 1960's (Armstrong et al., 2011), it is often characterised as an innovative wall technology because it has only recently become more popular for use in residential and commercial construction. Additionally, an ICF building shows significantly increased speed of construction, compared to traditional construction methods; hence ICF is often classed among the MMCs.

Using both empirical data and computational analysis, this study aims to find evidence with respect to the thermal storage capacity of the ICF concrete core and to demonstrate whether an ICF building could be characterised as a thermally heavyweight or lightweight structure. Furthermore, the combined analysis of monitoring and simulation results allows the accuracy of simulation predictions to be empirically evaluated. With the use of calibrated models (based on the monitoring data), the as-built scenario is compared to other known wall constructions with a degree of confidence in the reliability of predictions, aiming to assess its thermal performance against alternative high and low thermal mass constructions.

2 METHODOLOGY

The study was conducted in three phases. Phase 1 comprised the thermal monitoring of the selected ICF building case study. In phase 2 information from the monitoring was used to calibrate a simulation model, created using EnergyPlus 8.6. Then the monitoring data were plotted against simulation predictions to quantify their divergence and to empirically assess the accuracy of simulation predictions. The Root Mean Square Error (RMSE) and the Mean Biased

Error (MBE) as shown in the following equations were used to calculate the error between monitoring and simulation results (Coakley et al., 2014).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(m_i - s_i)^2}{N}} \qquad (1)$$

$$MBE\ (\%) = \frac{\sum_{i=1}^{N}(m_i - s_i)}{\sum_{i=1}^{N} m_i} \qquad (2)$$

Where,

RMSE is the root mean square error

MBE is the mean biased error

m_i and s_i are the respective measured and simulated data points for each model instance time step

N is the number of data points

Moreover, the diurnal internal and external temperature variations were used to calculate the decrement factor (Df) and the decrement delay (ω) of the building (Hopfe & McLeod, 2015).

$$D_f = \frac{t_{i,amp}}{t_{e,amp}} \qquad (3)$$

Where,

D_f is the decrement factor

$t_{e,amp}$ is the amplitude of the external temperature sine wave (K)

$t_{i,amp}$ is the amplitude of the internal temperature sine wave (K)

$$\omega = T_{ti,max} - T_{te,max} \qquad (4)$$

Where,

ω is the decrement delay (Hours)

$T_{ti,max}$ is the time of the maximum internal temperature (Hours)

$T_{te,max}$ is the time of the maximum external temperature (Hours)

In phase 3, three different wall constructions were compared among each other, ICF, high thermal mass (HTM) and low thermal mass (LTM). For ease of reference, these will be referred to as ICF, HTM and LTM from this point forward.

2.1 CASE STUDY BUILDING

Monitoring data were gathered from an ICF low-energy dwelling, designed to achieve near Passivhaus levels (Fig.1a). The case study is a two storey, three-bedroom house of approximately 250m^2, located in the wider area of Guildford, Surrey in a rural settlement called Gomshall, in the UK. The building envelope uses ICF walls, an insulated foundation raft, a prefabricated concrete hollow-core slab, and prefabricated EPS roof panels.

The county of Surrey has a temperate maritime climate with typically warm rather than hot summers and cool to cold winters. On average the hottest month is July in summer and the coldest is January in winter (Met Office, n.d.). Indicative values of the local climate are shown in Table 1.

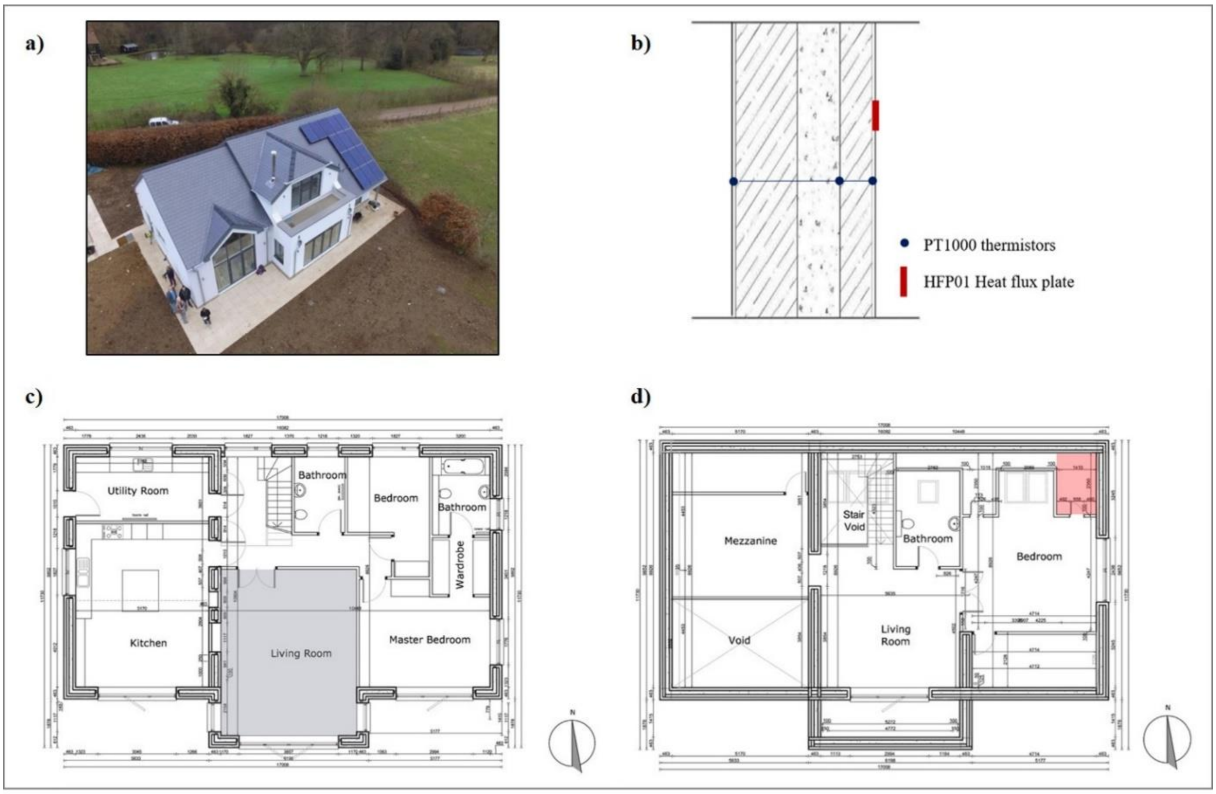


Figure 1: *The case study building: a) South-West view of the building, b) Cross-section of ICF wall showing location of the surface temperature and heat flux sensors, c) Ground-floor plan and d) First-floor plan of the building.*

Table 1: *Indicative values of climate data for Guildford, Surrey, UK (Met Office, n.d.; CIBSE, 2006).*

WEATHER DATA	
Dry Bulb Minimum Temperature (C°)	6.5
Dry Bulb Maximum Temperature (C°)	15.0
Heating degree days[28] (at 15.5°C)	1924.7
Cooling degree days (at 15.5°C)	487.6
Sunshine (hours per annum)	1564.2
Rainfall (mm per annum)	656.6
Mean wind speed at 10m (knots)	5.0

The monitoring study lasted for approximately 20 months, between April 2016 and February 2018. The recorded data comprised the following:

[28] In the UK, degree-days are published to a traditional base temperature of 15.5 °C (CIBSE, 2006).

- On-site weather data
- Surface and intra-fabric temperatures of the external walls
- Heat fluxes of the building fabric
- Internal air temperatures
- Internal relative humidity
- CO_2 levels
- Energy consumption
- Windows opening and closing activity

Weather data (i.e. dry-bulb temperature, dew point, relative humidity, atmospheric pressure, wind speed and direction) were recorded on site at a one minute time step (Gill Instruments Ltd, n.d.). An irradiance sensor (pyranometer) was also installed on site to record global solar radiation (again, at a one-minute resolution) (Hukseflux, n.d.). The Perez model was used in EnergyPlus to split global solar radiation into direct normal and diffuse horizontal components (Perez, 1992; DOE, 2010). Surface temperatures were recorded on the north facing wall using PT1000 thermistors. Three thermistors were installed across the ICF wall section; one in the external surface of the external layer of insulation, one in the interface between the concrete core and the internal layer of insulation and one at the internal surface of the ICF wall (Fig.1b). Heat flux measurements were also conducted on the internal surface of the North ICF wall, using thermophile flux sensors (Hukseflux HFP, n.d.). Both surface temperatures and heat flux measurements were recorded in a two-minute time step resolution. Internal air temperature and relative humidity were recorded in all rooms, every 15 minutes, using HOBO U12 stand-alone loggers (HOBO, n.d.).

The analysis reported here considers two periods, one week in the summer of 2016 (07 – 13 July 2016) and one week in spring of 2017 (14 – 20 April 2017[29]), both of which were at times when the house was unoccupied[30]. The aim being to reduce the level of uncertainty and investigate how the fabric would perform (with regard to internal air temperatures) under a free-floating mode, without the influence of other parameters (such as HVAC operation, mechanical ventilation, occupancy, user behaviour, etc). The results of internal air temperatures were presented for the ground floor living room, indicated in Fig.1c as the grey-shaded area. The room is south-facing and has a large opening on the south wall (without shading) and two more windows on its east and west walls. Heat flux and surface temperatures were measured at the north wall of the first floor, north facing storage room (indicated as the red-shaded area in Fig.1d). The room had no windows and it was unheated throughout the monitoring period.

2.2 MODEL SETTINGS AND CALIBRATION

The simulation model of the building case study was created using EnergyPlus 8.6 (DOE, 2010). EnergyPlus is an open-source, freeware, validated and commonly used dynamic BPS tool, developed by the Department of Energy (DOE) in the USA. In (Mantesi et al., 2018), the authors investigated the impact of default settings and the implications of the various calculation algorithms on the simulation of thermal mass when using different BPS tools. EnergyPlus was selected for the analysis presented in this paper, as it offers significant

[29] The ambient temperatures during the month of April 2017 were low enough to consider this period as a representative winter period. However, the solar radiation availability was relatively high compared to a typical winter week, resulting in higher internal temperatures than one would expect when the house operates in free-floating mode (no space conditioning).

[30] Although the building was unoccupied during the summer week under investigation, the MVHR system was running on constant low speed and air flow rates, to prevent heat accumulation.

flexibility to the user, through changing from default to advanced settings. Eight other BPS tools were considered and discounted (Mantesi et al., 2016). In that respect, the calculation algorithms regarding convection coefficient calculation, conduction heat transfer calculation and solar distribution were selected to match closely the actual building performance. Being a heavyweight structure, the conduction heat transfer was simulated using the finite difference algorithm. The solar distribution was simulated using the full interior and exterior algorithm, where the program calculates the amount of beam radiation falling on each surface of the zone, including floors, walls and windows, by projecting the sun's rays through the transparent surfaces. Finally, the appropriate convection coefficient algorithms were chosen according to the operation of the building for each of the analysed periods. The external convection coefficients were calculated using the DOE-2 algorithm for rough surfaces. The internal convection coefficients were calculated based on mixed and forced convection model for ceiling diffuser during the summer period (when the MVHR was running on constant low speed and air flow rates) and based on the temperature difference (TARP algorithm) during spring period, when the house was running with no mechanical ventilation (DOE, 2010).

Information from the thermal monitoring project regarding on-site recorded weather data, occupancy patterns and the use of MVHR and gas heating systems (for the spring period) was used to calibrate the simulation model. Reddy (2006, p.1) described calibrated simulation as "the process of using an existing building simulation computer program and "tuning" or calibrating the various inputs to the program so that observed energy use matches closely with that predicted by the simulation program." Once calibrated simulation is achieved, more reliable simulation predictions can be made (ASHRAE, 2009). Calibrated simulation is usually a very useful tool to explore hypothetical, alternative design and operational scenarios and measuring the savings of conservation retrofits to existing buildings (Wang et al., 2012; ASHRAE, 2009).

The model was found to be sensitive to three main parameters, the zone internal heat gains, the infiltration rates and the ventilation flow rates of the MVHR. Infiltration rates were predicted utilising data from the leakage test that was conducted on the building; according to this test, the effective leakage area (ELA) @ 4Pa was found to be equal to $0.39cm^2/m^2$. This was used as an input to the simulations by multiplying this value with the exposed area of each thermal zone. However, during the test the MVHR unit was not in operation. Under actual conditions, when the MVHR unit is on, the infiltration rates may be different (Emmerich et al., 2014). Since, the interaction between the MVHR and the airtightness of the building was not considered in the simulations, the ventilation flow rates were used as a variable in the calibration process. The analysis was focused on two unoccupied periods (to investigate the performance of the fabric in free-floating mode), however the simulation models were calibrated against occupancy patterns (internal heat gains from lighting, appliances and occupants), and heating setpoints/schedules for the weeks preceding the unoccupied periods. The calibration process was performed using the manual iterative technique (Reddy, 2006; Coakley et al., 2014; Fumo, 2014; Mustafaraj et al., 2014) in which the user of the BPS tool adjusts the input parameters on a trial-and-error basis until the model output matches the recorded data.

2.3 COMPARATIVE ANALYSIS

The ICF simulation model was used as a base-case, two additional models were created, the HTM and the LTM case. The only difference among the models was the construction of the external walls. Since the aim was to investigate the impact of the walls' thermal mass on thermal performance, the thermal transmittance (U-value) was kept consistent in all three models to allow a direct comparison. Details of the material properties of all three construction methods are included in Table A.1 in the Appendix. A comparative analysis was performed on the performance of the three wall construction methods, focusing on internal air temperatures and on the dynamic characteristics of the fabric (Df – Eq. 3 and ω – Eq. 4) as calculated based on the diurnal internal temperature variation in each of the three buildings.

Initially, all three buildings were identical, the only difference was the level of thermal mass in the walls. However, it was essential to quantify the impact of heavyweight floors and interior thermal mass on the internal environment stabilisation. To do that, a parametric analysis was performed on the construction of the ground floor for the ICF building. Three different levels of thermal mass were employed for the floor, varying from lightweight to medium and heavyweight constructions. Details of the three different floor constructions can be found in Table A.2 in the Appendix. The results were plotted against a lightweight floor for the LTM building and a heavyweight floor for the HTM building, both representing conventional construction methods of the UK housing industry.

Furthermore, Monte Carlo-based global uncertainty analysis (UA) was used to assess the role of the interior thermal mass (due to furnishing) on the internal temperatures of the space. Latin Hypercube Sampling[31] (LHS) method was employed as a sampling method to generate sampled variables desirable for the UA (Helton & Davis, 2003; Saltelli et al., 2004; Hopfe, 2009) using SimLab 2.2.1 (SimLab, n.d.). All physical properties of the internal furnishing were assigned a mean (μ) based on information found in literature (Johra & Heiselberg, 2017) and a uniform distribution, with a fixed relative range of 50%[32]. Details on the mean, minimum and maximum values used in the UA are summarised in Table A.3 in the Appendix. A total number

[31] The LHS is a probabilistic sampling procedure that incorporates features of both random and stratified sampling. A weight is associated with each sampled element for the estimation of integrals. It is easier to implement than stratified sampling, yet achieves a good coverage of the sample space of the selected elements [41],[42].

[32] Due to the high level of uncertainty on the properties of the internal furnishing, a fixed relative range of 50% was selected as appropriate to represent the likely variation on the level of interior thermal mass.

of 250 simulations were performed in JEPlus (JEPlus, n.d.), varying multiple parameters concurrently.

To determine the sensitivity of each of the three wall construction methods to physical uncertainties (including the thermal mass of the wall), global sensitivity analysis (SA) was adopted. Physical uncertainties refer to the physical properties of the wall materials; thickness (d), thermal conductivity (λ), density (ρ), specific heat capacity (c). Morris's method was employed to generate sampled variables desirable for the SA [47], using again SimLab 2.2.1 (SimLab, n.d.). All physical properties under investigation were assigned a mean (μ) based on the actual construction details from the building case study and a uniform distribution with a fixed relative range of 20%. Details on the mean, minimum and maximum values and used in the SA are summarised in Table A.4 in the Appendix. A total of 630 simulations were performed in JEPlus (JEPlus, n.d.).

As a final step, and in order to gain a better understanding of the transient thermal performance of the ICF wall and how it compares to the other two construction methods (LTM and HTM) with regards to its thermal mass, internal surface temperatures and heat fluxes were plotted based on both measured data from the building and simulation predictions from the models. Intra-fabric temperatures and heat fluxes calculated from the finite difference algorithm employed in EnergyPlus (DOE, 2010) were used to establish whether the thermal storage capacity of ICF concrete core made any contribution to the overall thermal performance of the building.

3 RESULTS AND ANALYSIS

The results section is structured in four sub-sections. Sub-section 3.1 focuses on the empirical validation of simulation predictions. Sub-sections 3.2 to 3.4 relate to the comparative analysis of ICF to the alternative wall constructions (i.e. HTM and LTM).

3.1 VALIDATION OF SIMULATION MODELS

The monitoring results in terms of zone mean air temperature for both periods of analysis (i.e. summer and spring weeks) were plotted against the simulation predictions provided by the BPS model. There was good agreement between simulation and measured data for both periods (Fig.2 and 3). During summer (Fig. 2) the error between monitoring and simulation results was calculated to RMSE = 0.25^{o}C. The Mean Biased Error showed that the simulation model tends to under-predict the zone mean air temperature by MBE = 0.02%. In cold weather (Fig.3), the error between simulation predictions and the actual zone mean air temperature was calculated as RMSE = 0.45^{o}C. The MBE indicated that the simulation model again under-predicts the internal air temperatures for the week under investigation by MBE = 1.05%. To date, there is no standard methodology available to calibrate a model in terms of indoor air temperatures. The International Performance Measurement and Verification Protocol (IPMVP) (EVO, 2012) and ASHRAE Guideline 14 (ASHRAE, 2014) provide some criteria for determining whether a model is calibrated, yet these are applicable only in the case that energy use is assessed.

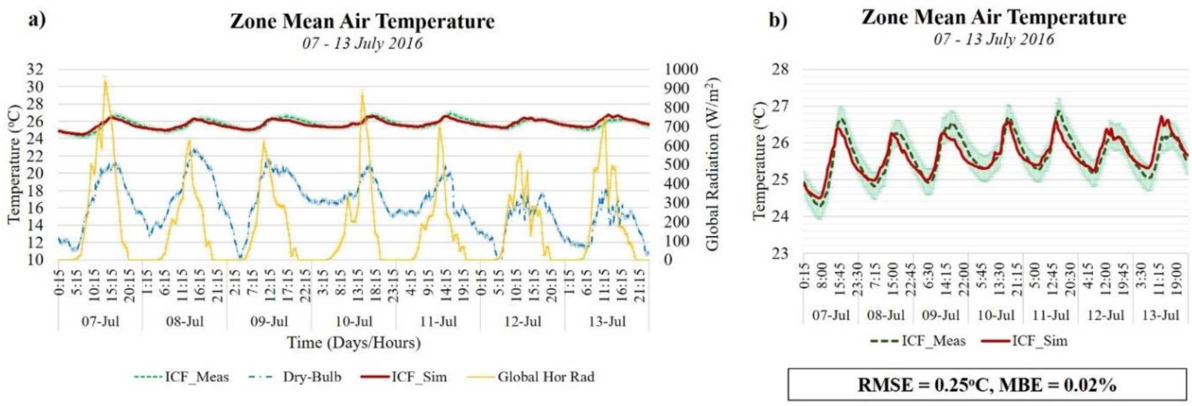


Figure 2: *Empirical Validation of ICF simulation results. a) Monitoring results on zone mean air temperature, dry-bulb temperature and global radiation, b) closer view of comparison between monitoring results and simulation predictions. Warm period analysis for the unoccupied week 07 – 13/07/16. The green area in the graphs indicates the measurement uncertainty of the internal air monitoring sensors.*

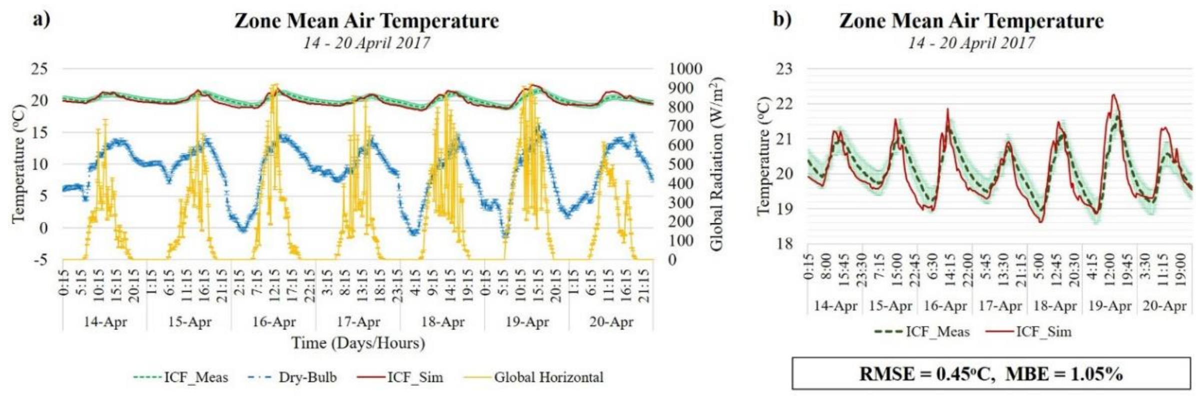


Figure 3: *Empirical Validation of ICF simulation results. a) Monitoring results on zone mean air temperature, dry-bulb temperature and global radiation, b) closer view of comparison between monitoring results and simulation predictions. Cold period analysis for the unoccupied week 14 – 20/04/17. The green area in the graphs indicates the measurement uncertainty of the internal air monitoring sensors.*

Looking at the dynamic characteristics of the building fabric (i.e. decrement delay ω and decrement factor Df) for the summer period (Fig.4), it becomes apparent that although there is a very good consistency between measured results and simulation predictions for the decrement factor Df (the percentage difference between average measured Df and the average simulated Df is c.2%), the model tends to under-predict the decrement delay ω (62% lower ω is estimated by the model compared to reality). A better agreement is observed in the prediction of the decrement delay during spring period[33] as shown in Fig.5a, yet once again the model under-predicts the decrement delay in comparison to the actual performance of the building (c.33% lower ω is calculated based on simulation predictions when compared to measured data). Furthermore, during spring period, the model over-predicts the average value of the decrement factor, in comparison to reality, by c.40% (Fig.5b).

[33] No time lag was evident in the measured data between the time of the maximum ambient and the maximum internal air temperature for the cold period. As a result, the decrement delay for spring was calculated based on the time lag between the minimum ambient temperature and the minimum internal air temperature.

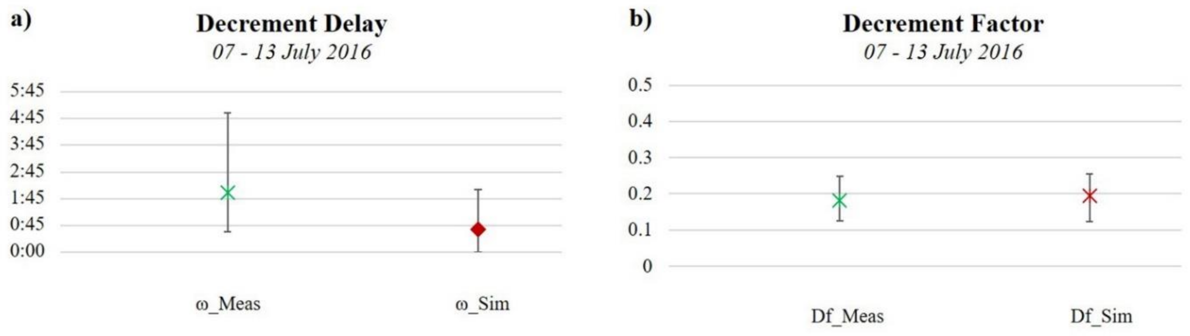


Figure 4: *Dynamic characteristics of the ICF fabric, as calculated based on monitoring results and simulation predictions for the summer unoccupied week 07 – 13/07/16; a) Decrement Delay, b) Decrement Factor.*

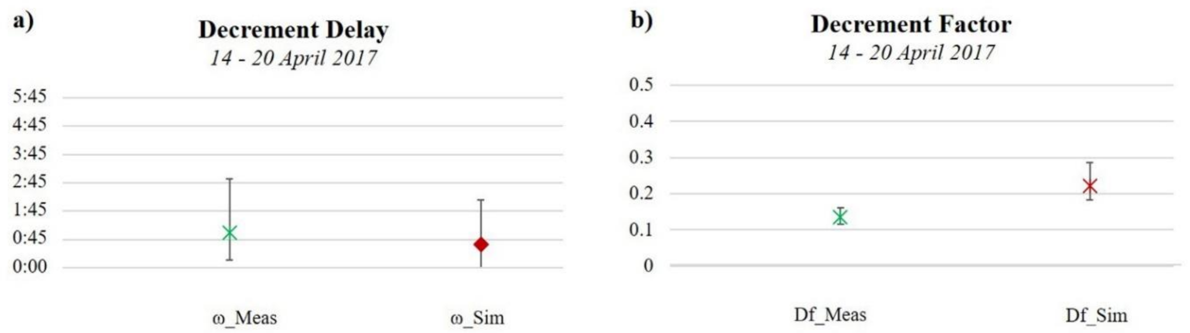


Figure 5: *Dynamic characteristics of the ICF fabric, as calculated based on monitoring results and simulation predictions for the spring unoccupied week 14 – 20/04/17; a) Decrement Delay, b) Decrement Factor.*

3.2 THE IMPACT OF VARYING THERMAL MASS ON ZONE MEAN AIR TEMPERATURE

3.2.1 The thermal mass of external wall construction

The zone mean air temperature of the ICF building was compared against the HTM and the LTM building, for the summer week, 07 – 13 July 2016 (Fig.6). The graphs show that the ICF building sits between the other two construction methods and behaves more similarly to the HTM building. The diurnal temperature variation of ICF increased slightly compared to the HTM building, with higher peaks of maximum air temperature. The diurnal profile of the LTM building was similar to the other two construction methods, yet the internal air temperature in the LTM building was higher, by an average of 2^{o}C.

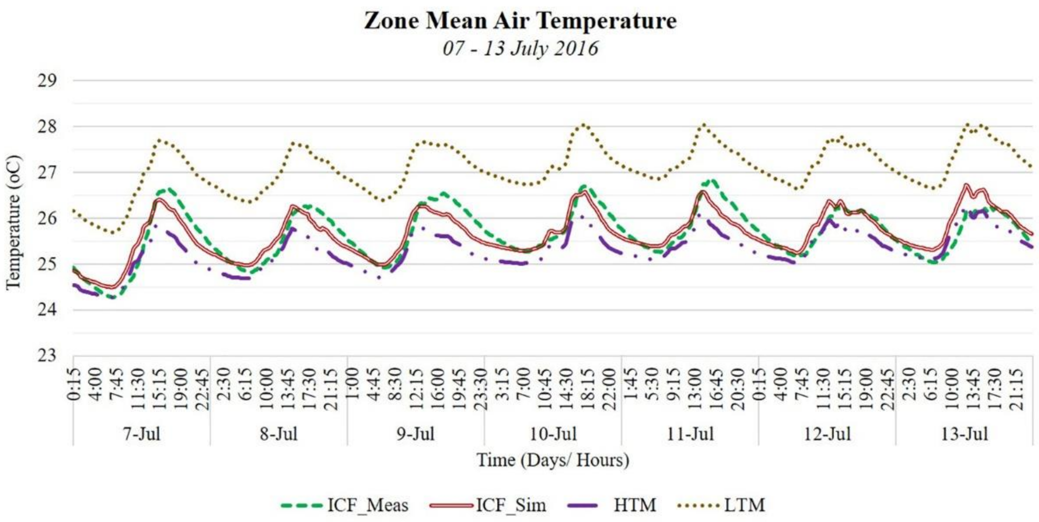


Figure 6: *Comparison of zone mean air temperatures between the three different construction methods for the summer unoccupied week 7 – 13 July 2016. Simulation results for the ICF, HTM and LTM buildings plotted against measured data for the ICF building.*

The daily temperature profile for all three building cases was plotted for a representative day in the summer week (Fig.7). The figure compares: the expected performance of the thermal mass based on theory (Fig.7a), the simulation results provided by the three models (Fig.7b), and the comparison between simulation and monitoring results for the ICF building (Fig.7c). One would expect the diurnal temperature fluctuation of the LTM building to be higher than the other two construction methods and closer to the ambient temperature profile (Fig.7a), due to the anticipated quick response of the low thermal mass fabric to changes in boundary conditions. However, based on the simulation results provided by the three models (Fig. 6 and 7b), the LTM building showed a similar dampening effect on the internal air temperature to the other two buildings. This can be attributed in part to the heavyweight ground floor, which was the same in all three models. The comparison between monitoring and simulation results, for the summer representative day (Fig. 7c), highlighted what was discussed earlier (Fig.2 and 4), i.e. that the simulation model was able to predict correctly the amplitude of the diurnal temperature wave, yet it under-predicted the decrement delay between the maximum internal and external air temperature. A finding which also applies to the other two construction methods (Fig. 7b).

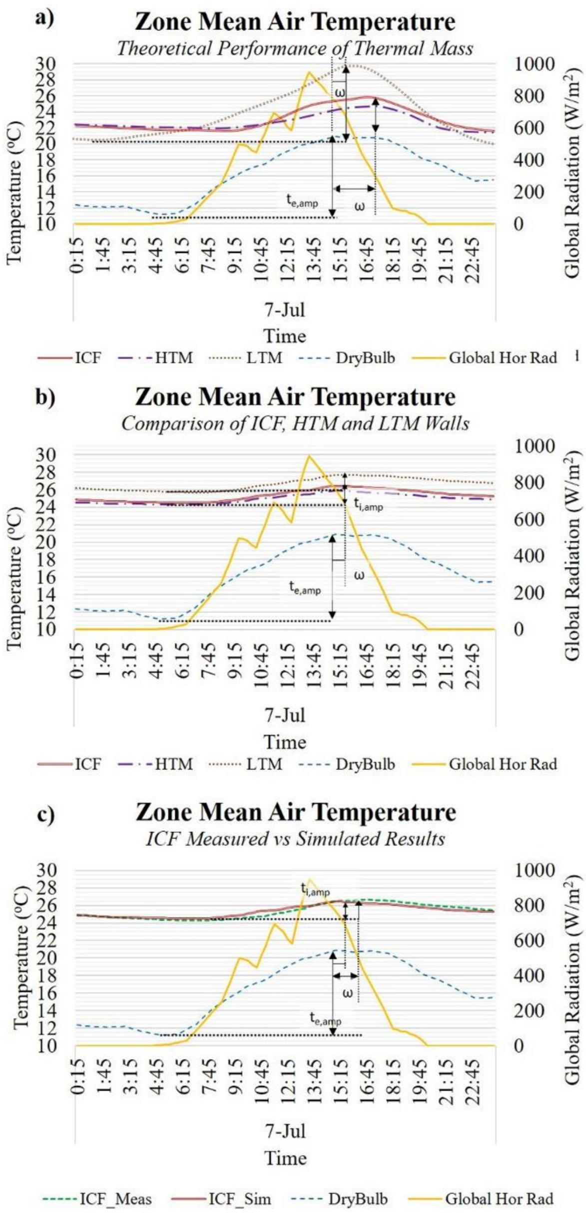


Figure 7 *Calculation of decrement factor and decrement delay of the three construction methods, ICF, HTM and LTM. Results plotted for a typical day in the summer unoccupied period. Comparison of: a) theoretical (expected) performance of thermal mass, b) simulation results for the three wall constructions, c) measured and simulation results for the ICF fabric.*

The daily decrement factor as calculated for the three buildings cases, based on the simulation predictions, was compared to the actual Df of the building, as calculated from the monitoring results (Fig.8). The graph shows that for the ICF building the simulation tends to slightly under-predict the decrement factor during warm weather, in comparison to the monitoring performance by RMSE = 0.04 (with an MBE = -2.15%). Based on simulation, the ICF and the LTM building had almost the same decrement factor D_f during the summer week, ranging between D_f = 0.15 and D_f=0.25. The HTM building showed a lower decrement factor, compared to the other two buildings, fluctuating between D_f = 0.10 and D_f = 0.21.

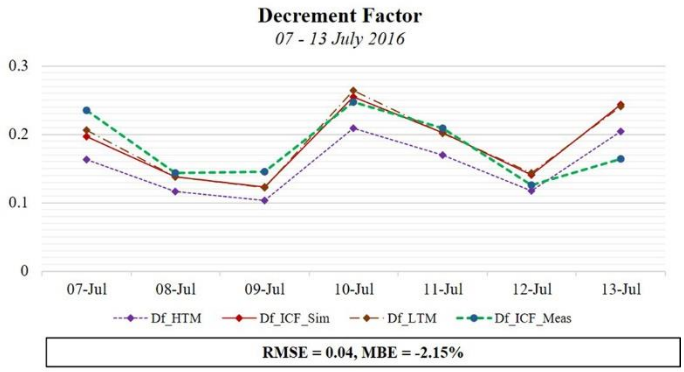


Figure 8 *Comparison of decrement factor for the three construction methods, ICF, HTM and LTM as calculated based on the monitoring results and simulation predictions for the summer unoccupied week 07 – 13 July 2016.*

The daily temperature variation of the ICF building was compared to the other two construction methods, for the spring cold week (Fig.9). Here, the daily temperature profiles are closer in all three models than it was in summer (Fig. 7). The LTM building showed a slightly increased internal air temperature compared to the other two buildings. The difference between ICF and the HTM buildings was insignificant.

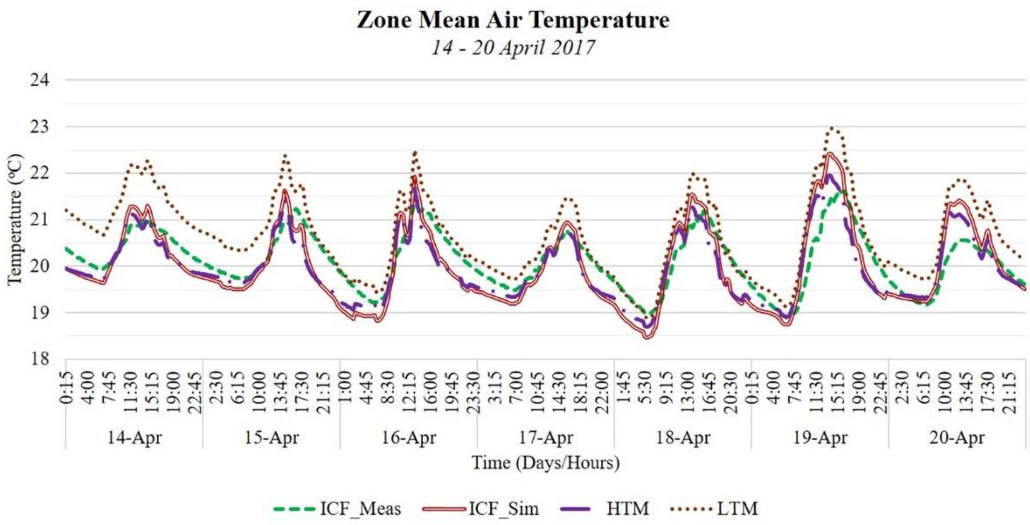


Figure 9 *Comparison of zone mean air temperatures between the three different construction methods for the spring unoccupied week, 14 – 20 April 2017. Simulation results for the ICF, HTM and LTM buildings plotted against measured data for the ICF building*.

The decrement factor as calculated for the three different buildings cases, based on the simulation predictions, as opposed to monitoring results is illustrated in Fig.10 for the cold week in April. Here, the simulation model of the ICF building over-predicts the decrement factor of the fabric in comparison to the actual Df calculated from monitoring data by RMSE = 0.1 (with an MBE = 40%). Based on the simulation predictions, the ICF and the LTM building had again almost the same decrement factor and the same range of variation throughout the week (i.e. between D_f = 0.18 and D_f = 0.3). The HTM building showed a lower average Df compared to the other two construction methods, and a smaller range of variation (between D_f = 0.15 and D_f = 0.23).

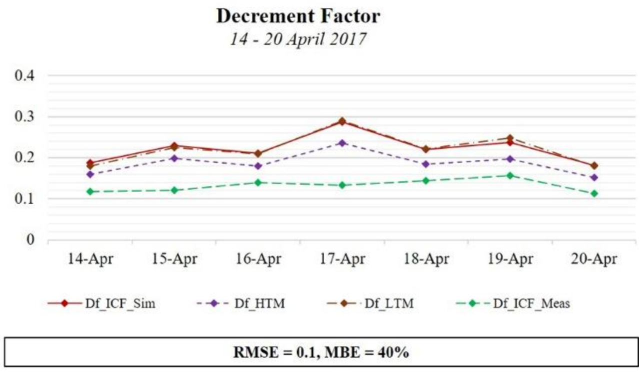


Figure 10 *Comparison of decrement factor for the three construction methods, ICF, HTM and LTM as calculated based on the monitoring results and simulation predictions for the spring unoccupied week 14 – 20 April 2017.*

3.2.2 Contribution of ground floor's thermal mass

To investigate the contribution of ground floor's thermal mass in the thermal inertia of the whole building, the LTM building was simulated with a lightweight floor construction, the HTM building was simulated as it was (i.e. with heavyweight ground floor) and the ICF building was simulated with three different floor constructions, varying the level of thermal mass from lightweight to medium and heavyweight. The results are illustrated in Fig.11 and confirm what was discussed earlier (Fig.6, 7 and 9). The LTM building had previously shown the same dampening effect in the internal air temperature to the other two building (Fig.6 and 7b) due to the high thermal mass of the floor. When the building was simulated with lightweight ground floor, its diurnal temperature variation was significantly increased during warm and cold periods. The performance of the ICF building was different according to the level of thermal mass in the ground floor. Its diurnal temperature variation, although similar to the HTM building when simulated with heavyweight floor construction, it significantly increased as the level of thermal mass in the floor was decreasing. In fact, when the ICF building was simulated with lightweight floor in the spring unoccupied period, it showed a similar diurnal temperature profile to the LTM building. Nevertheless, during summer, the thermal storage capacity of the

ICF walls, even when the ground floor construction was simulated as lightweight, resulted in an average of 2°C reduction in the internal air temperatures.

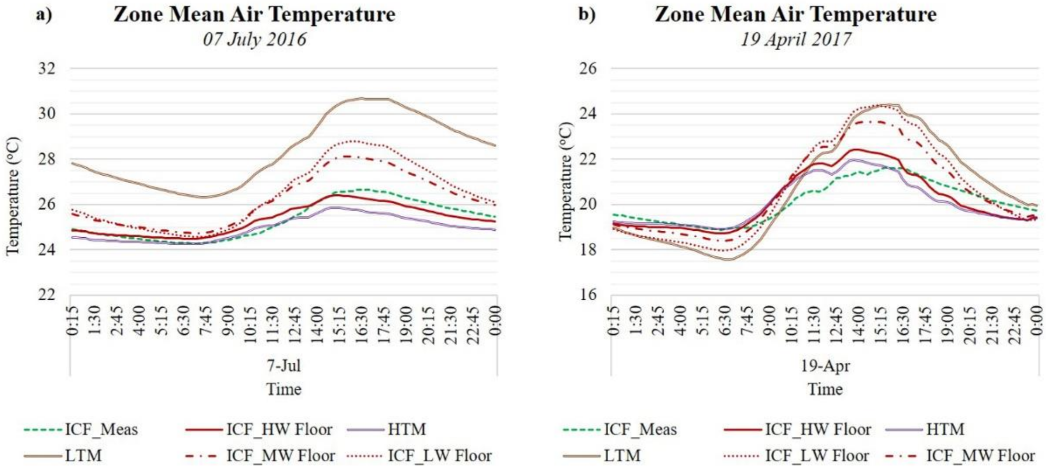


Figure 11: *Comparison of ICF zone mean air temperature when varying the thermal mass of the ground floor from lightweight to medium and heavyweight construction. Results plotted against measured data from the ICF monitoring project and simulation predictions for a lightweight floor construction in the LTM building and a heavyweight floor construction in the HTM building. a) summer unoccupied week, 07 – 13/07/16, b) spring unoccupied week, 14 – 20/04/17.*

3.2.3 The impact of interior thermal mass

The interior thermal mass was simulated in the models based on the material properties of the internal furnishing [from information found in literature (Johra & Heiselberg, 2017)] and the surface area of the furniture as measured in the actual building. However, the level of uncertainty in the input values remains high. In order to assess the role of interior thermal mass in the simulation results divergence, a global uncertainty analysis (UA) was performed. The results of the UA (Fig.12) indicated that the range of variation in the simulation of the zone maximum air temperature due to uncertainties in the interior thermal mass properties was small and equal to 0.47°C during warm period. During cold period the uncertainty in the zone maximum air temperature due to internal furnishing was insignificant.

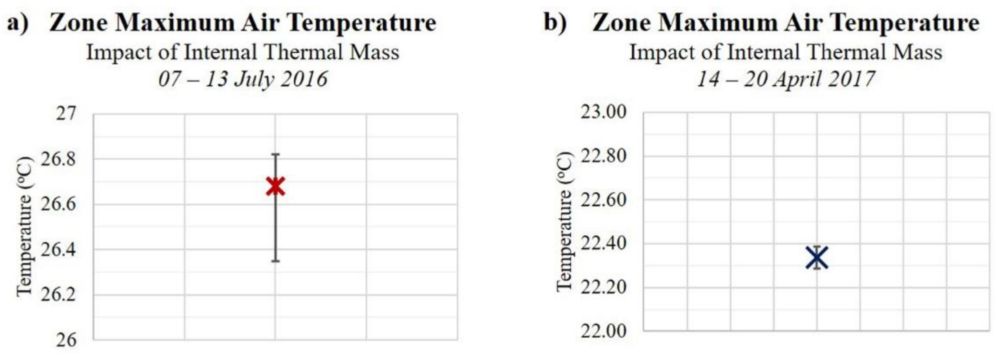


Figure 12: *Variation of zone maximum air temperature due to uncertain input values in the interior thermal mass due to furnishing: a) summer unoccupied week, 07 – 13/07/16, b) spring unoccupied week, 14 - 20/04/17.*

3.3 SENSITIVITY ANALYSIS OF WALL MATERIAL PROPERTIES

The results of the sensitivity analysis are shown in Fig 13 for all three construction methods, for the summer unoccupied week and in Fig.14 for the spring unoccupied week. The bar charts in Fig.13 and 14 show the ranking order of the input parameters, in other words the overall influence of each input factor on the simulation output (Campolongo et al., 2007; McLeod et al., 2013). The μ^* is an absolute value, and although it is considered as a good indication of the absolute importance of the input factor, it does not give any insight on the whether the input parameters have an influence on the results with a positive or negative sign. A graphical representation of σ vs μ^* (given in the scatter graphs of Fig.13 and 14) is given to evaluate the monotonicity of the input parameters. If the input factors are positioned below $\sigma/\mu^* = 0.1$ line then their behaviour is considered linear. If the input factors are positioned between the lines $\sigma/\mu^* = 0.1$ and $\sigma/\mu^* = 0.5$ then they are monotonic. If the input factors are between the lines $\sigma/\mu^* = 0.5$ and $\sigma/\mu^* = 1$ they are almost-monotonic. Finally, if they are above the $\sigma/\mu^* = 1$ line they are considered highly non-linear and non-monotonic (Mcleod et al., 2013; Brembilla et al., 2015).

The SA results showed that during the summer period (Fig. 13) the most significant parameters influencing the zone mean air temperature for the ICF building were the density, specific heat capacity and thickness of the concrete core, followed closely by the conductivity and thickness of the internal insulation layer, and the conductivity of the external insulation layer. In other words, the most important parameters affecting the internal air temperature of an ICF building during summer was the thermal mass of the concrete core and the thickness and conductivity of the internal insulation. Similar findings apply to the HTM building. The properties of the concrete (i.e. thickness, specific heat capacity and density) showed the most significant effect on the internal air temperature. The other two parameters that affected the zone mean air temperatures were the thickness and conductivity of the insulation layer.

During the unoccupied week in April the results of the sensitivity analysis (Fig. 14) showed that for the ICF building, similarly to summer (Fig. 13), the zone mean air temperature was mostly affected by the properties of the concrete core (i.e. density, thickness, specific heat capacity). Moreover, other influential parameters were found to be the conductivity of the layers of insulation both internally and externally. The external insulation layer, which was found to have an insignificant effect on the zone mean air temperature during summer, was found to be among the most sensitive parameters affecting the internal environment during cold weather. In the spring unoccupied week, the internal air temperature of the HTM building, in contrast to summer, was mostly sensitive to conductivity and thickness of the insulation layer, followed by thermal mass of the concrete layer (thickness, specific heat capacity and). In the LTM building, where there is no heavyweight layer in the construction of the wall, the zone mean air temperature was mostly sensitive to the thickness and conductivity of the insulation during both warm and cold periods.

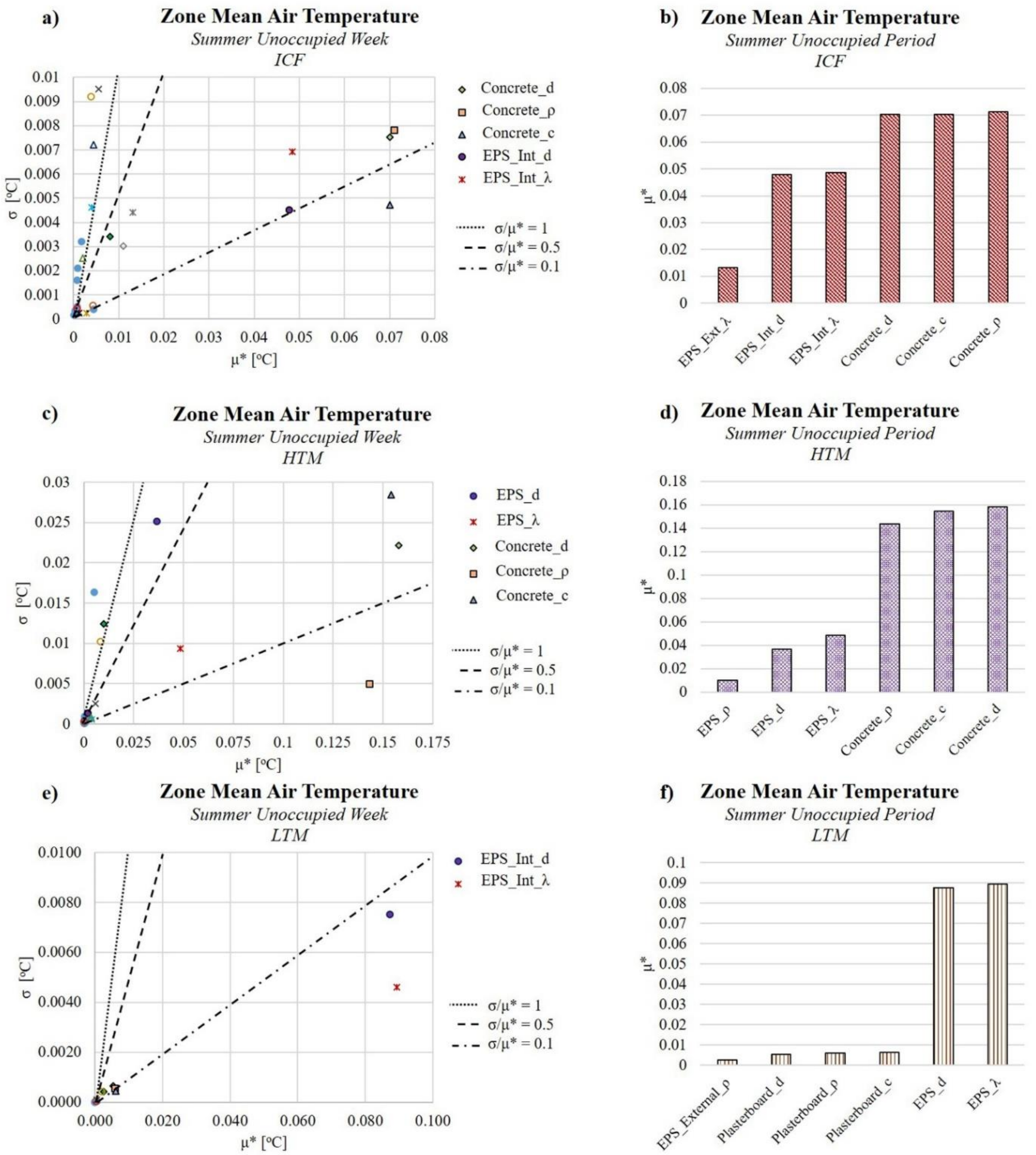


Figure 13 *Morris analysis of absolute mean (μ*) and standard deviation (σ) on mean zone air temperature when considering uncertainty in external wall material properties during summer unoccupied week: a) ICF Morris plot, b) ICF sensitivity ranking, c) HTM Morris plot, d) HTM sensitivity ranking, e) LTM Morris plot, f) LTM sensitivity ranking.*

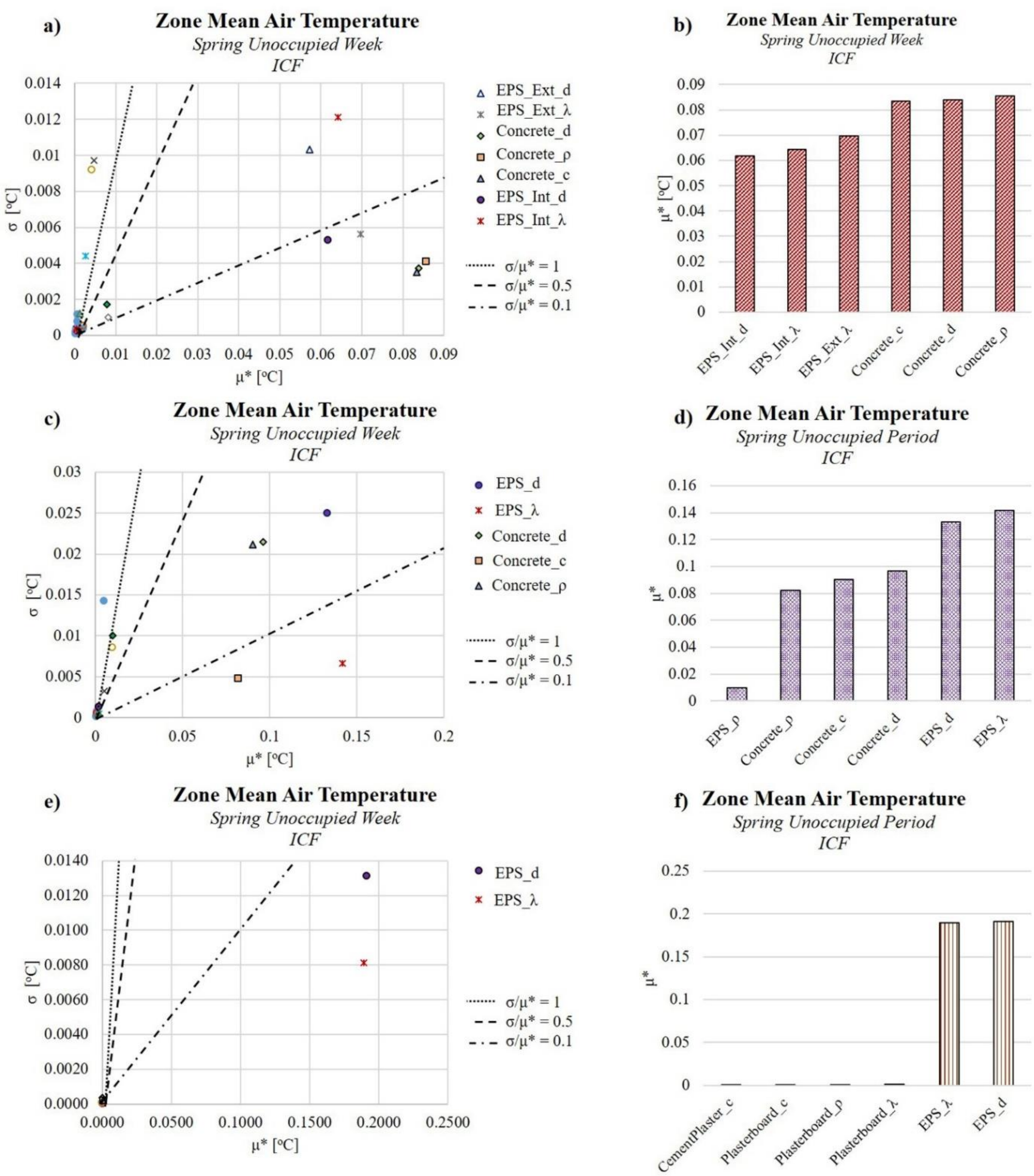


Figure 14 *Morris analysis of absolute mean (μ*) and standard deviation (σ) on mean zone air temperature when considering uncertainty in external wall material properties during spring unoccupied week: a) ICF Morris plot, b) ICF sensitivity ranking, c) HTM Morris plot, d) HTM sensitivity ranking, e) LTM Morris plot, f) LTM sensitivity ranking.*

3.4 THE IMPACT OF THERMAL MASS ON INTERNAL FACE HEAT FLUX

The results of the sensitivity analysis for the two analysed periods indicated that the thermal storage capacity of the ICF concrete core affects internal air temperatures. In the following section, to investigate this issue further, the transient performance of the three wall construction methods was investigated by analysing the internal surface and intra-fabric temperature and the internal surface conduction heat flow rate and energy.

Measured data for the inside wall surface heat flux were plotted in comparison to the inside surface, the intra-fabric and the zone air temperature for a three-day period in the warm summer weather (Fig.15a) and three days in the cold spring week (Fig.15b). During warm weather the temperature of the concrete core was relatively steady – around 24oC. The surface and zone air temperature fluctuated between 24.5^{o}C and 26^{o}C. The Δt between the inside wall surface and the concrete core temperature was always higher than the Δt between the surface and the zone mean air temperature. Throughout the three days under investigation the heat flow was consistently from the inside of the zone towards the interior of the fabric (constant heat loss to the exterior, indicated with negative sign). There was no evidence of reversed heat flow (i.e. heat dissemination from the wall to the space).

During the cold spring period, the monitoring results of the inside surface heat flux indicate a slightly increased heat flow rate (Fig. 15b) in comparison to the summer period (Fig.15a). Similarly to summer, the heat flow was consistently from the inside space towards the inside of the fabric. The wall surface showed slightly increased peaks of maximum in comparison to the zone mean air temperature. The monitored concrete core temperature was again relatively constant and around 17.5^{o}C. The Δt of the surface temperature to the intra-fabric temperature was always higher for the whole three-day period compared with the Δt of the surface temperature and the zone air temperature. As a result, the heat flow was always from the internal space towards the exterior (negative sign), and there was no evidence of heat gains from the wall to the space.

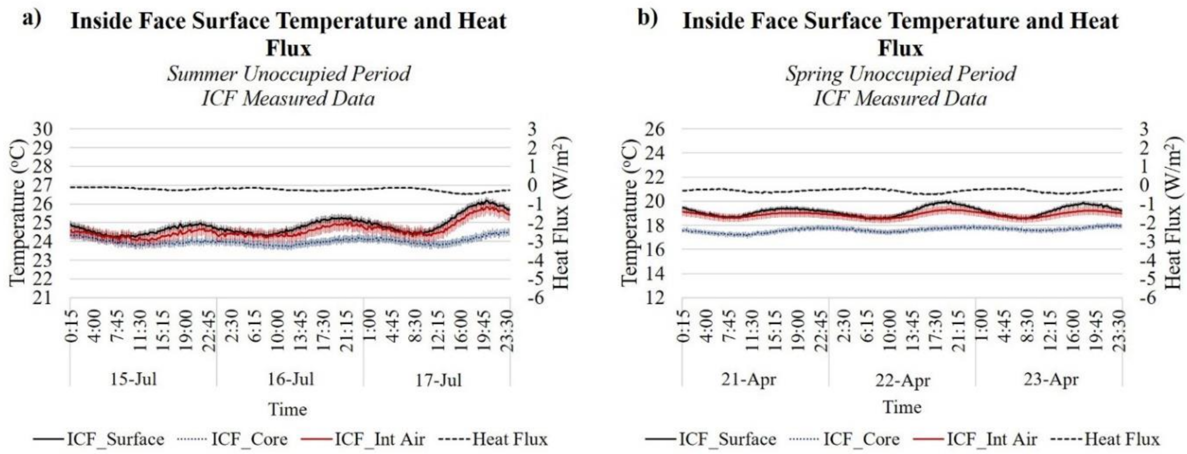


Figure 15 *ICF measured inside surface, intra-fabric and internal air temperature plotted in comparison to inside face heat flux: a) three representative days of the summer unoccupied period, 15- 17 July 2016, b) three representative days of the spring unoccupied period 21-23 April 2017.*

The simulation results provided by the three models for the inside wall surface heat flux, the inside surface, intra-fabric and the zone mean air temperature were plotted for the ICF building (Fig.16a), the HTM building (Fig,16b) and the LTM building (Fig.16c) for the cold period. Similar observations were found for both weeks (i.e. warm and cold weather), however for sake of brevity only the results of the cold period are presented here.

The comparison of monitoring results (Fig. 15b) to simulation predictions for the ICF building (Fig. 16a) show that the model tends to under-estimate the intra-fabric temperature, by approximately 1°C. This resulted in a slightly increased heat flux, compared to the actual monitored performance of the ICF wall. Moreover, the simulation model under-estimated the surface temperature in some instances and predicted a slightly higher daily temperature variation (reaching up to 2°C), when the monitoring results showed a maximum diurnal temperature variation of 1°C. In the comparison of the ICF building to the HTM and the LTM building (Fig.16), the ICF building showed the lowest heat flux of all three cases with a consistent heat flow from the interior of the space towards the inside of the fabric (similar to the monitoring performance – Fig. 15b). The HTM and the LTM buildings showed evidence of heat being disseminated from the wall to the internal space. In the HTM building (Fig.16b) the wall surface and intra-fabric temperature were almost the same with very little variation during the three days analysed. The zone mean air temperature fluctuated in a smaller range compared to the other two buildings. The heat flow was mostly from the internal space towards the fabric from midday until midnight. Some of this heat was released back into the space from midnight until the middle of the following day; showing evidence of the ability of the thermal mass to capture and store internal heat gains. The LTM building showed increased heat flow rates compared to the ICF building, with some instances of heat flowing from the outside to the internal space. The ICF and the HTM buildings showed a relatively stable intra-fabric temperature, around 16°C and 18°C, respectively. In the LTM wall, the intra-fabric temperature fluctuated in a range of 12°C, between 13°C and 25°C.

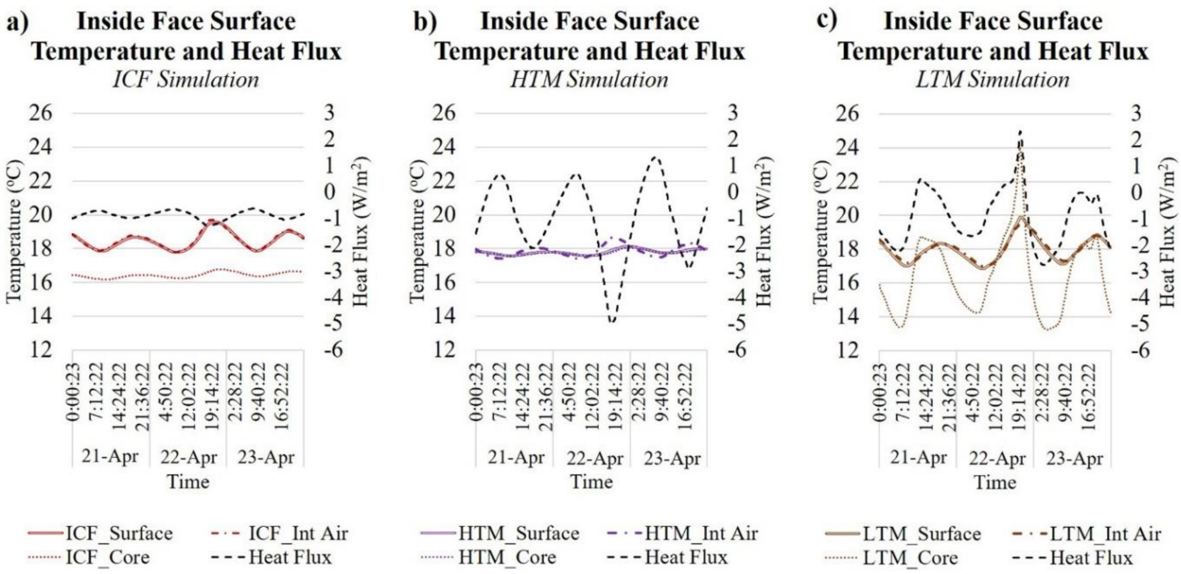


Figure 16 *Simulated inside surface, intra-fabric and internal air temperature plotted in comparison to inside face heat flux for three representative days of the cold unoccupied week, 21 – 23 April 2017: a) ICF wall, b) HTM wall, c) LTM wall.*

The intra-fabric temperature gradient of the three wall constructions was plotted in four time-steps during the course of a cold day (Fig.17). The temperature of the ICF concrete core was stable and around 16°C (Fig.17a). The inside wall surface temperature fluctuated by 1.5°C (between 17.5°C and 19°C), while the outside surface temperature showed significant daily variations in the range of 20°C (between 2°C and 22°C). Similar observations apply to the HTM building (Fig.17b). In the LTM building (Fig.17c), the outside surface temperature fluctuated in the same range as the other two construction methods (i.e. between 2°C and 22°C). However, the inside surface and intra-fabric temperature variation was significantly increased compared to the other two walls. More specifically, the inside surface showed a daily fluctuation between 15.5°C and 18.5°C and the intra-fabric temperature variation was in the range of 7.5°C (between 10°C and 17.5°C). The corresponding internal air temperature variation was plotted for the same cold day analysed (i.e. 23rd of April 2017) for all three constructions, ICF (Fig.18a), HTM (Fig.18b) and LTM (Fig.18c). The graphs show that, as anticipated, the HTM building had the smaller diurnal internal air temperature variation, $\Delta t = 0.7$°C. The ICF building showed higher internal air temperatures in comparison to the HTM building (with a range between 18°C and 19°C) and a higher diurnal variation ($\Delta t = 1$°C). The LTM building showed the highest variation of all three construction methods, $\Delta t = 1.5$°C, and its internal air temperature being in the range between 17.5°C and 19°C.

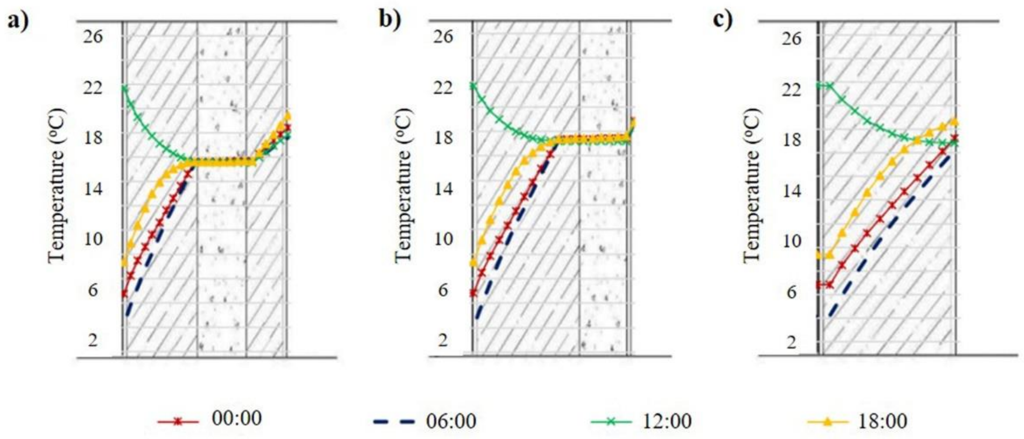


Figure 17 *Simulation results on intra-fabric temperature distribution for a representative day of spring, 23 April 2017: a) ICF, b) HTM, c) LTM.*

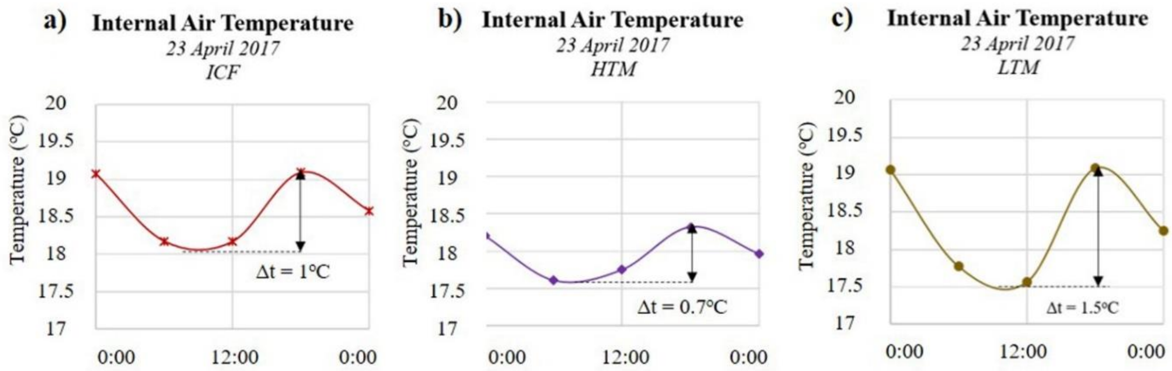


Figure 18 *Simulation results on internal air temperature variation for a representative day of spring, 23 April 2017: a) ICF, b) HTM, c) LTM.*

The cumulative conduction heat flow energy from the inside wall surface for the ICF and the LTM buildings was plotted for three days during the cold period (Fig.19). The aim was to perform a direct comparison between the LTM and the ICF walls to investigate the impact of the ICF thermal mass on the heat flowing in and out of the building. Since both wall constructions have the same thermal transmittance (U-value), any difference in the total heat losses and gains can be solely attributed to the thermal mass of the ICF concrete core. The total heat loss of the LTM building was calculated to be around 280Wh, whereas the corresponding total heat loss of the ICF building was around 180Wh. The ICF showed 100Wh less heat loss to the exterior due to the thermal storage capacity (and the constant temperature) of the concrete core. Moreover, the LTM wall showed 30Wh of heat gains from the outside to the interior of the space, when the ICF wall showed no evidence of heat gains.

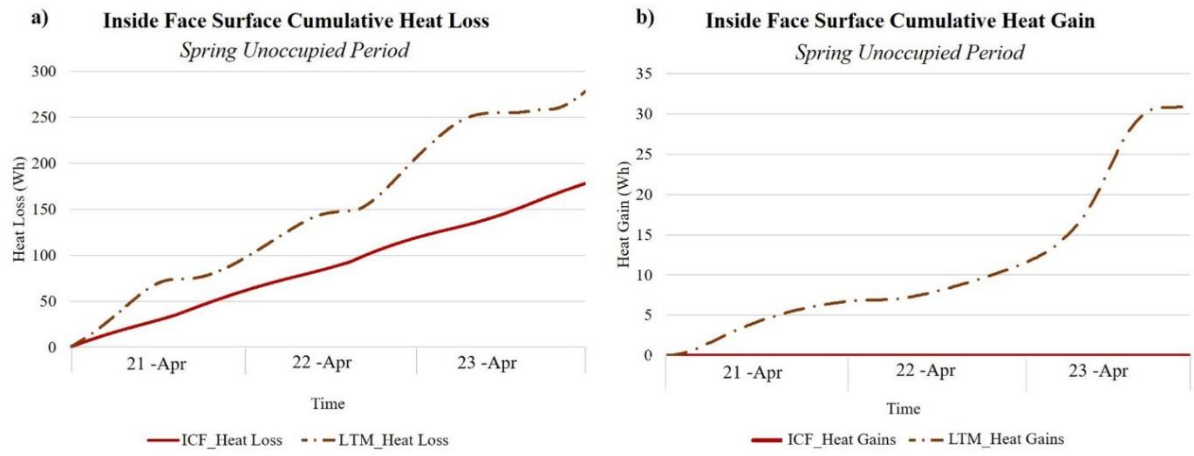


Figure 19 *Inside face surface cumulative conductive heat energy flow. Comparison of ICF and LTM walls for three representative days of the spring unoccupied period, 21 – 23 April 2017: a) Conduction heat loss from zone to the exterior, b) Conduction heat gain for the exterior to zone.*

4 DISCUSSION

The following section discusses the academic implications of this research, in respect of key literature in the area, and makes clear the contribution to knowledge. Although there is a number of previous studies analysing the thermal performance of ICF, these were mostly either field studies, measuring the performance of specific buildings in specific scenarios (NAHB, 1999), or simulation studies, without a means to evaluate the accuracy of simulation predictions (Gajda &VanGeem, 2000; Kosny et al., 2001; Hart et al., 2014). There are only a few studies that combine monitoring and simulation results, yet these typically focus only on surface temperatures and heat flow rates and were performed for the cold climate of Canada (Hill 7 Monsour, 2007; Armstrong et al., 2011; Saber et al., 2011). To the authors' knowledge that is the first whole building monitoring study which combines computational analysis and empirical data, to investigate the thermal performance of an actual ICF building located in the temperate UK climate. The actual thermal performance of an ICF building is evaluated empirically and the monitoring results are used to build confidence on the accuracy of simulation predictions. Subsequently, “what-if” scenarios of alternative wall constructions are combined to an in-depth computational analysis to draw conclusions on the transient thermal performance of ICF.

4.1 EMPIRICAL VALIDATION OF SIMULATION RESULTS

The analysis showed that the measured internal temperature of the ICF building is significantly more stable than the external dry-bulb temperature, which showed high diurnal swings. The small diurnal internal air temperature variation throughout both analysed periods confirms that the building fabric has a dampening effect, reducing internal temperature swings to a much smaller range than the ambient temperature, providing a stable internal environment.

The simulation model of the ICF building was able to predict with a relatively good accuracy the amplitude of the internal air temperature daily swings during both summer and spring (RMSE = 0.25^{o}C and RMSE = 0.45^{o}C, respectively). However, in cold spring period the peaks of the maximum internal air temperature were slightly over-estimated by the model compared to the monitoring results, resulting in a higher decrement factor (c.40% higher average Df provided by the simulation model in comparison to reality). Moreover, the simulation results under-estimated the decrement delay during both warm and cold periods under investigation, indicating a shortcoming of the models.

4.2 THE IMPACT OF VARYING THERMAL MASS

The comparison of ICF, HTM and LTM buildings confirmed the findings of previous studies (Kosny et al., 2001; Hart et al., 2014; Mantesi et al., 2018), i.e. that thermal performance of ICF sits between the other two construction methods. The diurnal temperature variation of the ICF building showed slightly increased peaks of maximum in comparison to the HTM building, but overall the two buildings performed very similarly. Surprisingly, the LTM building was found to have a similar diurnal temperature profile to the other two construction methods, although one would expect its decrement factor to be significantly higher than heavyweight structures, with a smaller time lag, resembling the diurnal temperature variation of ambient air. This was proven to be mainly attributed to the heavyweight construction of the ground floor slab, which was kept the same in all three buildings. Furthermore, the results of the analysis showed that the dampening effect of the ICF building in internal air temperature swings was very much affected by the thermal mass of the floor construction. Nevertheless, during warm weather, regardless of the floor construction, the thermal storage capacity of the ICF walls resulted in an average of 2^{o}C reduction in the internal air temperatures compared to the LTM building.

The decrement factor of the HTM building was the smallest of the three cases, during both warm and cold weather. The ICF building showed a comparable decrement factor to the LTM building during both periods of analysis, indicating that the thermal storage capacity of the ICF walls had no significant impact on a daily temperature variation cycle. The reduction of zone mean air temperatures by 2^{o}C in the ICF building however, when compared to the LTM building during warm period, showed that the thermal inertia of the ICF concrete core affected the overall thermal storage of the walls in longer cycles (i.e. weekly or seasonally) and had consequently an impact on the internal air temperatures. A finding which was further enhanced by the results of the sensitivity analysis.

4.3 SENSITIVITY ANALYSIS OF WALL MATERIAL PROPERTIES

The SA for the ICF building, indicated that among the wall material properties, the density, specific heat capacity and thickness of the concrete core were the most influential parameters (with regards to the zone mean air temperature during both warm and cold weather). In other words, the SA showed that the thermal storage capacity of the ICF concrete core is not as thermally decoupled from the internal space as one would expect and it does affect the internal air temperatures in the building. This finding becomes particularly relevant when considering several simplified methods used for the calculation of energy use in buildings for compliance, such as the BS EN ISO 13790: 2008 (BS EN ISO 13790, 2008) and the UK Government's standard assessment procedure for energy rating of dwellings (SAP2012) (BRE, 2012). Taking SAP as an example, to calculate the thermal mass parameter of an element, one needs to calculate the heat capacity of all its layers. However, it is specifically stated that starting from the internal surface, the calculations should stop when one of the following conditions occurs:

- an insulation layer (thermal conductivity <= 0.08 W/m·K) is reached;
- total thickness of 100 mm is reached.
- half way through the element;

Similarly in ISO 13790: 2008, the internal heat capacity of the building is calculated by summing up the heat capacities of all the building elements for a maximum effective thickness of 100mm. In other words, according to SAP and ISO 13790 the thermal storage capacity of ICF concrete core should be completely disregarded, which this research has clearly shown to be problematic. The results of this analysis indicate that ICF could be a viable alternative for energy efficient construction. However, the study has also shown that the use of reliable, validated dynamic whole building simulation is imperative in order to evaluate accurately the thermal performance of new construction methods, of which there is currently little empirical knowledge.

4.4 HEAT FLUX ANALYSIS

To investigate the thermal storage capacity of the ICF wall component further, the transient performance of the ICF wall was analysed by looking at internal surface and intra-fabric temperatures alongside the internal surface heat flux as recorded by the monitoring study and based on simulation predictions. The analysis showed that the concrete core of the ICF wall was kept at a relatively constant temperature, acting as a buffer to heat flowing in and out of the building. In the comparison of ICF and LTM buildings, the concrete core of ICF resulted in reduced heat losses from the internal space towards the exterior environment. Considering that the only difference among the two wall construction methods was the level of thermal mass due to the concrete core (same U-value, same internal and external surface materials), then this reduction of heat losses can be solely attributed to the thermal inertia of the ICF concrete core. Reilly and Kinnane (2017) introduced the concept of Transient Energy Ratio (TER), in order to assess the role of thermal mass. According to them, the role of thermal mass can be assessed by comparing an accurate, transient model which accounts for thermal mass effects, to a static model of the same scenario.

$$TER = \frac{Energy\ used\ in\ transient\ model}{Energy\ used\ in\ a\ static\ model} \qquad (8)$$

Applying the TER to this research, the transient energy ratio measured the energy flow through the ICF wall, divided by the energy flow through a LTM wall (with the same thermal resistance but zero heat capacity, i.e. no thermal mass). The results indicated a TER = 0.63. In other words, in the comparison of ICF to LTM building the thermal inertia of the ICF concrete core resulted in 37% less heat losses to the exterior.

Finally, the comparison of ICF to the HTM building indicated that the internal insulation layer of the ICF reduces the admittance of the wall considerably and moderates its ability to capture and store internal heat gains during times of surplus. Consequently, depending on the use, the design and the location of the building, ICF could be more vulnerable to overheating compared to a HTM building. For the specific case study however, the analysis showed that a high thermal mass floor construction is able to stabilise the internal air temperature significantly, even when the walls are lightweight. Considering that one of the advantages of ICF in comparison to lightweight MMCs is its structural ability to support heavyweight floors, the overall thermal mass of the whole structure could be significantly increased.

5 RESEARCH LIMITATIONS

The analysis presented in this paper focused on the thermal performance of ICF in terms of internal air temperature. To investigate how the fabric would perform (with regard to internal air temperatures) it was essential to focus on periods without space conditioning, when the house was performing under a free-floating mode. Hence, two, one-week long periods were included, when the house was unoccupied, one during summer warm weather and one during spring cold weather. This however, prevented several important factors related to thermal mass from being analysed, such as the impact of variable internal gains and air flows, the impact of intermittent occupation, the risk of overheating and others. Comparing the relative performance of the ICF building against the other two construction methods showed that, for this specific case study, the former behaves closer to the HTM building. However, extending the analysis to also include occupied periods, could improve the reliability of this outcome.

The cold unoccupied period included in the analysis was during a week in April 2017. For the purposes of this study it was crucial to investigate the performance of the fabric, when the house operated in free-floating mode. The ambient temperatures during April of 2017 were low enough to consider this period as a representative cold period. However, the availability of solar radiation was higher when compared to a typical winter week. This resulted in higher internal air temperatures than normally expected for a free-floating building operation in the winter period. It would enhance the reliability of the research findings, if the cold period analysis was repeated for an unoccupied week in the winter months (i.e. December to February).

A further limitation of the study was that during the monitoring period, only global horizontal radiation was recorded on site. The split between direct normal and diffuse horizontal components was performed in EnergyPlus using the Perez model (Perez, 1992). This however introduces a certain level of modelling uncertainty, since there are no monitoring data available to use as a reference point for direct and diffuse radiation values used in the simulation.

The internal air temperature was measured in one location within each room, using HOBO U12 stand-alone loggers. The loggers were placed at a height of 1.5m from the floor, away from heat sources and direct solar radiation, as suggested in literature (Kumar et al., 2017; Singh et al., 2010). However, this decision does not account for the effects of air stratification that may arise in the room due to buoyancy. It may also introduce a systematic error in the results, which would be significantly reduced if more than one sensor had been placed per room and their average was used to calculate the zone mean air temperature, instead of the values from a single logger.

6 CONCLUSIONS

This research was set out to evaluate the internal thermal conditions of an ICF building and to investigate the contribution (or otherwise) of the thermal storage capacity of the ICF concrete core to the transient heat flow in and out of the building. The study followed a stratified research approach, including:

1) ***Field-study analysis/ empirical evaluation*** of a real ICF building to collect high resolution data on the whole building performance (i.e. internal air temperature, energy consumption, dynamic performance of building fabric), which would serve as a reference point to validate the accuracy of simulation output against.
2) ***Calibrated, empirically validated simulation***, which framed the basis for understanding the key features associated to thermal mass, such as the transient heat transmission in and out of the building and the sensitivity of the internal environment to the physical properties of the construction related to its thermal storage capacity.

By doing this, a new procedure was presented for proofing the thermal storage capacity of new and innovative materials, where their thermal performance is not yet well-researched. This was tested using ICF. The internal layer of insulation in the ICF assembly, reduces the thermal admittance of the wall, making it difficult to quantify the actual thermal mass potentials of the element. Hence based on simplified calculation methods, ICF would be characterised as a thermally lightweight structure. The work reported here, followed a number of steps and proved that the element's concrete core is not as thermally decoupled from the internal space as has been thought to be the case. Rather, the concrete core of the ICF element was found to act as a buffer to the heat flow that occurs in and out of the building. Due to its thermal inertia the concrete was kept at a relatively constant temperature, thereby reducing transmission losses and gains (compared to a low thermal mass wall with equal levels of insulation). Undoubtedly, the internal insulation layer reduced the admittance of the wall, so decreasing the amount of heat penetrating the ICF fabric (compared to a similar wall with exposed thermal mass). Therefore, a higher risk of overheating might be anticipated for an ICF building compared to a high thermal mass building in scenarios with increased internal loads or in a building located in warmer climates than the UK.

In addition, the findings of this study showed that simplified calculation methods commonly used in industry to demonstrate regulatory compliance could be inaccurate for new and innovative construction methods. This could potentially lead to misconceptions about their thermal behaviour and affect their market penetration. Therefore, the use of reliable dynamic whole building simulation is necessary in order to evaluate accurately the thermal performance of specific buildings and non-conventional construction methods. Previous research has showed that the divergence in the simulation predictions provided by different tools for the same ICF building could be as high as 26%, when users rely on default settings and input values (Mantesi et al., 2018). This paper has shown that if the ICF building is correctly represented in BPS, (i.e. with correct input values representing its actual performance and suitable selection of calculation algorithms), then the BPS models are able to predict the thermal performance of the building with a good accuracy. While there was a discrepancy in the calculation of the fabric's dynamic characteristics (decrement factor Df and decrement delay ω), the simulation models showed an overall good representation of reality with regards to diurnal temperature variations.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Engineering and Physical Sciences Research Council and the Centre for Innovative and Collaborative Construction Engineering at Loughborough University for the provision of a grant (number EPG037272) to undertake this research project, in collaboration with Aggregate Industries UK Ltd. Furthermore, they would like to thank Mr and Mrs Karlsson for their kindness to offer their house for the monitoring project, and Mr Vince Smedley for advising and installing the monitoring equipment.

REFERENCES

Al-Sanea, S. a. & Zedan, M.F., 2011. Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass. *Applied Energy*, 88(9), pp. 3113–3124.

Armstrong, M.M., Maref, W., Saber, H.H., Rousseau, M.Z., Ganapathy, G. & Swinton, M.C., 2011. *The impact of the thermal mass on field energy performance of insulating concrete form (ICF) wall*, Canada: National Research Council.

ASHRAE, 2014. Guideline 14 - 2014: Measurement of Energy Demand and Water Savings, Atlanda, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers

AHRAE, 2009. *ASHRAE Handbook – Fundamentals*, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

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), pp.1–10.

BRE, 2012. SAP 2012 The Government ' s Standard Assessment Procedure for Energy Rating of Dwellings, London.

Brembilla, E., Mardaljevic, J. & Hopfe, C.J., 2015. Sensitivity analysis studying the impact of reflectance values assigned in climate-based daylight modelling, In *14th International Building Performance Simulation Association, Building Simulation Conference, BS2015, Hyderabad, India, 07-09 December 2015, Conference Proceedings.*

BS EN ISO 13790, 2008. Energy Performance of Buildings - calculation of energy use for space heating and cooling, Geneva.

Campolongo, F., Cariboni, J. & Saltelli, A., 2007. An effective screening design for sensitivity analysis of large models. *Environmental Modelling and Software*, 22(10), pp.1509–1518.

CIBSE, TM41: 2006. *Degree-Days: Theory and application*, London: The Chartered Institution of Building Services Engineers.

Coakley, D., Raftery, P. & Keane, M., 2014. A review of methods to match building energy simulation models to measured data. *Renewable and Sustainable Energy Reviews*, 37, pp.123–141. doi.org/10.1016/j.rser.2014.05.007.

Dincer, I. & Rosen, M., 2011. *Thermal Energy Storage Systems and Applications*, 2nd ed., Chichester: John Wiley and Sons, Ltd.

DOE, 2010. EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations. US Department of Energy, p.1051.

Emmerich, S.J., Persily, A.K., 2014. Analysis of US Commercial Building Envelope Air Leakage Database to Support Sustainable Buildings Design. *International Journal of Ventilation*, 12, pp.331-343. doi:10.5555/2044-4044-12.4.331.

EVO, 2012. *International Performance Measurement and Verification Protocol*, Canada: Efficiency Valuation Organization. doi:10.1126/science.15.390.961.

Fumo, N., 2014. A review on the basis of building energy estimation. *Renewable and Sustainable Energy Reviews*, 31, pp.53-60. doi:10.1016/j.rser.2013.11.040.

Gajda, J. & VanGeem, M., 2000. *Energy use in residential housing: A comparison of insulating concrete form and wood frame walls*, Portland Cement Association.

GILL Instruments Limited, 2015. MaxiMet GMX501 Compact weather station. Available at: http://gillinstruments.com/data/datasheets/maximet-gmx501.pdf?iss=1.20150501 [Accessed March 12, 2018].

Hart, R., Mendon, V. & Taylor, T., 2014. *Residential Wall Type Energy Impact Analysis*, Florida Masonry Apprentices & Education Foundation.

Helton, J.C., Davis, F.J., 2003. Latin Hypercube sampling and propagation of uncertainty in analyses of complex systems, *Reliable Engineering and System Safety*, 81, pp.23-69. doi:10.1016/S0951-8320(03)00058-9.

Hill, D. & Monsour, R., 2007. Monitored Performance of an Insulating Concrete Form Multi-Unit Residential Building, Canada.

HOBO U12. Temp/RH/Light/External Data Logger. Available at: http://www.onsetcomp.com/files/manual_pdfs/13128-C U12-012 Manual.pdf [Accessed March 12, 2018b].

Hopfe, C.J., 2009. *Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization*, PhD Thesis, Eidhoven University of Technology.

Hopfe, C.J. & McLeod, R.S., 2015. *The passivhaus designer's manual a technical guide to low and zero energy buildings*, 1st ed. New York: Routledge.

Hukseflux HFP01. Thermal Sensors User Manual HFP01 & HFP03 Heat Flux Plate/ Heat Flux Sensor. , pp.1–43. Available at: https://www.hukseflux.com/sites/default/files/product_manual/HFP01_HFP03_manual_v1721.pdf [Accessed on: [Accessed March 12, 2018].

Hukseflux SR03. Thermal Sensors User Manual SR03 Fast response second class pyranometer. Available at: https://www.hukseflux.com/sites/default/files/product_manual/SR05_manual_v1610.pdf [Accessed March 12, 2018a].

JEPlus, jEPlus User's Manual, Version 1.4. Available at: http://www.jeplus.org/wiki/doku.php?id=docs:manual_1_4 [Accessed March 12, 2018].

Johra, H. & Heiselberg, P., 2017. Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review. *Renewable and Sustainable Energy Reviews*, 69(September 2015), pp.19–32. doi.org/10.1016/j.rser.2016.11.145.

Kendrick, C., Ogden, P., 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, pp.40–49.

Kosny, J, Petrie, T., Gawin, D., Childs, P., Desjarlais, A. & Christian, J., 2001. *Energy Savings Potential in Residential Buildings*, USA: Oak Ridge National Laboratory.

Kośny, J. & Kossecka, E., 2002. Multi-dimensional heat transfer through complex building envelope assemblies in hourly energy simulation programs. *Energy and Buildings*, 34(5), pp.445–454.

Kumar, S., Tewari, P., Mathur, S. & Mathur, J., 2017. Development of mathematical correlations for indoor temperature from field observations of the performance of high thermal mass buildings in India. *Building and Environment*, 122, pp.324–342. doi.org/10.1016/j.buildenv.2017.06.030.

Mantesi, E, Hopfe, C.J., Glass, J. & Cook, M.J., 2015. Assessment of ICF Energy Saving Potential in Whole Building Performance Simulation Tools. In *14th International Building Performance Simulation Association, Building Simulation Conference, BS2015, Hyderabad, India, 07-09 December 2015, Conference Proceedings*.

Mantesi, E., Hopfe, C. J., Glass, J., Cook, M. J., 2016. Investigating the impact of modelling uncertainty on the simulation of insulating concrete formwork for buildings. In *3rd Building Simulation and Optimization Conference BSO2016. Newcastle, UK, 12-14 September 2016, Conference Proceedings*.

Mantesi, E., Hopfe, C. J., Cook, M. J., Glass, J., Strachan, P., 2018. The modelling gap: Quantifying the discrepancy in the representation of thermal mass in building simulation. *Building and Environment*, (131), pp.74–98, doi:10.1016/j.buildenv.2017.12.017.

McLeod, R.S. & Hopfe, C.J., 2013. Hygrothermal implications of low and zero energy standards for building envelope performance in the UK. Journal of Building Performance Simulation, 6(January 2015), pp.367–384.

McLeod, R.S., Hopfe, C.J. & Kwan, A., 2013. An investigation into future performance and overheating risks in Passivhaus dwellings, *Building and Environment,* 70, pp.189-209. doi:10.1016/j.buildenv,2013.08.024.

Met Office, Met Office: weather and climate data. Available at: https://www.metoffice.gov.uk/ [Accessed March 12, 2018].

Mourkos, K., Mantesi, E., Hopfe, C. J., Cook, M., Glass, J., Goodier, C., 2017. The Role of Fabric Performance in the Seasonal Overheating of Dwellings. In *15th International Building Performance Simulation Association, Building Simulation Conference, San Francisco, USA, 07-09 August 2017, Conference Proceedings*.

Mustafaraj, D., **Marini, D., Costa, A., 2014.** Model calibration for building energy efficiency simulation, *Applied Energy,* 130, pp. 72-85. doi:10.1016/j.apenergy.2014.05.019.

NAHB, 1999. *Insulating Concrete Forms: Comparative Thermal Performance*, USA: Department of Housing and Urban Development.

Navarro, L., DeGracia, A., Niall, D., castell, A., Browne, M., McCormack, S.J., Griffiths, P. & Cabeza, L.F., 2016. Thermal energy storage in building integrated thermal systems: A review. Part 2. Integration as passive system. *Renewable Energy*, 85, pp.1334–1356.

NHBC_Foundation, 2016. *Modern Methods of Construction: views from the industry*, London: NHBC Foundation.

Pan, W., Gibb, A.G.F. & Dainty, A.R.J., 2007. Perspectives of UK housebuilders on the use of offsite modern methods of construction. *Construction Management and Economics*, 25, pp.183–194.

Perez, R., 1992. Dynamic global-to-direct irradiance conversion models. Ashrae, 98(1), pp.354–369.

Rajagopalan, N., Bilec, M.M. & Landis, A.E., 2009. Comparative life cycle assessment of insulating concrete forms with traditional residential wall sections. In *2009 IEEE International Symposium on Sustainable Systems and Technology, ISSST '09 in Cooperation with 2009 IEEE International Symposium on Technology and Society, ISTAS, Conference Proceedings.*

Reddy, T.A. 2006. Literature Review on calibration of building energy simulation programs: Uses, problems, procedures, uncertainty and tools. *ASHRAE Transactions,* 112, pp.226-240.

Reilly, A. & Kinnane, O., 2017. The impact of thermal mass on building energy consumption. *Applied Energy*, 198, pp.108–121. doi.org/10.1016/j.apenergy.2017.04.024.

Rodrigues, L.T., 2010. *An investigation into the use of thermal mass to improve comfort in British housing*. PhD Thesis, University of Nottingham.

Saber, H.H, Maref, W., Armstrong, M.M., Swinton, M.C., Rousseau, M.Z. & Gnanamurugan, G., 2011. *Numerical Simulations to Predict the Thermal Response of Insulating Concrete Form (ICF) Wall in Cold Climate*, Canada: National Research Council.

Saltelli, A., Tarantola, S., Campolongo, F. & Ratto, M. 2004. *Sensitivity analysis in practice: a guide to assessing scientific models*. John Wiley, Chichester.

SimLab, SimLab 2.2, Reference Manual. Available at: https://ec.europa.eu/jrc/en/samo/simlab [Accessed March 12, 2018].

Singh, M.K., Mahapatra, S., Atreya, S.K. & Givoni, B., 2010. Thermal monitoring and indoor temperature modeling in vernacular buildings of North-East India. *Energy and Buildings*, 42(10), pp.1610–1618. doi.org/10.1016/j.enbuild.2010.04.003.

Wang, S., Yan, C., Xiao, F., 2012. Quantitative energy performance assessment methods for existing buildings. *Energy and Buildings*, 55, pp.873-888. doi:10.1016/j.enbuild.2012.08.037.

APPENDIX

Table A. 1 *Thermal properties of all three wall construction materials included in the analysis (i.e. ICF, HTM, LTM)*

Wall (outside to inside)		Thickness (mm)	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat Capacity (J/kgK)	Diffusivity (mm^2/s)	U-Value (W/m^2K)
ICF Wall	Cement Screed	3	0.8	2100	650	0.586	
	Cement Plaster	3	0.72	1760	840	0.487	
	EPS Insulation	210	0.037	25	1400	1.057	
	Cast Concrete	147	2	2300	1000	0.87	
	EPS Insulation	108	0.037	25	1400	1.057	
	Plasterboard	13	0.21	950	840	0.2632	
Total							**0.113**
HTM Wall	Cement Screed	3	0.8	2100	650	0.586	
	Cement Plaster	3	0.72	1760	840	0.487	
	EPS Insulation	318	0.037	25	1400	1.057	
	Cast Concrete	147	2	2300	1000	0.87	
	Plasterboard	13	0.21	950	840	0.2632	
Total							**0.113**
LTM Wall	Cement Screed	3	0.8	2100	650	0.586	
	Cement Plaster	3	0.72	1760	840	0.487	
	EPS Insulation	318	0.037	25	1400	1.057	
	Plasterboard	13	0.21	950	840	0.2632	
Total							**0.115**

Table A.2 *Thermal properties of floor construction materials included in the parametric analysis.*

Element (from Outside to Inside)		Thickness (mm)	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)
LTM/ ICF Lightweight Ground Floor	Stone Bed Blinding Layer Membrane EPS Insulation Timber Flooring	300 50 5 350 25	1.802 1.73 0.19 0.037 0.14	2243 2243 1121 25 650	837 837 1647 1400 1200
ICF Mediumweight Ground Floor	Stone Bed Blinding Layer Membrane EPS Insulation Mediumweight Concrete Slab	300 50 5 350 150	1.802 1.73 0.19 0.037 0.2	2243 2243 1121 25 600	837 837 1647 1400 840
HTM/ ICF Heavyweight Ground Floor	Stone Bed Blinding Layer Membrane EPS Insulation Concrete Slab	300 50 5 350 150	1.802 1.73 0.19 0.037 2	2243 2243 1121 25 2300	837 837 1647 1400 1000

Table A. 3 *Description of the interior mass material properties included in the uncertainty analysis; mean (μ) and uniform distribution ranges.*

Interior mass material properties		
Thickness	μ	0.5
	U	[0.25, 0.75]
Conductivity	μ	0.2
	U	[0.1, 0.3]
Density	μ	800
	U	[400, 1200]
Specific Heat Capacity	μ	1400
	U	[700, 2100]
Area[34]	μ	8.5
	U	[3.36, 16.8]

[34] The uncertainty range in the area of the interior mass represents a uniform distribution with minimum 10% coverage and maximum 50% of the total floor area of the zone.

Table A. 4 *Description of the material properties included in the sensitivity analysis; mean (μ) and uniform distribution ranges.*

ICF Wall		d (mm)	λ (W/mK)	ρ (kg/m^3)	c (J/kgK)
Cement Screed	μ	0.003	0.8	2100	650
	U	[0.0027, 0.0033]	[0.72, 0.88]	[1890, 2310]	[585, 715]
Cement Plaster	μ	0.003	0.72	1760	840
	U	[0.0027, 0.0033]	[0.648, 0.792]	[1584, 1936]	[756, 924]
EPS Insulation	μ	0.210	0.037	25	1400
	U	[0.189, 0.231]	[0.033, 0.041]	[22.5, 27.5]	[1260, 1540]
Cast Concrete	μ	0.147	2.00	2300	1000
	U	[0.1323, 0.1617]	[1.8, 2.2]	[2070, 2530]	[900, 1100]
EPS Insulation	μ	0.108	0.037	25	1400
	U	[0.0972, 0.1188]	[0.033, 0.041]	[22.5, 27.5]	[1260, 1540]
Plasterboard	μ	0.013	0.21	950	840
	U	[0.0117, 0.0143]	[0.189, 0.231]	[855, 1045]	[756, 924]
HTM Wall					
Cement Screed	μ	0.003	0.8	2100	650
	U	[0.0027, 0.0033]	[0.72, 0.88]	[1890, 2310]	[585, 715]
Cement Plaster	μ	0.003	0.72	1760	840
	U	[0.0027, 0.0033]	[0.648, 0.792]	[1584, 1936]	[756, 924]
EPS Insulation	μ	0.318	0.037	25	1400
	U	[0.2862, 0.3498]	[0.033, 0.041]	[22.5, 27.5]	[1260, 1540]
Cast Concrete	μ	0.147	2.00	2300	1000
	U	[0.1323, 0.1617]	[1.8, 2.2]	[2070, 2530]	[900, 1100]
Plasterboard	μ	0.013	0.21	950	840
	U	[0.0117, 0.0143]	[0.189, 0.231]	[855, 1045]	[756, 924]
LTM Wall					
Cement Screed	μ	0.003	0.8	2100	650
	U	[0.0027, 0.0033]	[0.72, 0.88]	[1890, 2310]	[585, 715]
Cement Plaster	μ	0.003	0.72	1760	840
	U	[0.0027, 0.0033]	[0.648, 0.792]	[1584, 1936]	[756, 924]
EPS Insulation	μ	0.318	0.037	25	1400
	U	[0.2862, 0.3498]	[0.033, 0.041]	[22.5, 27.5]	[1260, 1540]
Plasterboard	μ	0.013	0.21	950	840
	U	[0.0117, 0.0143]	[0.189, 0.231]	[855, 1045]	[756, 924]

APPENDIX E LIST OF BPS TOOLS USED IN THE INTER-MODELLING COMPARISON

Table E.1 *List of BPS tools used in the inter-modelling comparison (in alphabetic order) (IBPSA USA, n.d.; EnergyPlus, n.d., IES VE, n.d.).*

Name	Developer	Origin	Website	Capabilities
DesignBuilder	DesignBuilder Software Ltd	United Kingdom	http://designbuilder.com	Whole building energy simulation Load calculations Parametric analysis and optimization Ratings and certificates Air flow simulation (CFD)
DOE 2.2*	Lawrence Berkeley National Laboratory & James J. Hirsch Associates	USA	http://www.doe2.com/	Whole building energy simulation Load calculations
EnergyPlus*	U.S. Department of Energy (DOE)	USA	https://energyplus.net/	Whole building energy simulation Load calculations Combined heat and mass transfer Illuminance and glare calculations Component-based HVAC
eQUEST*	DOE2.com	USA	http://www.doe2.com/	Whole building energy analysis Loads calculations Comparative results summary
ESP-r*	Strathclyde University	United Kingdom	http://www.strath.ac.uk/esru	Whole building energy simulation Load calculations Combined heat and mass transfer Air flow simulation (CFD) Lighting control analysis using co-simulation with Radiance
IDA ICE	EQUA Simulation AB	Sweden	https://www.equa.se/en/	Whole building energy simulation Load calculations HVAC System selection and sizing Code compliance
IES VE	IES Ltd	United Kingdom	https://www.iesve.com/	Whole building energy simulation Load calculations Ratings and certificates Air flow simulation (CFD) Lighting control analysis using co-simulation with Radiance
Tas	EDSL Tas	United Kingdom	https://www.edsltas.com/	Whole building energy simulation Load calculations Parametric analysis and optimization HVAC System selection and sizing Code compliance
TRNSYS	Thermal Energy System Specialists, LLC	USA	http://www.trnsys.com/	Component-based simulation of of transient systems Whole building energy analysis Loads calculations

* Note: Freeware BPS tools are indicated with a star, all other tools are proprietary software, requiring user-license.

Table E.2 *Calculation Methods and Solution Algorithms used in the different BPS tools (Crawley et al., 2008; Zhu et al., 2012)*

	DesignBuilder	DOE 2.2	EnergyPlus	eQUEST	ESP-r	IDA ICE	IES VE	Tas	TRNSYS
Simulation Solution (Loads, Plant, System Calculations)									
Sequential Calculations		X							
Simultaneous Calculations	X		X	X	X	X	X	X	X
Time Step Resolution									
Hourly		X		X				X	
Sub-hourly	X		X		X	X	X		X
Heat Balance Solution Algorithms									
Surface Heat Balance	X	X	X	X	X	X	X	X	X
Air Heat Balance	X		X		X	X	X	X	X
Zone Weighting Factors		X		X					
Conduction Solution Method									
Frequency domain response methods						X	X		
Conduction Transfer Functions	X	X	X	X				X	X
Finite Difference Solution	X		X		X	X	X		
Internal Convection Coefficient Calculation									
Fixed Convection Coefficients							X		
Variable Convection Coefficients: Dependent on Temperature Dependent on air flow Dependent on CFD-based surface coefficient	 X X X		 X X X		 X X X	 X	 X X X	 X X	 X X
User-Defined	X	X	X	X	X		X	X	X
External Convection Coefficient Calculation									
ASHRAE Simple	X		X				X	X	
TART	X		X						
MoWITT	X		X		X				
DOE-2	X	X	X	X					
Ito, Kimura and Oka correlation					X	X			
User-Defined	X		X		X	X	X	X	X
Long-Wave Radiation Exchange									
Mean Radiant Temperature Model					X	X	X	X	
"Script F" (exchange coefficients between pairs of surfaces)	X		X						
Stefan-Boltzmann law	X		X			X	X		X
Inside radiation view factor			X	X	X	X	X	X	
Combined Conv. And Rad. Coefficients		X		X					
Participation of air emissivity in interior radiation exchange									
							X		
Weather Data									
With the program	X		X	X	X	X	X	X	X
Separately downloadable	X		X	X	X	X	X	X	X
Sky Model									
Isotropic					X		X	X	X
Anisotropic	X	X	X	X	X	X	X		X
User-selectable					X	X	X		X

APPENDIX F MONITORING EQUIPMENT DETAILS

Table E.1 summarises important information on the monitoring sensors and equipment used in the thermal monitoring project (see Section 4.3), along with details for the time-step resolution used in the measurements.

Table E.1 *Monitoring Equipment Details*

Technologies	Measure Parameter	Description	Units	Sensor Tolerance/ Sensitivity	Sensor Location	Time-Step Resolution
Pyranometer	Solar irradiance measurement	Hukseflux SR05 – DA1	1	Calibration uncertainty < 1.8 %	Roof Mounted	1min
In-situ U-Value measurement - Northern elevation	Exterior ICF Wall Temperature (°C)	PT1000	1	0.2ºC	North ICF wall in storage room A of first floor	2mins
	Core ICF Wall Temperature (°C)	PT1000	1	0.2ºC		
	Interior ICF Wall Temperature (°C)	PT1000	1	0.2ºC		
	AC100 High accuracy millivolt amplifier	AC100	1	N/A		
	Heat flux measurement through exterior northern wall	HFP03-05	2	Nominal sensitivity 500 μV/Wm², Expected typical accuracy within +5%/-5%.		
In-situ U-Value measurement - Northern elevation	Exterior ICF Wall Temperature (°C)	PT1000	1	0.2ºC	West ICF wall in storage room C of first floor	2mins
	Core ICF Wall Temperature (°C)	PT1000	1	0.2ºC		
	Interior ICF Wall Temperature (°C)	PT1000	1	0.2ºC		
	AC100 High accuracy millivolt amplifier	AC100	1	N/A		
	Heat flux measurement through exterior western wall	Hukseflux HFP03-05	2	Nominal sensitivity 500 μV/Wm², Expected typical accuracy within +5%/-5%.		

Technologies	Measure Parameter	Description	Units	Sensor Tolerance/ Sensitivity	Sensor Location	Time-Step Resolution
In-situ U-Value measurement - Roof	Exterior Roof Temperature (°C)	PT1000	1	0.2°C	EPS prefabricated roof in storage room C of first floor	2mins
	Interior Roof Temperature (°C)	PT1000	1	0.2°C		
	AC100 High accuracy millivolt amplifier	AC100	1	N/A		
	Heat flux measurement through exterior northerly roof	Hukseflux HFP03-05	2	Nominal sensitivity 500 μV/Wm^2, Expected typical accuracy within +5%/-5%.		
Heat flux data logger	Data logging	PT-104 Platinum Resistance Data Logger	3	N/A	Storage Room A and C	N/A
CO_2 sensors	Room CO_2 concentrations	Telaire 7001 CO2 sensor	6	± 50 ppm or ± 5% of readings up to 5000ppm (beyond 5000ppm not specified).	Ground floor: living room, master bedroom, guest bedroom First floor: living room, bedroom, mezzanine	15mins
Room temperature	Air temperature and relative humidity sensors	HOBO U12 - 011 stand-alone loggers	18	Temperature: ± 0.35°C from 0° to 50°C. RH: +/- 2.5% from 10% to 90% RH	Stand-alone loggers in every room (heated and unheated)	10mins
Small data server	Small data server to act as a central data collection point	Zotac	1	N/A	Storage Room C in first floor	N/A
Door & window opening sensors	Magnetic Door & Window Switch	LightwaveRF Wireless sensors	24	N/A	In every external window and door in the house	N/A
		LightwaveRF Hub to agreggate data from OPEN/CLOSE sensors	1			
Gas boiler kWh output	Heat meter to measure the gas boiler output	Super static 749 QP2.5 3/4	1	Meets the requirements of the European directive 2004/22/EC (MID) and the standard EN 1434 class 2	Installed in the gas boiler.	1sec

Technologies	Measure Parameter	Description	Units	Sensor Tolerance/ Sensitivity	Sensor Location	Time-Step Resolution
MVHR duct air temperatures - Efficiency of the MVHR unit	Air temperature ºC - Inlet (ambient)	PT1000	1	0.2ºC	At the ducts of the MVHR unit	1min
	Air temperature ºC - To diffusers	PT1000	1	0.2ºC		
	Air temperature ºC- Exhaust to atmosphere	PT1000	1	0.2ºC		
	Air temperature ºC- Extract (from rooms)	PT1000	1	0.2ºC		
Weather station	Air Temperature (ºC)	Gill Instruments Maximet GMX500	1	Accuracy ± 0.3°C @ 20°C	Roof Mounted	1min
	Barometric Pressure (hPa)			Accuracy ± 0.5 hPa @ 25°C		
	Relative Humidity (%)			Accuracy ± 2% @ 20°C (10%-90% RH)		
	Absolute Humidity (g/m^3)					
	Wind speed (m/s)			Accuracy ± 3% to 40 m/s, ± 5% to 60 m/s		
	Wind direction (deg)			Accuracy ± 3° to 40 m/s ± 5° to 60 m/s		

APPENDIX G PUBLIC ENGAGEMENT ACTIVITIES AND PRESENTATIONS IN INDUSTRIAL EVENTS

A number of presentations have been given to non-academic audiences in industrial events during the duration of this EngD and they are listed below:

1. ***"Academic Research: The Future of Heavyweight Construction"***, a presentation given in the East Midlands Housing Summit 2014, sponsored by Concrete Block Association, on the 10th of July 2014 in East Midlands Housing Group Conference Centre in Coalville.
2. **"*The Thermal Mass of Concrete*"**, a presentation given in the 2nd Slovenian Conference on Concrete and Sustainable Construction on the 15th of October 2015, in Ljubljana, Slovenia.
3. **"*The effective use of thermal mass in passive building design*"**, a presentation given in Aggregate Industries UK Ltd stand seminars at Ecobuild 2015, on 3rd - 5th of March 2015 in London, Excel.
4. **"*The Energy Saving Potential of Insulating Concrete Formwork*"**, a poster/ leaflet describing the preliminary results of the ICF monitoring study was distributed by the sponsoring company during the MPA Resilient Housing conference on the 3rd November 2016, in London.
5. **"*Introduction to Insulating Concrete Formwork (ICF) and ICF monitoring project*"**, a presentation given in the Concrete & Masonry Pavilion Seminars Programme: Innovations for housing using concrete and masonry at Ecobuild 2017, on the 8th of March 2017 in London, Excel.

6. **"*The Thermal Mass of Building Fabric*"**, a presentation given in one of the sponsoring's organisations CPD events that was held in the Building Centre, London, on the 5th of October 2017.