# INTEGRATED DESIGN SOLUTION OF A RESIDENTIAL STRUCTURAL INSULATED PANEL DWELLING

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# Abstract

In the transition pathway to low carbon construction, the UK Government affirms the legal commitment by setting ambitious targets that legislated for a reduction of carbon dioxide emissions of 34% by 2020 and 80% by 2050, against 1990 base level. This includes reducing the carbon dioxide emissions, associated with energy use in buildings whereas all new homes are required to be zero carbon by 2016. In parallel, there is a pressing need by 2016 to build 240,000 new homes per year at the affordable price to supply for the UK housing shortage. To supply for the needs of affordable and better quality homes, the Government is committed to promote Modern Method of Construction (MMC).

One area where significant development is taking place is through highly insulated and airtight building envelopes. These produce energy efficient designs whilst maintaining a stable thermal condition through low levels of heat loss/gain and air leakage. In addition to reducing the environmental impact of a building, fast-track prefabrication methods have recently been promoted in the UK to speed up the construction process, and reduce wastage and defects. There have been some successes achieved by the use of Structural Insulated Panels (SIPs), a ready insulated and prefabricated product, as part of the MMC that offers positive benefits in energy efficiency.

However, detailed field performance of SIP units are still relatively rare in the UK, and issues related to thermal bridging and other as-built effects on thermal performance coupled to lack of ventilation potential have not been fully assessed. Thus there is a need to monitor SIPs unit throughout heating and cooling cycles to understand what the potential energy demand patterns will be and thus enable suitable design and energy strategies to be developed, optimising the considerable potential benefits SIPs unit provide.

These have been assessed by a systematic post construction evaluation of a SIP based dwelling covering analytical verification, thermo-dynamic computer simulation, and field experimental work. This is the first time that this kind of systematic post construction evaluation of a SIP based dwelling has been undertaken in the UK. Focus throughout was on generating post construction performance data, which have been used to validate and verify models developed in simulation software to understand how gap between design and post construction performance can be closed. Consideration of a SIP based product was particularly important as this solved a number of challenges faced by the UK housing sector, particularly the need for cost effective and energy efficient solutions whose performance under a range of changing conditions or orientations can be predicted.

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# Abbreviations and Acronyms

ACH: Air Change per Hour (ac/h)

BRE: Building Research Establishment

CAD/CAM Computer Aided Design and Manufacture

CERT: Carbon Emissions Reduction Target

CIBSE: Chartered Institution of Building Services Engineers

CIE: Commission Internationale de L‘Éclairage

CfSH: Code for Sustainable Homes

DER Dwelling Emission Rate

DSY: Design Summer Year

EH: ErgoHome building

EST: Energy Saving Trust

EPS: Extruded Polystyrene

HLP: Heat Loss Parameter

IGT: Innovation Growth Team

IES<VE>: Integrated Environmental Solutions <Virtual Environment>

LZC technologies: Low and zero-carbon technologies

MMC: Modern Method of Construction

MVHR: Mechanical Ventilation Heat Recovery

ODPM: Office of the Deputy of Prime Minister

OSB: Orientated Stranded Board

PCM: Phase Change Material

PU: Extruded Polyurethane

SAP: Standard Assessment Procedure

SH: Standard Home (brick and block cavity wall with insulation filled)

SIPs: Structural Insulated Panels

TER: Target Emission Rate

TRY: Test Reference Year

UK: United Kingdom

# Chapter 1: **INTRODUCTION**

With the enactment of the Climate Change Act 2008 legally binding targets of a reduction in greenhouse gas emissions of at least 34% by 2020 and 80% by 2050 from 1990 emission levels are now required (Parliament, 2008). Residential buildings currently contribute around 27% of the UK total $CO_2$ emissions (24% in greenhouse gas emissions) (IGT, 2010). Consequently, the Government has committed to a programme of continuous improvement in building energy performance to ensure new homes built from 2016 onwards will not add any extra $CO_2$ This is driving developers to implement innovative and energy efficient design strategies to generate zero carbon homes by 2016 (DCLG, 2007b).

## *1.1 BACKGROUND*

In the transition to low carbon construction, there have been many challenges in the construction sectors, from legislation, building practices and societal behaviours. With regards to legislative matters, the requirements of thermal performance of building envelope are tighten together with implementing low carbon technologies in order to reduce the building environmental impact. In building practice sector, the lack of labour skills and resources in building practices, the need of supplying affordable homes to fulfil the current housing shortage, and the reluctant to innovations are obstacles to overcome in this new era.

Highly insulated and airtight building envelopes are means to produce energy efficient designs whilst maintaining a stable thermal condition through low levels of heat loss/gain and air leakage. There have been some successes achieved by the use of Structural Insulated Panels (SIPs), a ready insulated and prefabricated product that offers positive benefits in energy efficiency. In fact, it has been claimed that SIP construction can reduce heating costs by up to 60% (Bregulla and Enjily, 2004).

However such claims need careful validation through full assessments of building design, system performance and technologies. With this in mind, a recent Dorothy Hodgkin Postgraduate Awards, joint-funded by the Engineering and Physical Sciences Research Council and E.ON (over 3 ½ years), has been undertaken to understand building performance under the real weather conditions experienced on site without any unexpected interference from occupants. This project is nearing the end and this summary provides an overview of the results obtained.

## 1.2 PROBLEM STATEMENT

Before applying any low/zero carbon technologies that help to cover any energy cost of household appliances, the building envelope is required to provide a comfortable environment at the minimum use of heating/cooling energy. Hence, thermal comfort is taken into consideration together with suitable passive solar design strategies.

A good passive design relies on “build tight-ventilate right” which means constructing an airtight building envelope and supplying the required air exchange rate by natural ventilation design (Perera and Parkins, 1992). This is because losses due to ventilation and general air exchange can account for more than half of the primary energy consumed in dwellings (CIBSE, 2006a). As SIPs construction is an airtight structure, passive ventilation design needs to be sought to provide adequate air exchange through SIPs envelope. A lightweight construction like SIPs (or thermally fast response)is suitable for frequent use like a dwelling or an office. However, the key issue with this type of building is overheating, which is becoming increasingly important under the context of global warming effects that result in extreme hot days in summer (CIBSE, 2005b).

However, detailed field performance of SIP units are still relatively rare in the UK, and issues related to thermal bridging and other as-built effects on thermal performance coupled to lack of ventilation potential have not been fully assessed. Thus there is a need to monitor SIPs building throughout heating and cooling cycles to understand what the potential energy demand patterns will be and thus enable suitable design and energy strategies to be developed, optimising the considerable potential benefits SIPs unit provide.

## 1.3 RESEARCH AIMS AND OBJECTIVES

Possessing many key benefits for an energy efficient construction unit potentially for the domestic sector, SIPs construction built in the UK requires testing and a long-term monitoring. Thus these have been conducted using a test building unit constructed at the University of Birmingham that allows assessment on the thermal performance of the SIPs construction unit. The field data will then be used to calibrate against the computer model via its thermal performance so as to obtain a validated reliable model to test several passive design solutions.

The research aims to provide a framework for holistic evaluation model of SIPs based building from monitoring, simulation, development, and feedback to design for improvement. Through the framework, it enables designers/ developers a thorough understanding of the process for further work in developing evidence based case studies for any alternative building material and system in shifting to low carbon construction.

Using post construction evaluation for investigating SIPs performance and then used for building simulation calibration helps close the gap between design and as-built performance. The study aims to establish a base case for SIPs performance evidencing in promoting MMCs SIPs in new build construction, consequently, it addresses to establish whether a SIPs-based dwelling can deliver a comfortable, energy efficient environment. This includes investigating the impact of adopting passive solar strategies via integrated design solutions on thermal comfort, energy efficiency and cost effectiveness of dwellings in the UK. The dissertation is presented in nine chapters covering background information, literature review, case study for field test and building simulation, implementation of the design strategies for assessing building performance and improvements, cost analysis of the case study, and finally, discussion and implication of the work undertaken and conclusion. The research objectives in line with thesis structure are restated in brief as found in Table 1-1.

Table 1-1: Research objectives and thesis structures

| Research objectives | Thesis content |
|---|---|
| Review the current issues facing the UK housing building sector thus revealing the need of modern method of construction and where Structural Insulated Panels seen as potential key solution to resolve these issues. | Chapter 2 |
| Literature review on SIP building performance, methodology of conducting field test and building simulation, thus develop methodology and strategy monitoring and simulation of the building thermal behaviour. | Chapter 3 |
| Field test work and collecting the performance of the purposed-built unit allowing calibration of the simulation model | Chapter 4 |
| Evaluate the building performance and assess the improvements through implementation of passive solar design strategies | Chapter5 - Chapter 6 |
| Evaluate the economical values of the case study | Chapter 7 |
| Summarise the research results, and present implication of thermal insulation, solar radiation, thermal mass and natural ventilation to energy efficiency measures. The cost factor is also discussed. | Chapter 8 |

## *1.4 SCOPE OF RESEARCH*

In order to meet the aforementioned research objectives, an iterative process through 3 key stages has been adopted throughout simulation, monitoring and development. Field data measuring climatic data and indoor thermal conditions throughout monitoring of a purpose built and instrumented SIPs building over a one-year period has been used to calibrate the model simulation developed in IES<VE> software program. Then the validated model simulation was developed with passive house design strategies applied in a consistent manner to explore potential impacts in reducing heating and cooling energy demands.

For a qualified holistic evaluation of the building performance, the research approach is based on combination of simulated modelling and monitoring of the modular building unit to validate the simulation. Measuring selected environmental parameters provides a reality check for the simulated model and if the simulation can accurately predict the building performance, it increases the developer’s confidence in the model. Thus, integrated design solutions could be applied on the validated model simulation for low energy consumption with average occupancy behaviour and weather pattern. And life cycle costs for buildings are calculated to assess the cost efficiency of energy performance requirements for different design options.

## *1.5 NOVELTY*

This is the first time that this kind of systematic post construction evaluation of a SIP based dwelling has been undertaken in the UK. The results make a significant contribution to the development of the evidence based so desperately needed to help make the transition to a low carbon construction sector in the UK. The focus on generating post construction performance data which are used to validate and verify models developed in thermo-dynamic simulation software helps to address one the most pressing challenges in the required evidence base; namely the need to understand how to close the gap between design and post construction performance. Consideration of a SIP based product is particularly important as it offers the opportunity to solve a number of challenges faced by the UK housing sector, particularly the need for cost effective and energy efficient solutions whose performance under a range of changing conditions or orientations can be predicted.

# Chapter 2: **UK HOUSING CONTEXT**

There is compelling scientific evidence that our climate is changing as a consequence of the greenhouse gas (GHGs) effect (CIBSE, 2005b): p1). In order to tackle climate change, the UK set up a legal framework to achieve, through domestic and international actions, at least a 60% reduction of carbon dioxide emissions (CO2, the greatest contribution to GHGs) by 2050, with the real progress by 2020 to be a 26-32% reduction, against the 1990 baseline (DTI, 2007). This was replaced by a more ambitious target announced by the UK Government in October 2008 for the year 2050 to achieve a 80% reduction and 34% reduction to be made by 2020, against 1990 level (DECC, 2008). This commitment requires all industries to work towards carbon reductions, including the construction industry. In fact, construction activity is estimated to be directly and indirectly responsible for approximately 40% of total CO2 emissions in the UK (IGT, 2010).

Moreover, the UK Government has also highlighted that the domestic sector plays a key role in cutting CO2 emission rates. Indeed, residential buildings in the UK are responsible for 27 % of total carbon dioxide emissions at the rate of 556 Mt CO2 (DCLG, 2007b). In July 2007, the UK Government consequently announced in its consulting document “Building a Greener Future” that all new dwellings will have to be zero carbon homes by 2016 in a bid to tackle climate change (DCLG, 2007b).

In December 2008, the UK Government defined zero carbon homes using a hierarchical approach (DCLG, 2008b):

- Ensuring an energy efficient approach to building design
- Reducing CO2 emissions on-site via low and zero carbon technologies and connected heat networks
- Mitigating the remaining carbon emissions with the selection of Allowable Solutions

In addition, the housing industry has been subjected to a number of governmental reports and initiatives such as the £60000 home programme launched by the Office of the Deputy of Prime Minister (ODPM), in 2004, which addresses affordability of new homes (DCLG, 2006). There is increasing pressure for house builders to provide sustainable and affordable homes at the rate of 240,000 additional new dwellings each year by 2016 (DCLG, 2007c).

This chapter sets out the context of UK housing, especially for new homes, which addresses legislative, technical and social challenges facing house builders and developers. It then discusses several solutions to tackle these difficulties, including Structural Insulated Panels as part of a modern method of construction, which resolves current issues in the housing construction industry, with the material itself helping to reduce building environmental impact. This sets the scene for the work developed at the University of Birmingham.

## *2.1 HOUSING CONSTRUCTION IN THE UK*

The increase of population and reduction of average household size leads housing demand growing faster than supply. Indeed, the overall population of the UK was estimated to be close to 61.4 million in mid-2008 and was projected to approach 73 million by 2036 (DEFRA, 2009). In addition, the average size of households in the UK was 2.32 in 2006 and this was projected to fall slightly to 2.13 in 2031 (DCLG, 2009). In recent years, there has been an increase in the proportion of one person households and lone parent households (e.g. a two people household). Recently released housing statistics about household projections to 2031 in England show 18% of total population in England will live alone compared to 13% in 2006. One person households are forecasted to increase by 163,000 per year, equating to two thirds of the total increase in households (DCLG, 2009).

It is also essential to build more homes to meet the demand and in parallel, making them affordable is required for long term development. Indeed, it is observed that house prices have risen more quickly than earnings in all regions (DCLG, 2007d). As a result of demand being higher than supply, house prices have doubled, in real terms, in the last decade. In fact, it now costs over £210,000 for the average house, which is more than eight times the average salary ((DCLG, 2007d): p10).

In the UK, energy is produced majorly by burning fossil fuels (i.e. oil, gas and coal) and the remaining is primary electricity from low carbon sources including nuclear energy and renewable sources such as wind, hydro and bio-fuels. In 1989, over 95% of energy was sourced from burning fossil fuels that reduced to 91.4% in 2008 and 87.5% in 2011 (DECC, 2012b). An average emission per household is 5.4 tonnes of CO2 as a result of energy used for space heating and cooling, hot water, lighting and appliances (IGT, 2010). With the current number of nearly 27 million homes and the rate of new builds to meet the demand, it is critical to apply energy conservation in line with promoting low carbon technologies to meet the target of reducing carbon emissions.

Additionally, only 40% of new home buyers were satisfied with the quality of their purchase, according to the National Customer Satisfaction Survey in 2003 (ODPM, 2004b). The houses failing to conform to building design specification, or being built to poor specification, were either or both causes of dissatisfaction. These houses were built using traditional constructive method, and conformity failure is caused by uncontrollable factors like exposed conditions when building on site and quality mainly relying on labour skills.

Last but not least, construction activity contributes to environmental stresses with depletion of natural resources (fossil fuels for energy consumption and non-energy minerals for manufacturing building materials), pollution (waste, contaminant released into atmosphere, ground and water) and soil deterioration. It is reported that waste from construction and demolition materials (and soil) equates to 70 million tonnes annually, 13 million of which are delivered to site but never used (DTI, 2004).

In this context, there are a number of challenges, for the house building sector, in terms of legislation, construction practices and acceptance/behavioural issues, as discussed in this section, as regards the targets of cutting carbon emissions and delivering energy efficient solutions.

### 2.1.1 Legislative challenges

The Climate Change Act (2008) sets a target to reduce greenhouse gas emissions by at least 80% by 2050, from a 1990 baseline, in the UK. The Act requires the Government to commit to delivering the carbon budgets, which limit greenhouse gas emissions in the UK. To support this commitment, the broad strategy is laid out in the Low Carbon Transition Plan published by the previous Government and now being considered by the Coalition Government (IGT, 2010). For the residential sector, the strategy includes increased energy efficiency in homes to reduce emissions, all new homes to be zero carbon from 2016, smart energy consumption displays to be fitted to all homes by 2020, plus a major retrofit programme to increase energy efficiency of the existing stock (DECC, 2008).

In the Government Policy Statement “Building a Greener Future” published in July 2007, it was announced that all new homes will have to be zero carbon from 2016. The 2016 zero carbon target is executed by a major progressive tightening of the energy efficiency and carbon reduction requirement of the Building Regulations, with improvements of 25% by 2010, and 44% by 2013, compared to the 2006 Building Regulations (part L), as discussed later in Section 2.2.1.1 (DCLG, 2007b). The zero carbon home is defined as a home where net carbon dioxide emissions resulting from all energy used in the building are zero or better (DCLG, 2008b). The foundation for any zero carbon home is to ensure a high level of energy efficiency of building fabric that minimises energy consumption. Then onsite renewable or low carbon technologies such as photovoltaic, micro combined heat power pumps or micro wind turbine are integrated to achieve carbon compliance. There are also allowable solutions which may be considered when the zero carbon target is unachievable onsite (DCLG, 2008b).

However, the final report of the Innovation Growth Team (IGT) in October 2010 drawn across the UK construction industry to suggest areas requiring collaboration with the Government, addressed several key issues in new build construction. It pointed out that one of the key issues is to deliver a practical and workable definition of “zero carbon” on a nationwide basis (IGT, 2010). Indeed, an unclear definition of “zero carbon” has been seen as the most significant legislative barrier to house builders as indicated by the survey responses (Osmani and O’Reilly., 2009). The responses from house builders showed they were unsure about the requirements such as the need for provision of onsite renewable technologies that requires appropriate guidelines.

The IGT report also suggests a requirement to conduct whole life carbon appraisal covering embodied and operational, in assessing the feasibility studies based upon a realistic price of carbon (IGT, 2010). Energy consumption in the construction industry results from the production of buildings, including materials and construction procedure and through the usage phase of the buildings and facilities. Operational energy is concerned with the energy consumed by people in the building, which is influenced by occupant behaviour, building energy performance, and the energy efficiency of the building system and household appliances. Embodied energy refers to the energy consumed in extraction, manufacture, and transportation of the building materials and building demolition, which is counted as operational energy in the industrial and transport sectors. To achieve the carbon appraisal, a standard method of measuring embodied carbon, for use as a design tool, should be agreed between the industry and the Government (IGT, 2010).

The Government response to the IGT report in June 2011 provides a focus and framework within which the responses are to be taken forward, together with the actions. The response reaffirmed the legal commitment to low carbon construction of ambitious targets for applying zero carbon standards, from 2016, for new homes and from 2019 for non-domestic buildings as being set out in 2007 (UKGovernment, 2011). The Government sets out further key steps for future actions (i.e. publish an updated Carbon Plan) as well as clarifying and assuring certainty to stimulate investment in low carbon and growth, through a strengthening partnership with the UK Construction industry (UK Government, 2011). In these challenging contexts, there is an increasing need for new builds to cope with the shortage in housing, since the demand has grown faster than supply. This issue was addressed in the UK Government's green paper "Home for the future: more affordable, more sustainable". A target to deliver three million new homes by 2020, two million of which were set to be built by 2016, before the target of zero carbon homes comes into effect (DCLG, 2007d). That requires building 240,000 additional homes each year until 2016, which addresses energy efficiency and affordability issues according to the UK Government publication "The Callcutt review of house-building delivery" (DCLG, 2007c). The green paper also addresses tackling affordability pressures in parallel with increasing the provision of housing. This covers developing more affordable homes to rent or buy and supporting young people and families to get their first home with a low mortgage rate (DCLG, 2007d).

In a bid to tackle how low carbon construction can be funded and be made affordable, the Government has developed a package of incentives to remove financial barriers in reducing carbon emissions. The Carbon Emissions Reduction Target (CERT), an energy and carbon saving scheme, which commenced in April 2008 placed an obligation on energy suppliers to meet the household carbon saving target. In May 2010, the Government announced an extension of CERT to December 2012, paving the way for the Green Deal, a new and ambitious approach to home energy efficiency (DECC, 2010). The Green Deal is expected to create a new financing mechanism which allows installation in individuals' properties of a range of measures (i.e. loft insulation, heating controls and so on) at no up-front financial cost.

Significant changes in construction methods are mandatory in an attempt to reduce carbon emissions from the built environment, as stated in the IGT report. Changes are required in all areas, from design and planning of new buildings and infrastructure, materials, products and processes, as well as maintenance and management of these built assets. Thus new practices and technologies demand new skills and the application of current expertise in new ways.

Modern Method of Construction (MMC) (See Section 2.2.2.1), differentiated from traditional methods in house building, have been promoted by the Government with the aim of speeding up housing provision to meet demand (Corner et al., 2005).The Housing Corporation sponsored by ODPM set a target of 25% new homes to be constructed by MMC and it also looked at the implication of the use of MMC on the quality of design in social housing schemes. The English Partnership sponsored by the ODPM encourages MMC across its programmes. In 2005/6, English Partnership launched the Design for Manufacture Competition, to demonstrate that good quality homes can be built at a cost of £60000. Housing associations have been strongly encouraged to apply MMC ((DCLG, 2006) and (EST, 2005a): p3).

### 2.1.2 Building practice challenges

The construction industry in the UK has not seen significant change for the last 100 years. The traditional construction method in the UK is generally understood as a masonry structure, double skins of brick or block since about the1920s, with insulating material filling the cavity between the double skins of houses built since the1970s due to an energy crisis (Hens et al., 2007). Prior to 1919, the date of double skin masonry introduction, homes in the UK had been built as solid wall constructions with permeable fabric that both absorbs and readily allows the evaporation of moisture. It is reported that 22% of all dwellings were built before 1919 equating to around 4.7 million homes of the current stock and it still remains that a proportion of the 1920 - 1945 stock has similar characteristics to pre 1920s buildings (EHCS, 2009). The number of dwellings with cavity walls increased from 13.2 million in 1996 to 15.5 million, equating to 70% of the housing stock, in 2007 and 7.3 million of which were insulated (EHCS, 2009).

As discussed in the previous section, there is a need for significant changes in construction methods in all areas to reduce carbon emission from the built environment. However, there is a reluctance to innovate. Indeed, change can be difficult to introduce and the adoption of new construction methods requires a significant shift in attitude. Traditional construction methods are still the most widely used in the UK, as a consequence of reluctance to adopt excessive design changes and to traditional attitudes maintained within the building sector. Indeed, house builders tend to use a range of standard house sets, along with their development, in order to reduce costs and defects, according to a study which investigates the factors stopping sustainable building in England (Williams and Adair, 2007). Another study about MMC barriers showed that house builders are likely to support traditional methods due to lack of knowledge, skills and experience, and the low level of applying these technologies. It is stated that one barrier to the use of MMC in housing comes from the need for more organisational and methodical skills onsite, more involvement of computer aided design and manufacture (CAD/CAM) rather than artisanal skills in the traditional method (Gaze et al., 2007): p5). William and Adair (2007) also identified that there was an unwillingness to implement new sustainable materials, or products across the building sector. Such conservative attitudes which restrict the uptake of innovation are perceived as lack of demand for sustainable properties amongst the general public and a lack of requirement for sustainability from clients (Williams and Adair, 2007 and WWF, 2004).

In 2005, CITB Construction Skills published an analysis report about labour and skills needs, which suggested a skill shortage based on quantification of the size of the built sector and existing traditional building craft skills levels and needs (CITB- Construction Skills, 2005). In fact, 94% of local authorities reported, in January 2004, recruitment and retention difficulties and 80% of built environment professional service firms faced a lack of skills in their existing staff (DCLG, 2007d). However, there is no evidence that houses have not been built due to lack of labour. Though the training of new operatives has not yet been compensated for the current rate of those leaving the construction industry, the shortfall in operatives could be partly filled by inward immigrants (Gaze et al., 2007). Indeed, in July 2011 CITB-Construction Skills also revealed a recent poll of 1,450 construction employers, to indicate skills gaps such as understanding the implications of green issues (43%), identifying potential new business (39%) and not having sufficient IT skills (43%), were all areas picked out by industry managers and supervisors amongst these organisations.(CITB- Construction Skills, 2011). These gaps become a significant barrier in construction development whilst working towards sustainability and modernisation of construction methods.

While new technologies and new products can significantly contribute to achieving the “zero carbon” target, the survey suggests the supply chain as a major barrier in making this target achievable using the today’s technologies (Osmani and O’Reilly., 2009). With the aim of addressing the challenges and opportunities in shifting to a low carbon economy, the IGT identified the reason preventing the supply chain from innovating, offering new technologies and services, or investing in skills as the lack of demand from the market (IGT, 2010). Thus, in the Government response to the IGT report, the Government is liable to create a framework of incentives and interventions that will deliver the desired carbon reduction, while maintaining a healthy market capable of sustained growth and improvements in productivity (UK Government, 2011).

The IGT report suggested that further pilots and trials should be encouraged and monitored throughout, through greater collaboration, to ensure delivery of the rollout strategies. The response from government is whether to create a mechanism to allow companies to voluntarily differentiate the performance of their products, which is beyond the market standard, to drive innovation over time. Sufficient resources are needed for the government and building industry to research and develop appropriate and cost effective technologies. In term of research and innovation, one key issue in energy efficient products lies in the performance gap measures between “in-situ” and laboratory tests. The IGT indentified a number of critical research areas such as ongoing monitoring of new build and retrofitted buildings to assess actual performance against modelled prediction, research into consumer demand and behavioural studies, and knowledge transfer activities for data and practical experiences. The government will provide a framework which is sufficiently responsive to allow new evidence of performance to be incorporated.

### 2.1.3 Social challenges

There have been significant changes in the house building sector, as previously discussed, which requires increased attention on building energy consumption, energy efficiency measures and renewable technologies.

According to the UK Office for National Statistics Opinions Surveys, it was found that 76% of the public expressed concern over climate change issues (ONS, 2009). However, the value of low carbon and associated benefits may not be apparent to individuals and motivated consumers can be prevented from acting due to financial constraints. In addition, it is observed that there is an “empirical regularity” known as the “energy efficiency gap” between expected investment and real consumption in energy efficiency because consumers appear to undervalue future fuel savings from improved energy efficiency, relative to other decisions (Jaffe and Stavins, 1994). It is important, whilst shifting to a low carbon economy, to increase social awareness about climate change, legislation and current issues because this is one of the key factors driving the market demand for low carbon products. People need to be informed about the benefits and incentivised to request low carbon solutions and make optimal use of them.

Energy consumption in buildings is driven by the interaction between the building envelope the energy consuming systems providing thermal comfort, other energy consuming appliances and occupant behaviour. Energy savings can be through the adaption of poor thermal comfort (e.g. keeping the room temperature lower than a desired level or discontinued usage of the heating system) or investing in energy efficiency products. A well designed building badly run can perform poorly. Thus a culture change needs to accompany low carbon solutions to assist occupiers in simplifying building operational control.

It is suggested that prefabrication or MMC is subject to client scepticism due to negative connotations of system housing during the post-war period. The use of prefabricated systems in reconstruction in Britain (i.e. precast concrete with flat or pitched roof on steel frame or wooden frame), was encouraged from early 1960s to help accelerate house supply programme (Bullock, 2002). However, the rust from steel-framed or rot from wooden-framed prefab houses became problematic at the footing of the structure, pointing out the weakness of these early prefab homes. Besides, existing prefab houses from post-war builds are unlikely to be aesthetically pleasing. Also in 1968, the collapse of Ronan Point, a 22 storey tower block in the London Borough of Newham brought their use in high rise building to an end (Bullock, 2002).

In 2003, the Building Research Establishment (BRE) published the introduction of MMC referring to offsite construction or prefabrication, highlighting that “with developments in lightweight, high strength materials and modern production techniques, prefabrication has much to offer today’s construction industry” (Stirling, 2003: p1). It was acknowledged that the material manufacture was not as good as it is now and that high quality standards and longer lifespan of materials were envisaged. Additionally, there were two basic forms of prefab building systems in the post-war period: cross-wall and box-frame, both of which allow largely glazed and relatively lightweight construction (Bullock, 2002). With modernisation of construction methods, CAD/CAM helps to deliver highly building design specifications and affordability whilst reducing building environmental impact with energy efficient building fabric integrated with low carbon technologies.

## *2.2 NEW BUILD PRACTICES*

The UK Government has set an ambitious strategy to increase energy efficiency in housing, coupled with decarbonisation of energy supply to progress towards the 80% reduction of CO2 emission by 2050 compared to 1990 level. As the energy and carbon performances become more challenging, it leads to the need for consistent and transparent assessment of technical resources to deliver the right solution for different projects for given site conditions. It is therefore essential to set a limit on design specifications and building construction as a standardised approach applicable for most situations, as discussed in Section 2.2.1. Construction method, life cycle assessment and passive design practices are briefly discussed in Section 2.2.2 with regards to current practices.

### 2.2.1 Regulatory Compliances and Building Standards

Building Regulations apply to either new buildings or refurbishments of existing buildings within a range of domestic, commercial and industrial properties (England and Wales only). They deal with all aspects of the building construction (i.e. technical guides range from Parts A to P), energy efficiency and accessibility for all people. Regarding the purpose of building energy performance for new dwellings, this work is concerned with the Building Regulations part L1A: Conservation of fuel and power in buildings for new dwellings and Part F: Ventilation - Means of Ventilation, looking at ventilation strategies (i.e. trickle ventilators and extract ventilation performance).

The new 2010 Building Regulations part L1A and F1 documents became enforceable on the 1st October 2010, as the most recently effective documents. They set minimum standards that address, incrementally, energy efficiency performance towards zero carbon targets. Indeed, the 2010 part L1A energy efficiency standards for new homes should deliver a 25% reduction in carbon emissions in comparison with the standards set in 2006 part L1A. For future changes to energy efficiency standards, the time scale set for working towards zero carbon homes is a 44% reduction in CO2 emissions in 2013 (from 2006 level) and zero carbon homes from 2016 onwards. The annual energy savings of a building are estimated using the Standard Assessment Procedure (SAP), as discussed later in Section 2.2.1.2, to demonstrate building compliance. The current version SAP 2009 is used in operation with the 2010 Building Regulation part L1A whereas the SAP 2005 was used previously in 2006 part L1A.

#### *2.2.1.1* Building Regulations – Approved Documents part L1A

As this work is concerned with thermal performance and energy consumption, it focuses only on the limiting fabric parameters set by the Building Regulations. The Approved Document part L1 is specific to dwellings, with L1A concerned with new dwelling and L1B targets existing dwellings. Part L sets minimum standards for insulation values of building elements, air permeability of the structure and controls efficiency for heating appliances and systems together with hot water and lighting. Part L also sets out the requirements for Standard Assessment Procedure calculations as referred to in the Carbon Emission Targets for dwellings, for compliance with cutting carbon dioxide emission rate.

There was not a significant change in terms of limiting the fabric parameters set in 2010 part L1A compared to 2006 part L1A as shown in Table 2-1. The U-value measures the rate of heat loss through a building element, and the air permeability value expresses the volume of air that passes through the building envelope at the test condition of pressure difference. A detailed explanation of the meaning U-value, air permeability value and thermal bridging can be found in Appendix A.3.1.

Thermal bridges occur within the building envelope formed by geometry (e.g. at the junction between two or more building elements) or change in structural composition of building element (e.g. column in a wall). The control of thermal bridging heat loss was first introduced in 2006 Building Regulations and SAP 2005 as a result of tightening U-value to reduce total heat losses. The thermal bridges in construction of building fabric should be limited as much as possible, thus part L is supported by the use of Accredited Construction Details (DCLG, 2007a). By applying these tried-and-tested details to the mean of limiting air leakage and thermal bridging in construction, expensive onsite testing can be avoided. In the case of unaccredited construction details, a conservative default value Y-value of 0.15 W/K is used. In improved standards, the thermal bridging value for an accredited construction details can be 0.08 W/K and if fully complying with EST Enhanced Construction details, it can be 0.04 W/K (EST, 2010). Air permeability value, referring to uncontrolled ventilation heat transfer, becomes more significant in building practice as a result of tightening requirement for conductivity values of building elements. However, anecdotal evidence suggests that UK workmanship is poor and that there is a performance gap between design and construction and airtightness is key concern (Oliver (2001), Doran (2000)). In fact, it is reported that the UK mean airtightness value is 11.5 $m^3/(m^2h)$ at 50 Pa for the current housing stock of masonry dwellings, built by traditional methods.(Stephen, 2000).

Table 2-1: Limiting fabric parameters as set in 2006 and 2010 Building Regulations Approved Document part L1A (ODPM, 2006) and (DCLG, 2010a)

| **Building elements** | **Limiting fabric parameters** | |
|---|---|---|
| | 2006 | 2010 |
| External wall, U-value ($W/m^2K$) | 0.35 | 0.3 |
| Floor, U-value ($W/m^2K$) | 0.25 | 0.25 |
| Roof, U-value ($W/m^2K$) | 0.25 | 0.2 |
| Party wall, U-value ($W/m^2K$) | n/a | 0.2 |
| Windows, roof windows and doors, U-value ($W/m^2K$) | 2.2 | 2.0 |
| Air permeability at 50 Pascal, $m^3/(m^2h)$ | 10 | 10 |

There have been improvements of the standards contained from 2002 Part L1A to 2006, and to the most recent one, 2010 part L1A, for new dwellings regarding energy efficient fabric parameters. However, it is important to recognise that even the most recent fabric standards set by Building Regulations still lag behind those in many other European countries. Taking the airtightness standard as an example, the 2010 UK Part L1A requires 10 $m^3/(m^2h)$ at the test condition of 50 Pascal air pressure difference, while this value is 3 in Sweden since 1981. In Germany, the range is from 1.8 to 3.8, and for Passivhaus standards, it is only 1.0 (EST, 2010: p 44). Therefore, investment in labour skills training and development and modernisation of construction method are issues to be addressed for better enforcement in standards to bridge the gap in the UK.

#### *2.2.1.2* Standard Assessment Procedure (SAP)

In the UK, the SAP is adopted by the government as a widespread methodology for calculating the energy performance of residential buildings. SAP calculations are mandatory for any new-built dwelling, to indicate the building's compliance with the Building Regulations part L. The government released SAP 2009, v9.90 to be used in compliance with 2010 Part L1A from October 2010 (SAP2009, 2010).

SAP uses the values Dwelling $CO_2$ Emission Rate (DER), Target Emissions Rate (TER) and Heat Loss Parameter (HLP), to assess a dwelling. To show compliance with the Building Regulations, the DER of a building, as designed, should not exceed the TER value, whereas TER is an overall $CO_2$ emission target of the notional building. It is stipulated that the notional building is used as reference for constructions of the same size and shape as the actual building, constructed to concurrent specification and no improvement factor (SAP2009, 2010). The HLP combines the impact of the insulation value of the construction, the external surface area and the airtightness level of the assessed building. These values are the foundation of the Code for Sustainable Homes as discussed in Section 2.2.2.1.

The SAP rating relies on four indicators of energy performance known as: energy consumption per unit floor area, an energy cost rating, an environmental impact (EI) based on $CO_2$ emissions, and a Dwelling $CO_2$ Emission Rate (DER). The energy cost rating (or SAP rating) is expressed on a scale from 1 to 100 where a dwelling with a rating of 1 has poor energy efficiency, hence very high running costs, while a dwelling with a rating of 100 represents a completely energy efficient dwelling and zero net energy cost per year. The EI rating scale has been set so that EI 100 is achieved at zero net emission and can rise above 100 if the dwelling is a net exporter of energy. The DER is used to show compliance with the Building Regulations and the energy consumption per conditioned floor area informs the estimated consumption level of the designed dwelling.

The SAP calculation is based on an energy balance, taking into account a range of factors that contribute to energy performance, such as insulation and construction materials, fuel used for building systems (space heating, domestic hot water, lighting and ventilation/or cooling system if applicable), efficiency and control of the heating system, ventilation characteristics and renewable energy technologies (BRE, 2009). The emissions from energy consumption are established from a standard occupancy and standard heating pattern, independently of the heating behaviour of individual households. SAP uses a steady state calculation that assumes all variables are constant with each time step to be more detailed; thus it improves accuracy though it does not include feedbacks within the system. There are other influential factors including highly efficient gas boilers for space heating, usage of low energy lighting and applying a natural ventilation strategy to improve energy efficiency and the SAP rating.

In order to address the ambitious government target of delivering 2016 ZCH, there are a number of voluntary building standards that have been launched with the minimum standards set by the Building Regulations. The following sections from 2.2.1.3 to 2.2.1.5 present three standards which are related and well known in house building sectors listed as: Code for Sustainable Homes; Energy Saving Trust: Energy Efficiency Standards; and Passivhaus.

#### *2.2.1.3* Code for Sustainable Homes

In response to the report of the Sustainable Building Task Group, in July 2004, the government announced the development of the Code for Sustainable Homes (CfSH), a preliminary outline of the Code launched in the beginning of 2005. In December 2006 the CfSH was launched and made available on 10th April 2007 as a voluntary environmental assessment method for all dwellings in England, Wales and Northern Ireland. The code replaced the EcoHomes standards, which are still in used in Scotland. It was made mandatory from May 2008 to set standards for assessing new homes at both the design stage and post construction, with nine key sustainability issues. These are: energy and carbon dioxide emissions; water usage; materials; surface water run-off: waste (site and household); pollution; health and well-being; site management; ecology and land use. Each new build has its own assessment rated against the Code and given a certificate, ranging from Level 1 to Level 6, depending on performance. There is, however, no requirement to reach a specific level and a nil rating certificate can be issued if a code assessment is not carried out. It is required that new housing, funded by the government and its agencies such as English Partnerships and the Housing Corporation, need to meet CfSH (i.e. at least Level 3). New dwellings on sale are also required to provide a CfSH certificate (DCLG, 2008a).

Central to the CfSH are the energy efficiency and $CO_2$ emissions of new homes, which are embedded in a mandatory section of the CfSH in which minimum standards must be met in order to become accredited. The CfSH is considered as a pathway towards achieving zero carbon homes. Indeed, 2010 Part L1A aims to reduce $CO_2$ emissions by 25% over the 2006 document. This is a 40% improvement over a dwelling built to comply with the 2002 version. This corresponds roughly with the trigger point for the CfSH Level 3, in line with the governmental strategy for getting newly built dwellings to zero carbon by 2016. The standards set by the CfSH, will be gradually implemented through compulsory changes to the Building Regulations. Consultations are currently ongoing (DCLG, 2007c). However, the proposals involve incorporating level 4 (44% improvement) in 2013 before finally moving to zero carbon homes by 2016 (DCLG, 2007c).

The final aim is to achieve CfSH level 6, for new buildings, as legally binding from 2016 onwards. From the Code Level 4, the improvements are not only achieved by incorporation of solar passive design features but also by the reduction of heating demand to a point that a traditional heating system will not be required (i.e. with improved performance so solar passive design and micro-generation could be adequate). In order to achieve the mandatory requirements of CfSH Level 4, it is possible to use the fabric first approach which is discussed in the Energy Saving Trust publication “Fabric first” in the 2006 and 2010 editions (EST, 2010). By focusing only on fabric and service improvement, additional credits in ENE2 which covers the heat loss parameter (HLP) of the dwelling, will be added to offset the credit lost by not using low and zero carbon (LZC) technologies. It is noted that HLP is a measure of all the heat loss pathways per unit area, so it is calculated by the sum of U-value, thermal bridging, ventilation and air leakage losses, divided by the total floor area. In order to achieve CfSH Level 6 or ZCH, the CfSH specifies that any domestic energy required must be generated from renewable sources.

Table 2-2 shows the fabric limited values for different code levels which further exceed the current Building Regulations, observing that the minimum level (i.e. CfSH level 1) is slightly improved to the 2010 part L1A (See Table 2-1 and Table 2-2). The CfSH uses the star system to rate properties with one star representing a 10% improvement over the 2006 Building Regulation part L1A and six stars equating to a ZCH.

Higher standards of airtightness could result in the need to install highly efficient mechanical ventilation systems to maintain indoor air quality and thermal comfort. According to a study investigating the use of Passivhaus standards in the UK, it is believed that with a good design, applying natural ventilation strategies is more suitable than a mechanical system due to the milder climate and lifestyle (Schiano-Phan et al., 2008). It is acknowledged that the SAP calculation gives a higher rating for houses with mechanical ventilators rather than well designed passive low energy features thus it is fair to state that CfSH does not account for passive house design features.

Table 2-2: Fabric limited parameters for different Code for Sustainable Homes levels

| | **Limiting fabric values via different levels of CfSH** | | | |
|---|---|---|---|---|
| Building element | CfSH 1/2 | CfSH 3 | CfSH 4 | CfSH 5/6 |
| External wall, U-value (W/m$^2$K) | 0.3 | 0.26 | 0.2 | < 0.1 |
| Floor, U-value (W/m$^2$K) | 0.22 | 0.19 | 0.14 | < 0.1 |
| Roof, U-value (W/m$^2$K) | 0.22 | 0.19 | 0.14 | < 0.1 |
| Windows, glazed doors, U-value (W/m$^2$K) | 2.0 | 1.6 | 1.2 | < 0.8 |
| Air permeability at test pressure difference at 50Pa, m$^3$/(m$^2$h) | 3.0 | | 1.0 | |

#### *2.2.1.4* Energy Saving Trust Practices

The Department of Trade and Industry (DTI) established the Energy Saving Trust (EST) in 1993 and it has become one of the UK leading organisations targeting the damaging effects of climate change. In order to achieve the sustainable and efficient use of energy and to reduce carbon dioxide emissions, which are a key contributor to global warming, in the residential sector, the EST promoted Energy Efficiency Best Practice in Housing (EEBPH). The EST provides guidance in achieving higher levels of energy efficiency in new dwellings in England, Scotland and Wales using standards that exceed the current Building Regulations. The standards cover Good Practice, Best Practice and Advance Design, the specifications of which offer an integrated package of measures on how to achieve dwelling performance better than the legal minimum covering all aspects of new build and refurbishment (EST, 2003a).

The Good Practice Energy Efficiency (GPEE) delivers a package of measures that will meet the legal minimum (i.e. 2010 part L1A) and slightly improved performance in addition. The Best Practice Energy Efficiency (BPEE) employs the best established, cost-effective products and practices which have been tried and tested to avoid undue risk. Above these two practices, the Advanced Design addresses sustainability issues and aims to minimise environmental impact (EST, 2010). In terms of fabric requirements across these design practices, Table 2-3 lists the maximum permissible fabric values for exposed elements (EST, 2003a).

Table 2-3: Specification of building fabric values across EEBPH practices

| **Building element** | **GPEE** | **BPEE** | **ADEE** |
|---|---|---|---|
| External wall, U-value (W/m$^2$K) | 0.35 | 0.25 | 0.15 |
| In Scotland | 0.3 | | |
| Floor, U-value (W/m$^2$K) | 0.25 | 0.20 | 0.10 |
| Roof, U-value (W/m$^2$K): | | 0.13 | 0.08 |
| Pitched roofs:- Insulation between rafter | 0.20 | | |
| - Insulation between joints | 0.16 | | |
| Flat roofs | 0.25 | | |
| Windows, glazed doors, U-value (W/m$^2$K): | | 1.8 | 1.5 |
| - Metal frames | 2.2 | | |
| - Wood or PVC frames | 2.0 | | |
| Air permeability at the test pressure difference of 50Pa, m$^3$/(m$^2$h): | | 3 | 1.0 |
| For dwelling with Heat Recovery Ventilation | 4 | | |
| For dwelling with other ventilation systems | 7 | | |

With working towards zero carbon guidance, in the EST publication "Energy efficiency and Code for Sustainable homes level 5 and 6", the U-value requirements for external wall and floors is 0.15 W/m$^2$K and for a roof structure 0.13 W/m2K (EST, 2008). Windows must achieve a British Fenestration Rating Council rating in band A (U-value for whole windows, including frame factor, is around 1.5 W/m$^2$K). In terms of construction quality, the maximum permissible air permeability is 3 m$^3$/(m$^2$h) at 50 Pascal and thermal bridging is limited with the encouraged usage of the EST Enhanced Construction Details.

#### *2.2.1.5* Passivhaus

The term "Passivhaus" refers to a low energy construction standard developed by Dr Wolfgang Feist, of the Passivhaus Institute in Germany, in the 1990s. It is defined as "A Passivhaus is a building, for which thermal comfort can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air" (BRE, 2012). Since 1991, the Passivhaus Institute in Darmstadt has established principles and targets for low energy housing through research and monitoring of such housing.

The Passivhaus concept has received much attention in recent years, and indeed it is often stated that a Passivhaus is the ‘equivalent’ to a CfSH Level 4. This is not entirely true, mainly because the Building Regulations, and hence the Ene1 section of the Code for Sustainable Homes, set a target in terms $CO_2$ emissions whereas Passivhaus sets a maximum space heating demand in terms of energy use. As a result, direct comparisons are problematic. However, it should be remembered that all new dwellings, including Passivhaus dwellings, require an Energy Performance Certificate (EPC) and hence still require a SAP2009 assessment.

The PassivHaus standard consists of three elements: energy limit (i.e. heating and cooling demand) of less than 15 kWh/m$^2$ per year, a quality thermal comfort (i.e. indoor operative temperature in winter is maintained at 20°C), and a defined set of passive system allowing energy limit and quality requirement to be met cost effectively. The PassivHaus standard is summarised in Table 2-4.

Table 2-4: Passivhaus design features

| | |
|---|---|
| Compact form and good insulation | All components of the exterior shell of a PassivHaus are insulated to achieve a U-value that does not exceed 0.15 W/m$^2$K |
| Energy-efficient window glazing and frames | Windows (glazing and frames, combined) should have U-values not exceeding 0.80 W/m2/K, with solar heat-gain coefficients around 50%. |
| Building envelope air tightness* | Air leakage through unsealed joints must be less than 0.6 times the house volume per hour (this is the equivalent of an air permeability value of less than 1 m$^3$/m$^2$h at the pressure difference of 50 Pascal |
| Highly efficient heat recovery from exhaust air using an air-to-air heat exchanger | Most of the perceptible heat in the exhaust air is transferred to the incoming fresh air (heat recovery rate over 80%). |
| Hot water supply using regenerative energy sources | Solar collectors or heat pumps provide energy for hot water. |
| Passive preheating of fresh air | Fresh air may be brought into the house through underground ducts that exchange heat with the soil. This preheats fresh air to a temperature above 5°C even on cold winter days. |
| Energy saving household appliances | Low energy refrigerators, stoves, freezers, lamps, washers, dryers etc are indispensable in a PassivHaus. |
| Total energy demand for space heating and cooling | Less than 15 kWh/m$^2$ per year |

*The airtightness result in Passivhaus standard uses a term $n_{50}$ refers to the number of air change per hour (unit: $h^{-1}$ or ac/h). It differs to the air permeability result $q_{50}$ measured leakage rate in $m^3/h.m^2$ which is irrespective of building volume.

A detailed study of Passivhaus performance in the warm climate of southern Europe, which is published by the Passivhaus Institute, shows that double glazing is acceptable in more temperate climates and movable external shading is essential. There may be a need for active cooling and dehumidification and energy consumption for additional cooling demand, which should be equal to or less than 15 $kWh/m^2$ per year (BRE, 2011). The Passive-on project delivers a revised proposal for Passivhaus standard application in southern Europe but also addresses the UK and France in a “warming” climate (Passive-On, 2012). Several features are listed, as cooling energy demand should not exceed 15 $kWh/m^2$ per annum and the airtightness result at a reference pressure difference of 50 Pa should be no more than 0.6 ac/h. For locations with a milder winter (i.e. winter design ambient temperatures above 0°C), a higher airtightness value of 1.0 ac/h is in most cases sufficient to achieve the heating criterion (i.e. heat energy does not exceed 15 $kWh/m^2$) (Passive-On, 2012).

## 2.2.2 Reducing building environmental impact

Reducing building environmental impact could be achieved by modernisation of building construction activities through promoting modern methods of construction (MMC), using recyclable/reusable materials, applying good passive design, then integrated with suitable and allowable low carbon technologies.

### *2.2.2.1* Modern Methods of Construction in housing (MMC)

The MMC refers to a number of construction methods that differ from traditional masonry construction, including off-site construction, factory-built, system building and prefabrication (Gaze et al., 2007). MMC takes in a number of forms in today’s construction listed as volumetric units, panellised systems, hybrid construction, sub-assemblies and components, and site based innovative methods as defined by the ODPM (ODPM, 2004a). Volumetric assemblies can provide a complete three dimensional factory-built room or group of rooms, with limited dimensions due to transportation to site so the complete buildings are constructed more quickly. Panellised systems refers to manufactured built flat panel units using purpose-made jigs or machinery to ensure dimensional accuracy and are transported to site for assembly. The construction system could be steel, concrete, composite or timber (timber framed dwelling with studs or Structural Insulated Panels). The hybrid method is the combination of volumetric and panellised for stacked modulus units (e.g. kitchens or bathrooms). Sub-assemblies and components are factory built items for replacing part of the structure onsite. The site based innovative method uses sustainable/recyclable materials on site in modern process, that differs from traditional onsite construction (e.g. insulated concrete formwork) (Stirling, 2003).

Applying MMC can lead to improved performance by means of reduced assembly times onsite, increased control over onsite processes and improved quality. A study conducted by the National Audit Office in November 2005 showed that the use of MMC could bring in the following benefits in comparison with traditional building methods: four times as many homes to be built with the same onsite operatives, the construction time reduced by over a half;  performance at least as good as traditional build (Corner et al., 2005). The cost of prefabricated assemblies could be initially higher but the overall project cost could be reasonably comparable to a conventional construction project as a result of speed, control and large prefabricated components.

#### *2.2.2.2* Passive design

Passive design may be considered in the context that domestic energy consumption required 38.842 million tonnes of oil equivalent in 2011 accounting for 26% of the total UK primary energy consumption. This is 5% higher than 1970 but slightly lower than other years in between, but 20% lower than in 2010 as a result of unusually high level of consumption driven by colder temperatures in 2010 and warmer temperatures than usual in 2011 ((DECC, 2012a: p1). Energy use in the home includes space heating, water heating, lighting, cooking and operation of electrical appliances and the rise in energy usage is likely given with the increase in the number of households. The heating demand is dominant in energy consumption in residential buildings, with space heating and hot water accounting for 60% and 18% of the total domestic consumption respectively ((DECC, 2012a) and (DTI, 2002)). Passive solar design employing the freely available, unlimited and pollution free source of energy is therefore a vital solution for low energy buildings.

Energy efficient building design integrates three general approaches: energy efficient building envelope, which is highly resistant to heat transfer; good passive design; and employing renewable energy resources. Passive design aims at the optimal use of free energy from the sun in the form of solar heat gain, daylight and wind power to reduce requirements for heating, ventilation, lighting and cooling. Developed from vernacular architecture, which lost ground over the last couple of centuries while modern technologies (concrete, glazing materials) have prevailed, passive design is further developed with modern technologies from the traditional concept (Oliver, 2004). Taking account of the site factors, including microclimate (environmental conditions driven from local topography, landscaping and prevailing winds) and location (orientation and surroundings), passive design considers form and fabric of the building regarding the ratio of height to length and glazing to floor area, together with mass conditions. In today's context, passive design will then be integrated with active design which refers to environmental services that consume energy from fossil fuels and/or renewable sources to deliver the desired performance (of heating, cooling, ventilation and lighting) efficiently and at a low consumption rate. The interactions of building occupants with the building itself and its service systems are also taken into account for evaluation of the whole building performance.

The key strategy in passive design is to design and build according to the climate where the building is located. The task of designers is to interpret the climate in ways the building is in harmony with the site environment. The UK climate has been recognised as "cold, wind and wet of the relative long cool season" (Thomas, 2006): p53) thus the primary concern via passive design has focused on providing sufficient heating demand for residential building. With the new tendency of rising temperatures affected by climate change, the added task of meeting cooling requirements challenging designers, especially for free-running houses (e.g. ventilation system only includes extract fan that there is no active cooling system). Employing passive design requires careful consideration as each design solution improves one condition but worsen another. For instance, the design working effectively in heat provision may cause thermal discomfort in the warm season and the system providing natural cooling for the house could have greater heat loss in winter.

#### *2.2.2.3* Life cycle assessment

Throughout a building's life, the building in use requires the highest amount of energy consumption, approximately 83% of total $CO_2$ emission that construction industry can potentially influence which accounts for 47% of the total UK emissions (IGT, 2010). Manufacturing accounts for the largest amount of emissions within the construction process (15% over a building lifespan). However, for low energy new built homes, the operational energy consumption (energy consumption in use) can decrease thanks to highly insulated envelope with extremely low levels of heat loss and air infiltration. These measures contribute in increase in energy use for the production phase. Several studies on low energy houses have revealed that the energy for production can account for between 40 – 60% of the total energy use ((Crowther, 1999) and (Nielsen, 1995)). Another comparative study showed that even the operational energy was significantly reduced and energy for production slightly increased, the total energy usage over a building lifetime was still lower than a building with high operational usage (Feist, 1996).

Figure 2-1: Broad phase of a building's life cycle (IGT, 2010)

Minimising the carbon emissions over the lifespan of a building becomes critical. The approach of using life cycle assessment is important in building design as it takes a holistic view of a material, a product or whole building over its entire life. As a basic structure is expected to last as long as a lifespan of the building (50 years, 100 years or longer), other elements like windows, cladding, heating system which have shorter life spans are required to be replaced. The impacts of these replacements add into the total building impact over lifetime. The end of life includes demolition, recycling, reuse and waste disposal thus to reduce its impact, the recycling capacity of building materials is important.

Building materials today are required to have dual benefits that not only they provide easy to maintain buildings of highly energy efficiency but also reducing the amount of embodied energy in their production. The embodied energy refers to energy consumption for extract, process, supply the materials under consideration. If supposing the embodied energy for waste was calculated that waste was generated from new building materials, the potential energy saving through recycling could be up to 50% of the embodied energy. Likewise the emission of energy related pollutants, the $CO_2$ emission are concerned over the building span, given under notion as embodied carbon.

*<u>Operational energy and associated carbon</u>*

Operational energy is the amount of energy use when the building is occupied to respond to occupant demand regarding thermal comfort and everyday activities. Figure 2-2 depicts the primary energy consumption by end use in domestic buildings since 1970s, reviewed by Energy Consumption in the UK (ECUK) which brings together statistics from variety of approved/reliable sources. Energy consumption for space heating takes the major part and depends on the environmental conditions indoors which are majorly driven by external environment conditions and the performance of building envelope (partly caused by efficiency and losses from heating system). The usage is then followed by water heating, lighting and appliances and finishes with the lowest and slightly decreased consumption from cooking. Such consumptions are mostly driven by occupant behaviour (i.e. driven factors are usage patterns and societal expectation) and the energy efficiency of household appliances.

It is obvious that energy use is influenced by number of occupants and the conditioned floor area of the dwelling. The term “conditioned floor area” in relation to energy use in dwellings refers to the total floor area being heated and/or cooled which excludes any enclosed spaces like storage, attic and garage. However, there seems to be a minimum annual energy use in dwellings that is independent to either number of occupants or conditioned floor area (DECC, 2011): p14).

The number of people in a home, and the home’s floor area both influence energy use. However, dwellings seem to have a minimum annual energy use that is not related to the number of occupants or floor area. How people use energy in their homes is usually more significant in shaping consumption than either household size or the size of the dwelling.

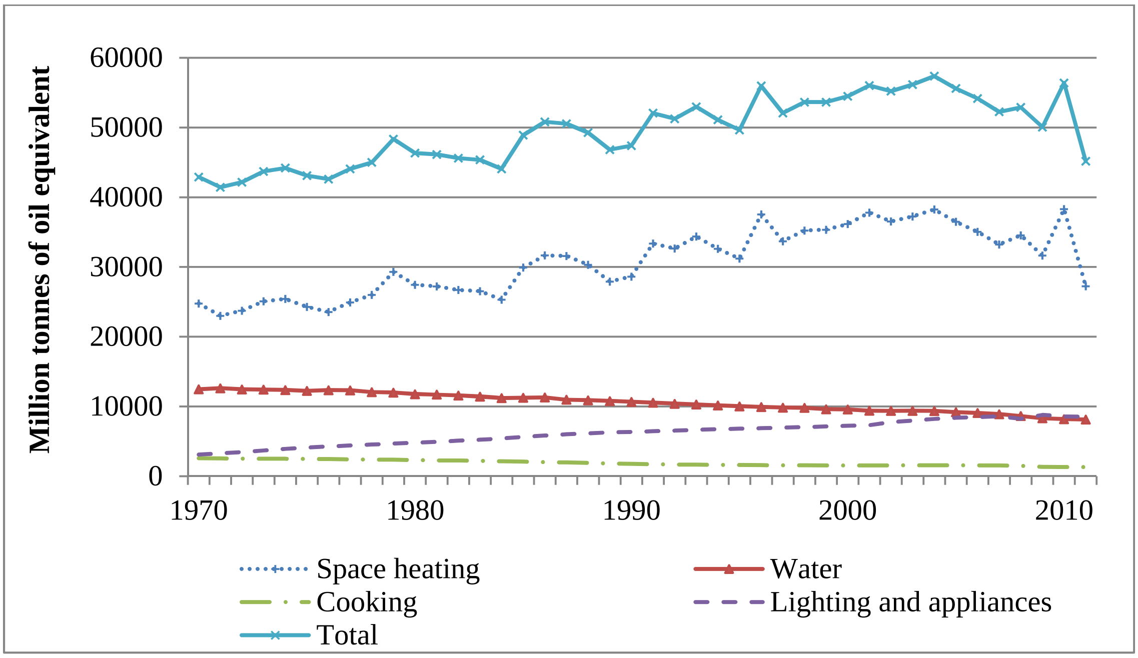


Figure 2-2: Domestic final energy consumption in the UK from 1970 to 2011 - ECUK: Table 3.6 (DECC, 2012b)

For the 50 year life cycle consideration, several studies found that operational energy was between 83 and 94% of the overall energy use (Cole and Kernan, 1996) and (Blanchard and Reppe, 1998). As illustrated in Figure 2-3, the embodied energy is swamped in comparison with operational energy in almost all building types over 50 years life cycle energy usage. For this reason, concentrating on operational energy as main subject for energy conservation and emission reduction is obvious at the initial stage. However, in low energy buildings and in working towards zero carbon homes for new built from 2016, the contribution of embodied energy/carbon increases and needs to be taken into account at the design stage.

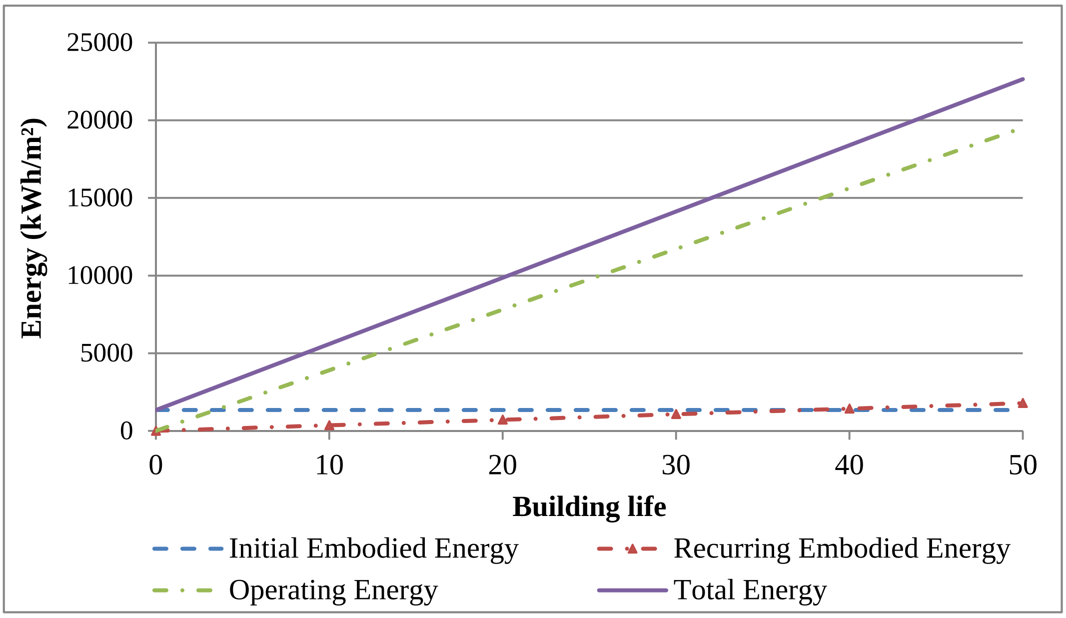


Figure 2-3: Energy profile for most type of building over the 50 year life cycle energy use (Cole and Kernan, 1996)

### *Embodied energy and carbon*

There is an obvious need for reliable data of embodied energy and carbon of construction components and systems. A comprehensive source of embodied energy and carbon of materials in use in the UK is the Inventory of Carbon and Energy (ICE) which use a live database of open source references and publicly available, written by Professor Geoff Hammond & Craig Jones (Hammond and Jones, 2011). With consideration of building materials or products over their life time, the ideal approach for embodied energy would take account of all energy in primary form from the extraction of raw materials until the end of the product lifetime. Energy consumption over the whole process includes manufacturing, transport, manufacturing capital equipment, heating and lighting of factory, maintenance, disposal or recycle and this is known as “Cradle-to-Grave” approach. However, the approach “Cradle-to-Gate” has become more common practice which accounts all primary energy until the product leaves the factory gate as the transport from factory to the construction site is considered separately due to variability. Besides, the last approach known as “Cradle-to-Site” includes all energy used until the product is delivered to the construction site. Likewise, the emissions ($CO_2$) of energy related pollutants refer to embodied carbon.

Embodied energy data are generally given in terms of gigajoules per tonne or megajoules per kilogram (GJ t−1/ MJ/kg) of material. However, in order to assess the embodied energy of an element (e.g., external wall or floor) in the context of a building design, the mass of each material (e.g., steel or cement or wood) in a square metre of the element is multiplied by respective embodied energy values. The sum of these individual material components constitutes the initial embodied energy of the element expressed in ($GJ/m^2$) element area. Embodied energy data in ICE carry at higher accuracy as it was directly monitored while embodied carbon data were majorly not collected and estimated by ICE authors from the typical fuel mix in relevant industries in the UK. The embodied carbon should be considered in addition to operational energy for a full whole life carbon which becomes as important a mean of appraisal as zero carbon future should deliver. A product that delivers zero operational emissions may raise the embodied emissions thus a whole life emissions should be the assessment basis. The choice of building materials has a significant impact on low energy building.

Figure 2-4 compares different materials for the main components in a typical house. Timber frame dwelling which uses as much timber as possible would release the least carbon during the process because the sink effect that carbon is “locked up” in the materials. As observed from the ICE database concern, the steel and aluminium emit far more $CO_2$ in their manufacture than reinforced concrete.

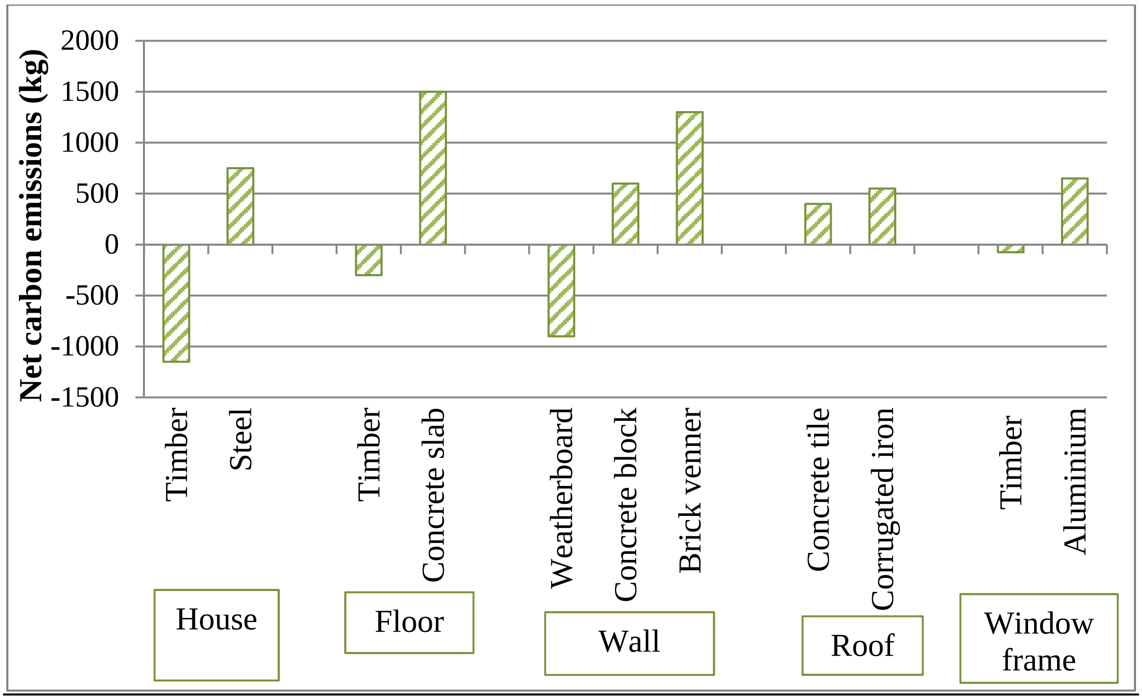


Figure 2-4: Comparison of carbon emissions from different materials of building components (Yohanis and Norton, 2002)

For a typical building construction¸ the contribution of embodied energy from major building elements is estimated as shown in Figure 2-5. It is quite obvious for green building design to go for timber frame rather than steel frame building structure or concrete structure to obtain less carbon penalty for building design. Also for highly insulated building envelope, the increase in embodied energy due to the use of more insulation is significantly small in comparison with the energy embodied of the whole building structure.

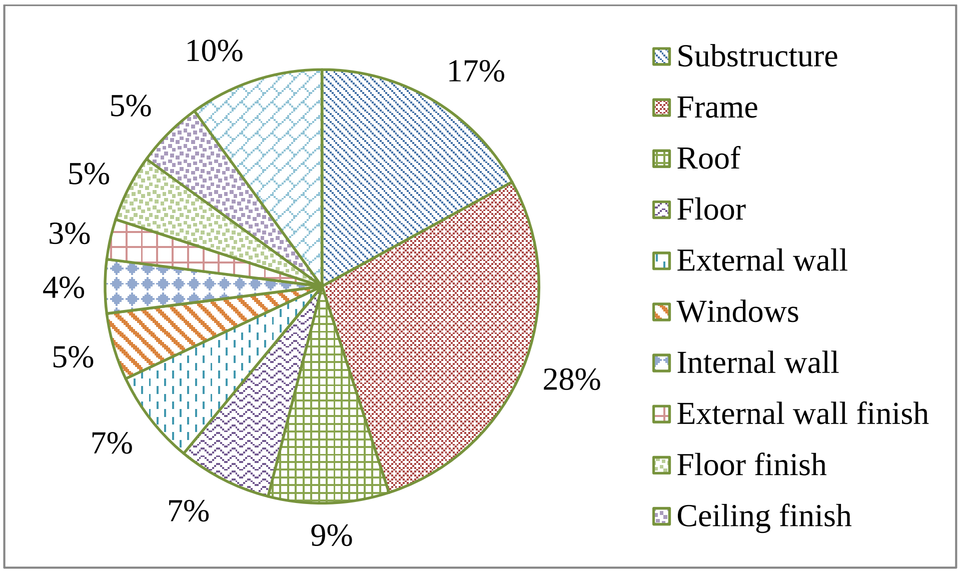


Figure 2-5: Percentage distribution of embodied energy in major building elements (Yohanis and Norton, 2002)

## *2.3 STRUCTURAL INSULATED PANELS*

Structural Insulated Panels (SIPs) is light weight, off-site manufactured and used as principal loadbearing components. The panels are made by sandwiching a low density, cellular core rigid insulation between two skins of wood based panels, typically orientated strand boards (OSB) ((Bregulla and Enjily, 2004: p1). The foam core of the panel is typically composed by extended polystyrene (EPS), polyurethane (PU), extruded polystyrene (XPS), polysio-cyanurate. Between the three layers, there is a strong structural bond between the three layers created during lamination process. Such structural adhesive is essential to loadbearing ability of SIP that high loads can be transmitted without the use of timber studs. Once laminated, the panels are manufactured to meet the design specifications then they can either be shipped onsite for building or in the manufacture plant to build a volumetric unit as a whole then deliver to onsite. Figure 2-6 illustrates the composition of a typical SIP element. In either ways, SIPs support MMC and inherits all benefits from applying MMC as presented in Section 2.1.2.1.

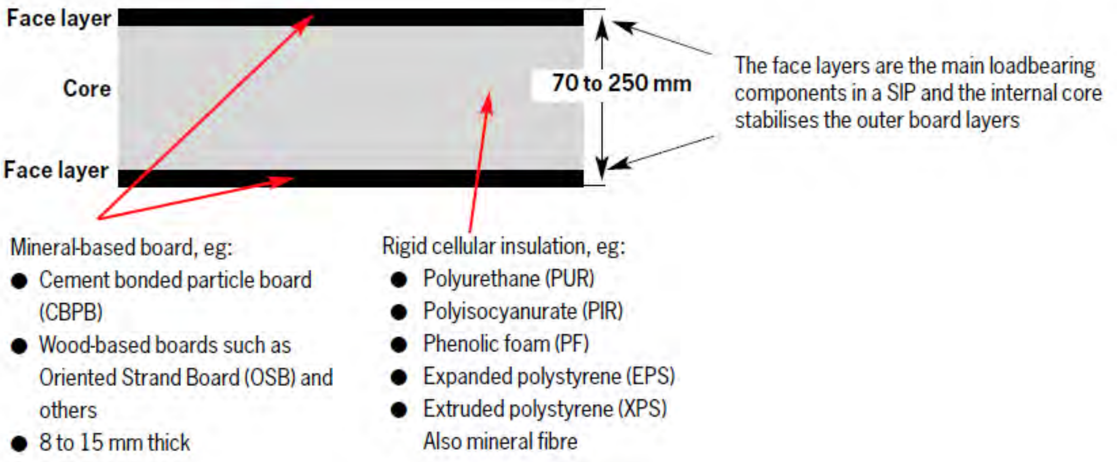


Figure 2-6: Cross section of a typical SIP (Bregulla and Enjily, 2004).

### 2.3.1 Benefits

Applying MMC panelised system - SIPs which are offsite and fast track constructive method helps to solve the alerted shortage in housing and labour skills. In fact, the manufacturing process of SIPs is fully integrated with the computer aided design which enhances flexibility, accuracy of the design specifications for the actual construction onsite. Being custom fabricated to each project, CNC cutting machines allow the creation of any shape/form panels making SIP built project unlimited to any architectural creativity, reducing complex measuring and mathematics onsite (SIPA and

APA, 2007). Besides, SIPs are manufactured for mass provision of standard or designated panels thus able to supply more homes at affordable price. In addition, SIP as a ready insulated product which combines three stages of conventional shell construction: framing, sheathing and insulating reduces dramatically erection time and labour in comparison with conventional method. Thus, using SIP simplifies the construction process, requires less skilled labour onsite and assures high quality of design specification for house building. Indeed, it is demonstrated from the time and motion study conducted by RSMeans team that the use of SIP resulted in significant time and labour cost savings, of 45% labour hours less compared to conventional construction (RSMeans, 2006). .

In addition, SIP is environmental friendly product. Being highly design specification, SIP manufacturing uses efficiently material resources hence minimises construction waste. OSB is wood product which is a renewable, recyclable and biodegradable source. According to the life cycle assessment conducted by Consortium for Research on Renewable Industrial Materials (CORRIM), there was a scientific validation that wood was a green building product and was better for the environment than steel or concrete in terms of embodied energy, global warming potential, air and water emissions, solid waste production (Puettmann and Wilson, 2005). Also, the insulating core, both EPS and PU are made using a non chlorofluorocarbon (CFCs) blowing agent, with acknowledgment that CFCs emissions from building materials and the use of refrigerators cause ozone depletion. And the production of lightweight insulating foam composed of 98% air only requires a relatively small amount of petroleum (SIPA and APA, 2007). Furthermore, an additional benefit of wood construction is the carbon which is 'locked up' in wood products for the life of the building.

Importantly, the use of SIPs enhances high performance buildings. The development of SIP in reducing building environmental impact is achieved by its anchor point of energy efficiency because reduction in energy use leads to reduction in carbon dioxide emissions, thus having smaller impact to the environment. The strong bond between core insulation and two skins of OSB that assures loadbearing capacity allows no internal studding within SIP structure. And the rigid insulation foam which cannot shift provides a constant and uniform thermal insulation within a building structure. These features of SIPs enable structure to be assembled with a small fraction of framing thus provide minimal thermal bridging compared to timber frame dwellings or other construction types. With the heating loss due to thermal bridging in traditional dwellings up to 30% of the total energy loss, minimise thermal bridging issue in building is essential. The thickness of core insulation can vary to provide a range of thermal resistances that comply with a range of design requirements and allow flexible design specifications.

Besides, as SIP building structure are assembled from components to manufacturing tolerance and connections are ensured by both tightly fitting with overlapping plasterboard linings and sealing techniques, a high level of air tightness can be achieved thus resulting in a positive effect in energy efficiency. While fibreglass and other low density insulating materials are subject to gap, voids or compression which leads to degradation of thermal performance (e.g. higher air leakage rate, risk of condensation and mould growth). Thus, SIP makes establishing a whole house air barrier simple and effective ((SIPA and APA, 2007): p4). The need for new dwellings to provide an airtight envelope and controllable ventilation either naturally or mechanically can be referred to Appendix A.3.2. It is stated that SIP homes built in the US have proven to reach the levels of infiltration rate as low as 0.03 air change per hour (ac/h or h-1) consistently enough for the Environmental Protection Agency to remove the required air leakage test in complete SIP building envelope to receive ENERGY STAR rating (i.e. standard for energy efficient consumer product originated in the US) (SIPA and APA, 2007). It is notified that the airtightness level in the UK, is described by the leakage rate measured by $m^3/(m^2h)$, such unit is irrespective of building volume (See Section 2.2.1.1). Therefore, a SIP building envelope with highly insulated and airtightness levels has been claimed to reduce annual heating costs by up to 60% (Bregulla and Enjily, 2004).

In fact, the BASF corporation – a chemical company has published a comparative study between different insulating systems of a residential building (i.e. SIPs using PU, SIPs using EPS, two stick frames with fibreglass with different timber fraction) over a building’s life cycle (Uhlman, 2008). Amongst these, SIP using PU requires the least amount of resources, causes the lowest total emissions and lowest global warming potential because it is high insulating value and low air leakage, leading to the lowest energy requirement for heating and cooling the home over its lifetime.

### 2.3.2 Drawbacks

There are several drawbacks in promoting the use of SIPs known as it requires special skills to work with and building SIPs needs to be designed carefully as it is sensible to water and leak problems because OSB is vulnerable to moisture. Besides, the implication of SIPs requires key decision to be made very early in development process (i.e. building types, forms and specialist input) as it is design freeze at early stage. Additionally, SIP is perceived as more expensive than traditional materials (e.g. masonry, concrete, timber framed with studs)

Furthermore, there have not yet any British or European Standards for designing SIP construction systems. As a consequence, the performance of SIP structure is determined through testing. Another barrier is that SIPs as lightweight construction system is exposed to the risk of being overheated. In fact, SIPs form a highly insulated and airtight building envelope that provides temperature buffering. Thus it achieves sharp reduction in reducing heating loads but worsen the occurred overheating in summer. There is therefore a concern regarding increased overheating risk in lightweight buildings under projections for future climate change effect. Indeed, it is projected that climate change is expected bring more periods of extreme hot weather in summer: the raised mean summer temperatures are followed by a heat wave of four day period, during which the peak temperatures are around 35 C (Hulme et al., 2002). This matter worsens due to the high airtightness level of the SIP envelope that requires a good ventilation strategy or installation of air conditioning is obliged to ensure thermal comfort which defeats the benefits of heating savings of SIPs.

### 2.3.3 Knowledge gap

As discussed in Section 2.1.1, it is required in research and innovation activities to conduct ongoing monitoring to assess the actual performance of the buildings against the modelled predictions. As SIP offers improved thermal performance, low embodied energy and carbon emissions, it is considered as a potential material which reduces the building environmental impact. Besides, promoting MMC by using SIP construction helps resolving shortage in housing supply and labour skills.

In addition, changes in building regulations meant an increase in insulation levels in the effort of reduce energy demand for heating leads to a rising risk of overheating. Homes built using certain MMC configurations (SIP included) that do not incorporate thermal mass are more sensitive to any alteration in heating and cooling energy inputs. Indeed, it is reported that overheating risk increases as a result of increasing levels of insulation and decreasing on thermal mass level in not just summer but also spring and autumn (Orme and Palmer, 2003). The modelling work carried on to identify peak temperature and degree hours in four houses types then investigates the influence of each possible measure to alleviate the overheating. The study found that the more highly insulated house presents 16% increase in overheating hours in comparison to the base case dwelling set in the Building Regulations (Orme and Palmer, 2003). However, the overheating risk could be resolved by implementing a combination of passive cooling techniques. The case studies showed a reduction of 70% of overheating degree hors and that the internal temperatures stayed 2.5 C lower than the external temperature through using the combination of mass, night cooling, solar protection and reduced internal gains (Orme and Palmer, 2003: p29). Or another study looked at eliminating overheating risk by number of cooling socio-technologies traditionally employed such as shading from the sun, thermal mass to stabilise temperature, passive heating and cooling systems and afternoon siestas (Hacker et al., 2005).

There is therefore a rising need of conducting overheating risk assessment for SIP construction. SIPs have been used in all kinds of climates, in hurricane zones and earthquake belts but, in the relatively tame UK, SIPs were perceived to be just a little bit too expensive to bother with. But the benefits of reduced construction cost with less time building and less labour and reduced energy cost from lower operational energy by improved performance should be taken into account. Whether the total construction cost of SIP building is lower than conventional building, it depends on the considered circumstances, including local labour conditions and the degree to which the building design is optimized for one or the other technology. For a full comparison of SIP construction with any other building materials, a life cycle cost is required.

It is then identified that the knowledge gap is as below:

- SIP is potentially a building material which helps reducing the building environmental impact. However, there is a lack of evidence of real performance of SIP construction in the UK. As a solution of MMC, a question of whether SIP ensures to bridge the gap in performance existing in the traditional constructive method.
- Overheating risk in lightweight construction has been perceived to be an issue and SIP with good insulation and airtightness levels might result in worsening the condition. With the temperature getting warmer, there is a greater risk of overheating inside UK houses as most of them rely on natural ventilation for cooling design. Thus, it is important to investigate the overheating risk in SIP

construction with integrated passive design solutions (ventilation, shading and thermal mass).

- SIP is perceived to be more expensive than traditional building materials and its benefits in energy savings are somehow still hidden to the customers who show more interest in putting insulation in cavity (wall and roof loft) to meet the Building Regulations. Thus a cost benefit study to compare typical construction using SIP and traditional building material is needed to demonstrate their cost implications.

## *2.4 SUMMARY*

The house building industry is under pressures of shortage in housing supply and labour skills, poor quality of current housing stock built by traditional methods, need of affordable homes. These emerged by mandating improved energy efficiency by Building Regulations and UK Government's legal binding of carbon emission reduction with zero carbon homes built from 2016 onwards. This urges developers to implement innovative and energy efficient design strategies to generate zero carbon homes by 2016.

Some success has been achieved by the use of SIP, a composite of wood and insulation material, which have much improved thermal properties when compared to traditional materials like brick, block. In addition the use of less traditional material allows offsite construction and ease of assembly, thereby providing potential to significantly reduce embodied impacts, both in the short and long term. Reductions occur in the short term through easier construction using light weight materials and long term through enhanced thermal performance throughout the year. It is also interesting to note that with controlled and highly precise design and manufacturing through MMC, SIP assures good quality of building design specifications. Thus SIP construction can deliver the fabric energy efficiency target with highly insulating and airtight levels or at least meets the minimum standard set in the Building Regulations.

However, there is likely a resistance to promote SIP as part of MMC in house building sector. This comes from lack of understanding and reluctance to innovate (e.g. applying CAD/CAM, utilising building performance and energy simulation tools), skepticism towards MMC and lightweight building construction. These issues should be addressed through trainings, developing methodical and organisational skills for operative engineers. Besides, successful demonstration projects promoting MMC and SIP will give confidence for designers and house builders to work together to deliver good quality and affordable homes and towards building zero carbon homes by 2016. Indeed, it is very rare to find short-term or long term monitoring of a SIP building envelope yet to allow being fully assessed. This issue is addressed in the research work through presenting a detailed field performance data of SIP construction units, including thermal performance, issues related to thermal bridging and other as-built effects on thermal performance coupled to lack of ventilation potential leading to overheating risk.

# Chapter 3: **LITTERATURE REVIEW**

This chapter starts by giving a background of previous studies, experiences and methodologies which allows understanding and investigating the building thermal performance. Through mapping out what have been done, it introduces the novelty of this project, contribution and benefits into the fast moving facet of the UK construction industry.

Early decisions made in a design process have a key impact on energy consumption, price and cost of each building as well as comfort for living inside. Simplified design methods such as design guidelines, rules of thumbs or the use of degree days used for estimation of energy consumption and carbon dioxide emissions, have the limitation only providing approximate results. Degree-days calculations can be carried out manually or within computer spreadsheets providing transparency, thus offers preference as relative ease and speed of use. However, the predictions vary largely from reality, sometimes unreliable due to a number of simplifications related to average conditions (internal temperatures, casual gains, air infiltration rates, etc.). In addition, advanced energy-efficient techniques can individually solve a building issue (e.g. minimise heating/cooling demand or alleviate overheating problem) but often raise other concerns (e.g. moisture and ventilation). Thus a holistic approach of integrating different design solutions is needed for delivering energy efficient design solutions and bridging the gap between predicted and actual performance. Besides, thermal analysis typically requires many calculations (e.g. heat transfer process, irradiance, air flow) which might discourages designers and practitioners in taking account of evaluating energy consumption and emissions in building design, particularly in domestic sector.

Building simulation is an attempt to emulate the real physical conditions in a building by creating a model that ideally represents all energy flow paths in a building as well as their interactions (Clarke, 2001). By using a building simulation tool, users can specify in details which parameters influencing the building performance from which predictions of building performance can be made and improvements can specifically be determined. Integration helps to provide a holistic performance prediction of co-operating design solutions, and visualisation enhances the feel of the design for decision making (Clarke, 2001). For a qualified holistic evaluation of building performance, the research approach is based on combination of simulated modelling and monitoring of test units to validate the simulation. Indeed, the model provides information of generalised energy performance of a building while basing on average occupancy behaviour and typical weather patterns (US Department of Energy, 2005). Monitoring of a building is used to inform the as-built performance under on-going weather conditions. The field data from monitoring a building can be used to calibrate against computer simulation which increases the faith of reliability of the simulation model. Thus development on further improvements and optimisation on energy efficiency and cost effectiveness can be carried out in working towards reducing the building environmental impacts and delivering a good number of affordable homes meeting the demand.

Section 3.1 is devoted to previous studies and the novelty of the project. Section 3.2 gives the background for the design of experiment and measurement methods, and reviews several previous studies executing these methods. The last section discusses the suitable approaches for assessing thermal performance of a test building used for the research project.

## *3.1 SIP BUILDING PERFORMANCE*

There have been a number of wide ranges of completed projects employing SIP construction methods in the UK as being demonstrated in several cases studies at the BRE Innovation Park, BASF Homes at the University of Nottingham (Rodrigues, 2010), and other projects promoted by UK Structural Insulated Panels Association. These case studies are illustration of the application of SIP technologies in building social housing, hotel/ school and self-build dwellings. However, there is a lack of evidences of as-built thermal performance of SIP construction. Indeed, energy savings and reduced $CO_2$ emissions were drawn from simplification methods using heating degree-days method and the design value of the element alone without taking into account of all the other components that go into making a wall. These could lead to less accurate predictions and result in significant gap of real building impact to the environment. Current challenges and issues for UK housing builder as discussed in Chapter 2 make it important to develop a methodological framework in achieving energy conservation in buildings. Research in monitoring and integrated computer model of SIP construction is therefore needed thus providing a holistic picture of the SIPs building thermal performance.

### 3.1.1 Previous studies

From the material perspective, a life cycle assessment conducted by BASF compared four insulating systems for application in residential housing SIPs using EPS, SIPs using PU Foam, timber frame construction: 2x4 stick build with fibreglass batt insulation, and 2x6 stick build with fibreglass batt insulation (Uhlman, 2008). By comparing newer construction techniques (both EPS and PU SIP) to traditional (in the US) timber frame with wood studs insulated by fibreglass, the study highlighted environmental and cost benefits of SIP techniques outweigh the traditional techniques thanks to heating and cooling energy savings over the life-time of the building. This was based on the predicted energy consumption using simplification methods. Amongst the four systems, PU SIP also has a higher thermal resistance and low air leakage thus leading to the most energy efficient alternative. Both SIP techniques are consistently the most eco-efficient technology according to the life-cycle assessment for four systems, PU and EPS SIP offering low environmental impact and high thermal efficiency over the lifetime of the building (Uhlman, 2008).

Two modular office units of 49 square metres floor area were tested at the National Renewable Energy Laboratory in the US to compare the thermal performance of building using SIP techniques compared to timber frame construction (Judkoff et al., 2000). Both units were initially tested under the controlled steady-state conditions in the NREL large-scale environmental enclosure. They were then moved outdoors for thermal testing of building units in-situ. Experimental techniques included blower door test, tracer gas test, infrared imaging test, co-heating test and heating/cooling sequences. The study concluded that primary advantage of the SIP construction compared with frame construction was the reduction in envelope thickness and air leakage. In fact, the results of air pressurisation/depressurisation test showed that the SIP unit has a leakage area of one third that of the timber frame unit. Tracer gas test showed that the number of air exchange in SIP unit is steadier at around 0.2 ac/h whilst varying between 0.4 and 0.6 ac/h in timber frame unit. Portable electric heaters were used during March – May 1994 whilst air conditioning test taken place between June and August 1994. Electricity used for heating in SIP modular unit is 299 kWh during 12 days test against 524 kWh in timber frame unit. Regarding cooling performance during one week monitoring in July, the average daily electric energy usage for air conditioning was 12.2 kWh for the frame unit and 8.9 kWh for the SIP unit (Judkoff et al., 2000)

Another study by Dr Tony Shaw at Brock University called “Side-by-Side Study Proves SIP Advantage” with support from National Research Council of Canada (Thermapan, 2012). The work involved evaluation of two identical semi detached homes built adjacent to each other, one constructed with SIPs and one conventionally framed with studs and fibreglass batt insulation (or 2x6 stick build with batt insulation). The test included thermal images, air pressurisation test and a range of temperature sensors inside two units. The results of the air leakage tests showed the SIP house to be much tighter than the timber framed house: 1.55 ac/h at 50 Pa pressure difference against 2.60 ac/h. And the building thermal images provided visual confirmation of areas of thermal weakness in the stick build where thermal bridging is visible around each stud. Data from the temperature sensors showed that SIP wall maintained much higher temperature at the same sensor location.

Earlier testing and monitoring attempt was made to compare two SIP houses and one timber framed house (2x4 stick build) which were all single storey, slab on grade, similar in size with conditioned floor area of 102 square metres. The testing and monitoring was conducted by three developers Armin Rudd, Bob Abernethy, and Wayne Nelson in 1998, in Plains, Georgia (SIPA, 1998). The air pressurization results showed a 1.8 ac/h for SIPs buildings, against 5.3 ac/h of timber framed dwelling at the pressure difference of 50 Pa. These three comparative studies demonstrated a high level of airtightness of SIP building envelope and their results are steadier in different building sizes and locations while timber framed buildings is less controllable.

Other cases studies of comparison between EPS SIP and timber framed with fibreglass batt were using heating degree-days methods, with different heating sources at different locations. The case study of identical floor plan of 95 square metres homes heated by the supply of natural gas and forced air furnace in Watertown, SD showed the heating bill is one third cheaper in SIP dwelling than the conventional timber dwelling (ORNL, 2010).

Another case study in EJ Jebel, Colo in which the whole house using electric baseboard with heat recovery ventilation system of 120 square metres showed a three quarter savings on heating bills in SIP house in comparison with 2x6 stick build homes (ORNL, 2010). The results were drawn from simplification methods using heating degree days.

In the case study of BASF homes at the University of Nottingham, SIPs panels were used in the first floor walls and the roof where it was finished by metal cladding (Hormazabal and Gillott, 2009).The study aimed to investigate the influence of occupants in the performance of sustainable homes. Prior to construction, the thermal performance of the design was modelled using the thermodynamic simulation tool (i.e. EDSL TAS). The simulation results informed changes in design so that the predicted energy consumption for BASF house is just under Passivhaus requirement of 15 kWh/m$^2$ per year (Gillot et al, 2010).

Osborne demonstration house was constructed in 2006, at the BRE Innovation Park in Watford, UK using SIPs to showcase innovative method of construction. Their key facts compared heating/cooling demands, and associated carbon emissions of the building with 2006 Building Regulations. Predictions derived for comparison were the manufacturing design value for individual elements and there were not any available information of testing and monitoring conducted at the building at its actual performance (BRE, 2006).

### 3.1.2 Novelty of the project

From the literature review, there has not been a field testing and monitoring of a post construction SIPs based dwelling in the UK. Current issues discussed in Chapter 2 about the UK housing context and the potential benefits of SIPs in delivering quick built, affordable and energy efficient dwelling set the demand for assessing the real performance of SIP construction in the UK. Investigation of the thermal performance of SIPs built with the UK current techniques and labour skills, under the on-going weather conditions, informing the current climatic state under effect of climate change impact.

This research introduced a methodology to predict and evaluate the holistic buildings energy performance, and implement these methods by developing an evaluation model which can test, simulate, evaluate, and aid in thermal design decisions. The new evaluation method provides a holistic picture of the actual contribution of major building elements on energy consumption.

## *3.2 METHODOLOGY*

This section reviews methods and case studies which conducted testing and monitoring on site to evaluate the real thermal performance of buildings, not limited to SIPs, as well as computer programmes for simulating integrated design strategies allowing an overall design evaluation.

## 3.2.1 Simulation

Although both computer simulation programs and intelligent CAD/CAM system contribute significantly to energy conservation, they cannot cover all design aspects. These computer simulation and optimization models usually target the design process from specific physical design aspects. The designer has a major role in evaluating the design from a holistic point of view and producing innovative techniques to conserve energy while considering other design aspects such as aesthetic, human needs, function, practical operating strategies, practical construction techniques, as well as the particular specifications of the owner.

### *3.2.1.1* Building performance simulation tools

Building simulation was developed during the 1980s for early energy analysis to aid the development of more energy efficient and sustainable buildings. As a result, subsequent evolutions produced a variety of building performance simulation (BPS) tools that are scientifically and internationally validated (Hensen, 2004). However, it is repeatedly reported that there is a growing gap between architects as users and BPS tools (Warren, 2002). Indeed, most BPS tools are developed by technical researchers and Heating, Ventilating and Air Conditioning (HVAC) engineers who are mainly concerned with empirical validity, analytical verification and calibration of uncertainty as defined by IEA BESTEST (Hong et al., 2000). Therefore, understanding architect’s problem of interacting with such tools is a basic criterion for BPS tools.

For the past 50 years, there is an increasing number of building simulation programs developed and in popular use.  These include: HEED, Energy 10, IESVE, ECOTECT, eQUEST, Tas, TRNSYS, ESP-r and EnergyPlus, and these will be briefly described in turn below.

(1) HEED aims to combine a single-zone simulation engine with a user-friendly interface. It only requires four inputs (e.g. floor area, number of stories, location and building type), hence is used at the very beginning of design process (Crawley et al, 2005). HEED is appreciated for its ease of use, simplicity, computational speed and a range of graphic output displays. Additionally, it can offer quick comparison between multiple design alternatives and consistently provide design guidelines for different climate zones (Attia et al., 2009).

(2) Energy-10 was developed by the US Department of Energy in 1992 to evaluate and advise designers at early design stage. It targets at small commercial and/or residential

buildings of less than10,000 ft² (≈ 930 m²) characterised by one or two thermal zones (NREL, 2008). Energy-10 allows rapid exploration of broad design issues effecting energy performance by entering basic parameters such as geographic location of building, total floor space, type of HVAC system and weather data at the nearest station. Ranking graphs for individual strategies helps to guide early design decision making, and built-in graphs allow flexible review summary and hourly results (Crawley et al., 2005).

(3) IES <Virtual Environment> (IES <VE>) provides design professional with a range of design-oriented building analysis within a single software, which is beneficial in term of interoperability among applications (IES, 2009a). The program allows detailed evaluation of building and system designs to be optimised in the best compromise between comfort criteria and energy efficiency. IES <VE> employs Vista, a graphic driven tool for data presentation and analysis which provides the result in detail or at various level of aggregation and includes functions for statistical analysis (IES, 2012b)

(4) ECOTECT is another building analysis program covering a full range of simulation and analysis functions required to provide designers useful building performance feedback, both interactively and visually (ECOTECT, 2008)(ECOTECT, 2008). As this software can handle geometry at any size and complexity of modelling and analysis competency, it is beneficial to be used at conceptual design stage. Beside its own broad range of internal calculation, ECOTECT can import/export to other more technical and focussed analysis engines (i.e. Radiance, EnergyPlus and ESP-r) (Crawley et al., 2005).

(5) EnergyPlus is primarily a simulation engine (e.g. input and output are simple text file) that provides an integrated (simultaneous loads and systems) simulation for accurate temperature and comfort prediction((Crawley et al., 2001) and (EnergyPlus, 2009). Developed from most popular features and characteristics of BLAST and DOE-2.1E, EnergyPlus also includes some new innovative simulations such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, water use, natural ventilation, and photovoltaic systems (EnergyPlus, 2009).

(6) eQUEST is an building energy analysis tool, which combines a building creation wizard, an energy efficiency measure wizard and a graphical results display module. This software utilises enhanced DOE-2 features with full capabilities but generates detailed simulated results quickly (Hirsch, 2009). Another impressive feature of eQUEST is that it allows users to perform multiple simulations and view the alternative

results in side-by-side graphics. The latest version offers a three-dimensional view of the building geometry and HVAC system diagrams (Crawley et al., 2005).

(7) ESP-r is an integrated modelling tool for simulation of thermal, visual, acoustic performance of the building developed by Department of Mechanical Engineering at the University of Strathclyde, UK. It is distributed as a suite of tools as well as interacts with 3rd party tools to provide higher resolution assessments (ESRU, 2009). Although, ESP-r has a powerful capability to simulate many innovative or leading edge technologies, it relies on user selection and control of the building geometric complexity, environmental control and operations hence requiring specialist knowledge base.

(8) Tas is a suite of software product, which simulates the dynamic thermal performance of buildings and their systems (EDSL, 2009). It was originally developed at Cranfield Institute, UK and has had a reputation for robustness, accuracy and a comprehensive range of capabilities during 20 years of commercial use. There is an extensive Theory Manual detailing simulation principles and assumptions. Its developments are tested against ASHRAE, CIBSE and ISO/CEN standards (Crawley et al., 2005).

(9) TRNSYS is a simulation program with a modular structure designed to solve complex energy system problems by breaking the problem down into series of smaller and simpler components. TRNSYS library includes many of components commonly found in thermal energy systems (i.e. HVAC equipment: dual source of heat pumps) and is also extendable. In fact, all TRNSYS components are formulated using the same structure and that helps users to add their own components to TRNSYS package (TRNSYS, 2009).

#### *3.2.1.2* Criteria of selection

A number of criteria namely “Architects Friendly” BPS tools have been identified that are used in daily architecture design practice. Amongst these the four following criteria are the most highlighted: (1) Usability and information management (UIM) of interface, (2) integration of intelligent design knowledge-base (IIKB), (3) interoperability of building modelling (IBM), and finally (4) the accuracy of the tool, and its ability to simulate complex and detailed building components (AASDC) (Crawley et al., 2005, Hopfe et al., 2005, Reinhart and Fitz 2006).

The popularity of using a software tool depends firstly on its interface, or more specifically, the UIM of interface. The term “usability” incorporates simple navigation, concise and straightforward way of presenting the simulation input/output data and flexible control. Additionally, usability also requires support through online help, training, look-up tables and error traps to facilitate learning/using process (Donn, 1997). Also, information management becomes a growing issue for users while interacting with computer model. There is a need for qualified control of simulation input together with ability of evaluating alternatives quickly, accurately and providing a complete analysis for the design. Users typically expect the simulation program to have the ability to allow assumptions, to use default values and to use templates to facilitate data entry (Donn, 1997).

Advances in science and technology provide continuingly improved solutions hence more options to design sustainable buildings. Thus, computer models are required to increase input design data, operate at a higher level of knowledge-base and with more details provided. The integration of such design knowledge-base is vital to support sustainability in decision making. It is observed that most users of simulation tools are concerned with meeting the provision and guidelines for building codes and rating systems compliance, using case study databases for decision making together with weather data, as well the provision of extensive libraries of building components and building systems (Attia et al, 2009). In addition, the integration of intelligent knowledge-base and compatibility in the design process is mostly concerned with accurate and quick energy analysis that supports decision making at different design phases. Moreover the ability to examine sensitivity and uncertainty of key design parameters coupled to the ability to analyse weather characteristics area also considered important. From this suitable climatic design strategies can be suggested and examined (Attia et al., 2009).

Interoperability of building information modelling (BIM) is enhanced by recent innovations creating direct links between BIM and non-BIM modelling tools. Hence enables the creation and the ability to edit input files (i.e. plug-in of IES and EnergyPlus for Google Sketchup and Revit Architecture plug-in IES and ECOTECT). For a suite application, interoperability facilitates up-to-date changes made between model and other tools such as simulations of weather, thermal calculations, airflow estimations and energy analysis. Thus, parameters affecting building performance will be determined, allowing design improvement to be made.

Selection of a BPS tool also depends on its accuracy and its ability to simulate complex and detailed building components. This criterion can vary in scope with the requirement of different projects and different design phases. Indeed, at the early design phase, rough evaluation of the performance is just enough for cost estimation and rapid prediction. A simpler BPS tool will be more appropriate while considering time utilised for building and running the model. However, at the design development phase, parameters influencing the building performance need to be determined requiring a detailed and more complicated model utilising a more complex BPS tool. It is recommended to use BPS tools possessing a suite of applications, which would respond to a range of simulation needs in the design process without taking a repeated data entry (Crawley et al., 2005).

## 3.2.2 Testing and Monitoring

This section deals with instruments, methods and principles of measurement that can be used whilst evaluating the building thermal performance. It includes measurement of physical quantities of external and internal environmental conditions, infiltration, and thermal performance of building. The background of building physics as found in Chapter 3 facilitates the understanding of the terms, building components and material properties that influence the thermal behaviours. The building testing and monitoring can be done either as unoccupied or occupied building. Energy flows in unoccupied building include solar radiation, infiltration losses, transmission losses and heating system. Occupied building adds occupant factors into the aforementioned energy flow with energy from people and for appliances and hot water heating usage, ventilation and airing for indoor air quality and comfort. In order to validate the thermodynamic simulation of building model, monitoring unoccupied test building is required as it excludes occupant factors that complicate the model and more likely cause errors with more interactions due to occupancy..

### *3.2.2.1* Background

"Before validating a thermal environment, the comfort criteria, specified by the design engineer and the owner, must be defined" (ASHRAE, 2004): p2). This means the validation task is to evaluate the ability of meeting and maintaining desired comfort level (ASHRAE, 2004). It is stated that thermal comfort of a space can be assessed by 4 environmental parameters namely air temperature, mean radiant temperature, air velocity and humidity and 2 parameters relating to human presence: metabolic heat production and clothing (CIBSE, 2006a).

There are two methods of validating the thermal environment: the first one is based on evaluation of survey results about occupant satisfaction and the second one is to technically establish comfort conditions through the analysis of environment variables (ASHRAE, 2004). This field research relies on the second method for evaluating comfort conditions in compliance with the design criteria. Parameters of internal environmental conditions taking account of occupancy factors for comfort criteria are listed as following:

- Room air temperature (°C)
- Mean radiant temperature (°C)
- Relative humidity of indoor air (%)
- Air velocity (m/s)
- Clothing (clo) and activity level- metabolic rate (W/m$^2$)

Furthermore, parameters physically describing weather conditions also need to be specified in order to interpret the measured data. Data collected at the nearest weather station to the test house are available from CIBSE weather data file of 16 local weather stations in UK. Nevertheless, it is useful to investigate the microclimate surrounding the test house to calibrate the readings at local weather station thus improving the accuracy of input data for simulation. Parameters of external environmental conditions are (not limited to) given below:

- Outdoor air temperature (°C)
- Relative humidity of air ambient (%)
- Global and diffuse solar radiation (Wh/m$^2$) from that direct solar radiation on horizontal plane can be calculated.
- Wind direction (Degree clockwise from North)
- Wind speed (knots)

#### *3.2.2.2* Instrumentation and testing methodologies

In order to evaluate the building performance, the following aspects need to be considered and tested: thermal insulation, natural ventilation and solar radiation. Moisture is also one concern that greatly affects the building performance, hence it is required to consider the relative humidity of air ambient. The measuring equipment is selected based on the simplicity of use, suitable measuring range and acceptably required accuracy.

Short-term tests provide a quality check in ventilation, temperature performance like measurement of airtightness, air exchange rate and the temperature background. During the short-term test period, the long-term monitoring can be installed and executed. Long-term monitoring is designed to take place at least one year to capture a whole year variation of weather conditions. It involves measurement of surface temperature, heat flux, relative humidity of air ambient, air ventilation, exterior air ambient conditions and solar radiation.

By considering the temperature difference and heat flow across the building envelope, the thermal resistance of the assembly is determined. The internal surface temperature also contributes to determining its potential for condensation. Natural ventilation can be assessed through the determination of air exchange rate (or measurement of air speed/ air flow). It is necessary to execute an initial check about the airtightness of the building envelope in order to assess the envelope state and ventilation requirements hence determine improvements. Short-term testing and long-term monitoring provide data to validate thermal performance in and by that, validate the as-built computer model through comparing thermal environmental variables obtained from practical field and that from simulation.

#### *3.2.2.2.1 Short-term testing*

For a detailed understanding of building performance, it is important to know the actual ventilation and infiltration rate. Therefore, determination of leakage rate of and air exchange rate within the building envelope in a specific weather condition is the main aim of taking short-term tests. Indeed, such these initial checks are necessary for assessing the real performance of the building envelope hence determine improvements (i.e. sealing techniques and/or strategies to increase natural ventilation). The tests should be ideally taken place in different seasons or during some specific periods when extreme conditions are observed to occur (Norton et al., 2005). A blower door test is used to determine the leakage rate so as to assess the airtightness of the building envelope. By using a calibrated fan and metering equipment, airflow can be measured at a variety of pressure differences up to 50 Pascal. Testing results can be expressed by 3 ways: air changes per hour under natural condition (nnat) or at test pressure ($n_{50}$); air flow at test pressure ($Q_{50}$) on the equivalent leakage area ($m^2$).

Ventilation performance can then be assessed by applying tracer gas monitoring system which provides direct measurement of air exchange rate at normal condition. The principle of tracer gas technique relies on the decay in concentration of the tracer gas (e.g. sulphur hexafluoride $SF_6$) to express the rate of air exchange with outside, in number of air changes per hour (ac/h). Initially, the tracer gas is periodically injected into building envelope then mixed to a nearly uniform concentration. Intentional ventilation driven by any ventilation system (e.g. trickle ventilator, extract fan) or infiltration of outside air results in dilution of the tracer gas. This test can compliment blower door test to investigate strange inputs obtained from the calculation of air pressurisation test (Hancock et al., 2002).

Infrared camera or thermal imaging is a building diagnostic tool which helps identify issues related to energy loss, pattern of heat loss, missing insulation, thermal bridging, water damage or mould development. In many cases, improvement in thermal performance by filling in the missing insulation might not be significant but beneficial in eliminating condensation risk as well as avoiding avoid draught(Hendron et al., 2006).

Co-heating test is defined as a quasi steady state method that can be used to measure the whole building heat loss. It involves heating inside an unoccupied dwelling using electric resistance point heater to a “mean elevated internal temperature, typically 25°C over a specific period of time, typically between 1 to 3 weeks” (Johnston et al., 2012). This is not new method, which has been around since 1970’s (Sonderegger et al., 1979), in fact it was conducted in the study of SIP modular office in the US (Judkoff et al., 2000). However, the methodology is still at initial stage in the UK and currently subject to much research and debate (Johnston et al., 2012). The testing period varies but typically ranged between one to three weeks, including measurement of electricity consumption, indoor temperature and relative humidity and various external climatic conditions. The heat loss coefficient is obtained by plotting daily heat input against daily temperature difference between outdoor and indoor conditions.

#### *3.2.2.2.2 Long term monitoring*

The field monitoring includes measuring of outdoor and indoor conditions that thermal parameters for evaluating the building performance were identified through understanding of building physics as discussed in Chapter 3 Section 3.2 to 3.4.

Temperature sensor generally records a temperature between air temperature and mean radiant temperature (ASHRAE, 2009). In order to properly measure air temperature, the effect of radiant heat exchange is to be minimised by using a shield. It is in form of an open and polished aluminium cylinder around the sensor that reflects most of the coming solar radiation and gives space for the sensor exposed to record the environmental conditions (ASHRAE, 2009). At ambient temperatures that provide comfort or slight discomfort, the thermal effect of humidity is only moderate, and highly accurate humidity measurements are unnecessary(ASHRAE, 2009)

The radiant temperature is more complex than the air temperature as it is dependent on direction of reflectance and surface temperature. The term “mean radiant temperature” is defined as the uniform surface temperature of a radiantly black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space (CIBSE, 2006a).Unless there is a particular reason for knowing the radiant temperature, it is best to use the globe thermometer to represent the room temperature. The designed thermal conditions recommended in CIBSE guides and Building Regulations relate to the term operative temperature, which combines room air temperature and mean radiant temperature (CIBSE, 2006a).

The globe thermometer is an instrument that combines the effects of air and radiant temperature in a way related to the response of a human subject. It consists of metal/plastic sphere of 40mm diameter, which is revealed as optimum diameter and has an inserted temperature sensor (electronic or liquid-in-glass) at the centre of the globe. The surface of the sphere should be painted grey or black to approximate the reflectivity of the clothed human body to any diffuse solar radiation reflected from the room surfaces (CIBSE, 2006a).

Furthermore, assessing operative temperature requires several readings of globe thermometer taken and averaged. Depending on thermal capacity of the sphere and sensor, the time for instrument to stabilise can vary from 5 to 20 minutes before the final reading is taken (CIBSE, 2006a).

Indoor air velocity is usually small, ranging from 0 to 0.5 m/s (ASHRAE, 2009). However, it still contributes to thermal comfort since both evaporative and convective heat transfers are enhanced by air movement. Even when higher air speeds are desirable for their cooling effects, the value of greater than 0.3 m/s are probably unacceptable in naturally ventilated buildings during summer (CIBSE, 2006a).

Besides, it is difficult to identify the direction of air velocity at low intensity and this direction may unpredictably change. Hence, an omni-directional sensor with a short responding time should be used. A thermal (or hot-wire or hot-film) anemometer is suitable. If a hot-wire anemometer is used, the direction of measuring flow must be perpendicular to the hot wire (ASHRAE, 2009).

### 3.2.3 Validation techniques

Testing and monitoring help to validate the computer simulation. Indeed, measurements provide the reality check for the simulated model and if the simulation can accurately predict the building performance, it increases the confidence of designer in their model. Moreover, monitoring provides insight into interaction between occupants and technology, occupant behaviour, issues related to equipment installation. Once the simulation is valid, further development on the computer model can be made. The model can create the “what-if” scenarios where incorporated different energy-efficient technologies, from that critical analysis of building performance can be made and suggested to apply for real building design (Norton et al., 2005). Modelling and monitoring complement each other, hence both processes are needed to understand building behaviours and evaluate its performance.

#### *3.2.3.1* Background

There are 3 ways to evaluate a whole building energy simulation program’s accuracy (Neymark and Judkoff, 2002 cited in ASHRAE, 2009): analytical verification, empirical validation and comparative testing. Analytical verification compares calculated results from software program or subroutine to results from a known analytical solution or a generally accepted numerical method calculating isolated heat transfer under very simple and highly constrained boundary conditions. Empirical validation compares outputs from a program, subroutine or software object to monitored data from a real building, test cell or lab experiment. Comparative testing compares a program to itself or other programs.

It is important to ensure that the model simulations are tested blind that the program user hasn’t acknowledged about the actual measured performance of the building (Lomas et al., 1997). Besides, analytical test which is the use of mathematical solutions or empirical values hence the predictions for a simple situation from simulation tool could be compared with expected results. This could be beneficial to provide a quick check for model simulation.

It was suggested that testing the simulation results against the field data for a period of 7-15 days of the tested period is reasonable for calibration the simulation results against the readings (Dickson et al., 1996, Judkoff and Neymark, 1995).

#### *3.2.3.2* Method

From the field literature review, the following requirements of data set collection for empirical validation of building energy simulation program are laid down to guide the monitoring execution (Lomas et al., 1997).

- There is no operative active solar space heating or cooling system is included within the building structure.
- The weather data must have been collected at the building site. Especially all three major elements of the weather, air temperature, wind speed and the direct and diffuse components of solar radiation must be measured at the site of the building for the whole comparison period.
- During the comparison period, the building must be unoccupied and each zone within it must have independent heating/cooling plant and controls.
- Also the measured infiltration and where appropriate, inter-zonal airflow rates must be available during this period.
- The building construction must not contain any passive solar features or environmental control system which cannot be modelled explicitly by the simulation program being validated.
- The measured data of the building performance and weather data must be available at hourly or at shorter intervals.

## *3.3 SELECTED METHODOLOGY*

### 3.3.1 Selection of BPS tool

The Virtual Environment (VE) v6.4 was selected to perform this case study as it is a suite of simulation products that facilitates data exchange among applications. Utilising this simulation tool can avoid repetition of data input, hence, save design time and cost. Also, input and output data are presented and managed in a concise and straight-forward manner that facilitates performance analysis and alternative considerations.

Important IES <VE> features are listed as followed (IES, 2012b).:

- The program is one of UK leading industry software tools so that its simulation results will be accepted across the UK as well as worldwide.
- Being a suite product, this single software facilitates data exchange among applications. Utilising this simulation tools can avoid repetition of data input, hence, save design time and cost.

- The IES <VE> library is extensive. A model component can be chosen from abundant components available in the library or imported from other existing projects or created by Component Modeller application.
- Input and output data are presented and managed in concise and straight-forward manners that facilitate the performance analysis and alternative considerations. In addition, the software offers default values and templates that facilitate quick entry and support users from non-expert background. Thus, it is suitable for both research and education in the field.
- Building geometry created in a 3-D model gives users the “feel” of their design. IES <VE> has its own model creation and editable tool as well as a direct link to import model built in other 3D building modelling tools like plug-ins to Google SketchUp and Revit Architecture IES. VE also has a tight connectivity with ArchiCAD.
- <VE> analysis tests compliance with UK Building Regulations (Part L) and its approach and calculation method rely on industry standards (CIBSE and ASHRAE), which are reliable and fully approved.
- <VE> VistaPro [BETA] provides new look and feel features, which facilitate decision making during the design process.
- This tool provides training, web-based tutorials, online support and builds IES user community to exchange ideas and experiences during design and research process.

IES <VE> is relatively inexpensive for academic use (e.g. student package of £50 annual license) for VE-Pro, a full version of suite analysis tools.

It is very important for the full impact of performance to be realised that the simulation is undertaken right from the very earliest designing stage and then developed to completion and beyond throughout design the entire process. IES provides a wide range of analysis options for efficient feedback at relevant level in design phases where the simulation can be detailed at hourly or smaller increment if necessary (IES, 2012b). The detail and accuracy of the model will be increased in parallel with developed performance analysis, which quantify and inform iterative decisions to further refine the design (IES, 2012b)

### 3.3.2 Monitoring

There are 6 parameters used for assessing thermal comfort of a space that includes 4 environmental parameters (e.g. air temperature, mean radiant temperature, relative humidity and air velocity) and 2 index relating to human presence (e.g. clothing and metabolic heat production) (CIBSE, 2006a). Besides, it is recommended for the empirical validation process that data are from monitoring of unoccupied experimental buildings rather than complex occupied ones (CIBSE, 1998). Therefore, the two occupant index could be ignored at the monitoring stage that leaves to measuring the 4 environmental values. With regard to building design, recommendation and guidance on comfort range employs the operative temperature that combines the air temperature and the mean radiant temperature into a single value to express their joint effect (CIBSE, 2006a). The operative temperature is therefore a human comfort indicator that expresses how a person thermally senses about his/her surrounding environment. The measurement of indoor air velocity is desirable however with acknowledgement of equipment cost compared to the project budget and its beneficial offer in use, such measurement is excluded. The reason for this is the room air movement resulting in draughts that might affect human comfort. As SIPs construction is reported to be at a very good airtightness level and the building is located at a sheltered place where air velocity is found between 0- 3 m/s with trees and a 5 floor building nearby, it is predicted not to cause any problem. Also real occupancy by people involved in the project or other business reinforces the decision. Therefore, air temperature, operative temperature and relative humidity are measured at the test building to be indoor environmental parameters.

During the monitoring period, the test building unit is left free of occupancy and system in operation. Selected environmental parameters to be measured inside the unit are listed as: air temperature, operative temperature and relative humidity. Data have been recorded in 10 minutes interval then averaged for hourly data that facilitates evaluation and comparison. This helps to interpret any change occurring in environmental conditions within an hour.  For calibration of building model simulation, it requires measurement of parameters physically describing the on-going external environmental conditions are (not limited to): ambiance temperature, relative humidity, direct and diffuse component of solar radiation, wind speed and wind direction.

Measurements should be taken place in occupied zones of the dwelling where occupants are expected to spend time. Or without a specific occupancy distribution, the measuring instruments are recommended to locate in the room centre or 1m inward from the centre of each roof’s wall. In case of external wall with windows, location should be at 1.0 m inward from the centre of the largest window. Clearly if we are interested in the conditions experienced by the occupants of a room, the vertical height at which the sensor is placed should be representative of the occupants' experience. Therefore, at the selected location, instruments measuring each type of variables are placed at different levels (height above floor, h (m)). Air temperature and air speed shall be measured at the 0.1, 0.6 and 1.1 m levels for sedentary occupants at a chosen location. Standing activity measurements shall be made at the 0.1, 1.1 and 1.7 m levels (ASHRAE, 2004). With regard to building design, recommendation and guidance on comfort range employs the operative temperature that combines the air temperature and the mean radiant temperature into a single value to express their joint effect

Operative temperature which combines air temperature and mean radiant temperature shall be measured at the 0.6 m level for seated and 1.1 m level for standing occupants. Humidity shall be measured at any level within the occupied zone and because the preferable relative humidity range for comfort is quite large 30 – 60%, this measurement only requires one instrument per each room (ASHRAE, 2004).

### 3.3.3 Validation

The simulated model was built to as close as practically represent the real conditions of building construction. It is very important to make sure the model simulation contains as-built data, i.e. data that are as close to what is in built. For example, U-values generally accepted and provided by manufacturers are design values and to some extent do not include any bridging materials as being considered to be homogenous layers. However, thermal bridging occurs in real construction and it leads to significant amount of heat exchange via bridging parts. As-built U-value determinations that take account of this are shown in Appendix B Section B.1.1.1.

#### *3.3.3.1* Analytical validation

As the <VE> program utilises CIBSE models (e.g. Steady state model and Cyclic model) and methodologies, analytical verification mainly relies on the model built, hypotheses and assumption as well as empirical values provided in CIBSE guide A-Environmental design (CIBSE, 2006a), British Standards and other reliable information sources cited in CIBSE.

The model simulation is first validated by analytical verification, in which simulated results are compared with a known analytical solution (e.g. empirical values for various building type and opening type given in CIBSE (2006a)) or by use of a generally accepted numerical method calculation (e.g. CIBSE Heating and Cooling Loads).

### *3.3.3.2* Empirical calibration

The simulation is then validated by empirical comparison that comparing hourly data or shorter interval between simulation results and monitoring of the unoccupied experimented building with the real weather data collected at the nearest to the construction site over a period from 7-15 days.

Figure 3-1 illustrates the research scope of selected approach:

Figure 3-1: Illustration of the holistic assessment of the study

# Chapter 4: **CASE STUDY: ERGOHOME DWELLING**

The ErgoHome test building was constructed in 2009 for research agreement between ErgoHome Ltd, a private owned company and University of Birmingham. The business develops ErgoHome as a “new living concept, ready for deliver, at an affordable price” through delivering environmental design prefab house (Chadwick, 2009). Its main aim was introduced to provide a framework for modular new built dwellings to deliver a step change in environmental performance.

Indeed, ErgoHome test building is designed as modular building which possesses a unique energy efficient feature. Traditional buildings lose embodied energy containing in construction materials when the buildings are demolished. With modular built technology, the embodied energy is locked when buildings are relocated to another site. Such abilities of relocate and reuse minimise the required landfill and use of materials. Therefore, ErgoHome housing product could respond to the UK shortage in residential buildings and it might be of zero carbon home generation that conforms to the government commitment of cutting greenhouse gas emission by 80% from 1990 level by 2050.

Besides, ErgoHome design concept has a compact building form/shape and also unlike traditional wall structure which has inner and outer brick layers that double the occupied structural space compared to SIPs wall structure of ErgoHome dwelling. Thus it is beneficial in term of landfill, as in fact the density of new dwellings built in England has nearly doubled, from 25 dwellings per hectare to 43 dwellings per hectare between 2000 and 2009 (DCLG, 2009).

No system was in operation as the test unit was employed for testing the real thermal performance and also because there is no occupancy for the building onsite. However, many energy efficiency design solutions are to be considered as mechanical ventilation heat recovery, low energy light bulb and energy efficient household appliances.

## *4.1 OVERVIEW*

The approach of the project is to understand the building performance under the real weather conditions on site without any unexpected interference from occupants. It is achieved by monitoring of a purpose built and instrumented SIPs building over a one-year period. The field data measuring on-going climatic and indoor thermal conditions allow reliable assessment of the building performance. They are used to calibrate against the model simulation built in a building thermal performance tool (e.g. IES<VE>). Once the building simulation is validated, in order to provide an insight about the building consumption over one year, a generic thermal template will be built with a generic occupancy pattern and selected household appliances in use. At the development stage, several passive house design strategies are applied in a consistent manner to explore potential impacts in reducing heating and cooling energy demands. In brief, the work targets at evaluating improvement in energy efficiency whilst applying change on the building envelope itself of the modular building unit with careful passive building design for building layout.

The ErgoHome test units had been factory built and those two units were delivered on site at the University of Birmingham, Tennis Court. Each unit has 6 steel legs installed on the concrete pad system that enhances the installation (e.g. facilitate foundation work and delivery to site). The test units are executed on the grass field, facing the Edgbaston Park Road where elm trees are distributed at regular distance. Taking account of the effect of surrounding buildings and elms for the purpose of simulation, the location is assumed as sheltered. Figure 4-1 describes the location of the test building and its surrounding environment.

Figure 4-1: Site plan in 3D

The 2 test units were distanced in order not to generate any shading from EH1 to EH2. However, the neighbouring building campus, some 20 metres distance from EH1 might cause some shading when the sun position is low during heating months. The EH1 is a one-storey dwelling of rectangular shape with a roof slope of 15°. Due to construction safety onsite, the test units were mounted at the height of 1.25 m by steel chassis frame relying on 6 steel feet. The EH2 was constructed in the way that the external layout was opposite to the EH1 and the internal layout was reversed to that of EH1. By arranging in such a way, solar access and heat loss studies could be executed on south and north facing windows as well as east and west facing fully glazed doors of the bedroom and living room. The EH2 has the same building fabric and shape with similar layout to EH1 except that the wall facing north containing higher glazed area and central heating using water for floor heating is applied. However, due to financial restrain, the completion of the EH1 was prioritised to allow measurement taken place. Until the research work is being written, the EH2 test unit have not been finished.

## *4.2 BUILDING DESCRIPTION*

The research studies a modular SIP construction unit, one storey dwelling with the overall floor area is 45m$^2$, 11.85 m length and 3.80 m width (referred later as ErgoHome building unit, EH). Steel feet are at 1.25 m height, the overall height: 3.5m and plan: 11.85 x 3.88 m. The space volume is of 132 m$^3$ with the roof slope (no loft cavity) of 15°, containing five thermal zones and designed regarding their usage purposes as five different rooms: living space, bedroom, office, bathroom and entrance hall. Building dimensions are given in the plan and front section of the building unit as shown in Figure 4-2 and 4-3. All windows are at 0.8m height level except the fixed window W3 is at 0.96m.

The higher glazing area is on short sided wall that faces south east and north west compared to the building front and back facades on south west and north east orientation. In fact, the window-to-wall ratio (WWR: net glazing area to gross exterior wall area) on short sided wall is 0.24 and 0.18 against its value on long sided wall of 0.04 and 0.08.

The test unit does not have self -shading as it has a very simple shape (rectangle) and not equipped with any overhang. Trickle vents of 40 cm$^2$ are included in small and large window types as required for new buildings in order to provide a controllable ventilation source.

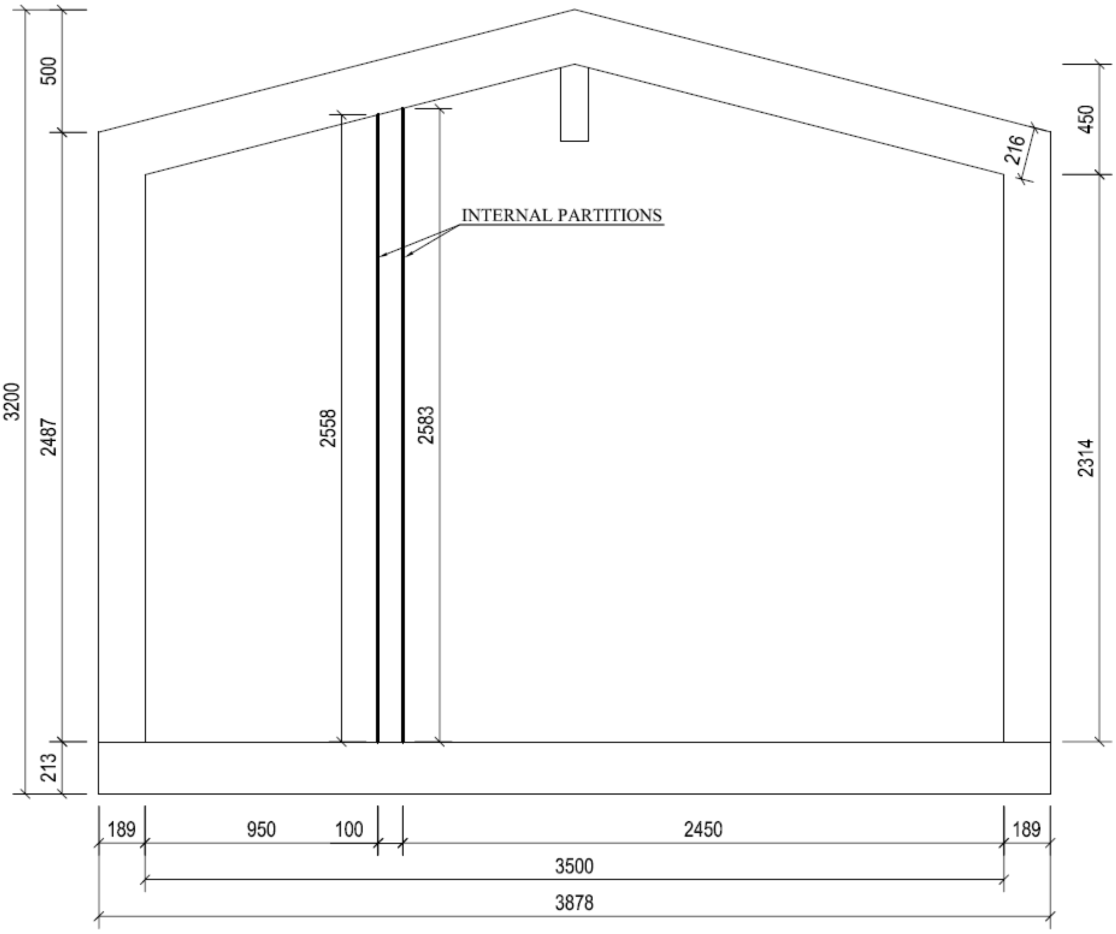


Figure 4-2: Side view of ErgoHome test building

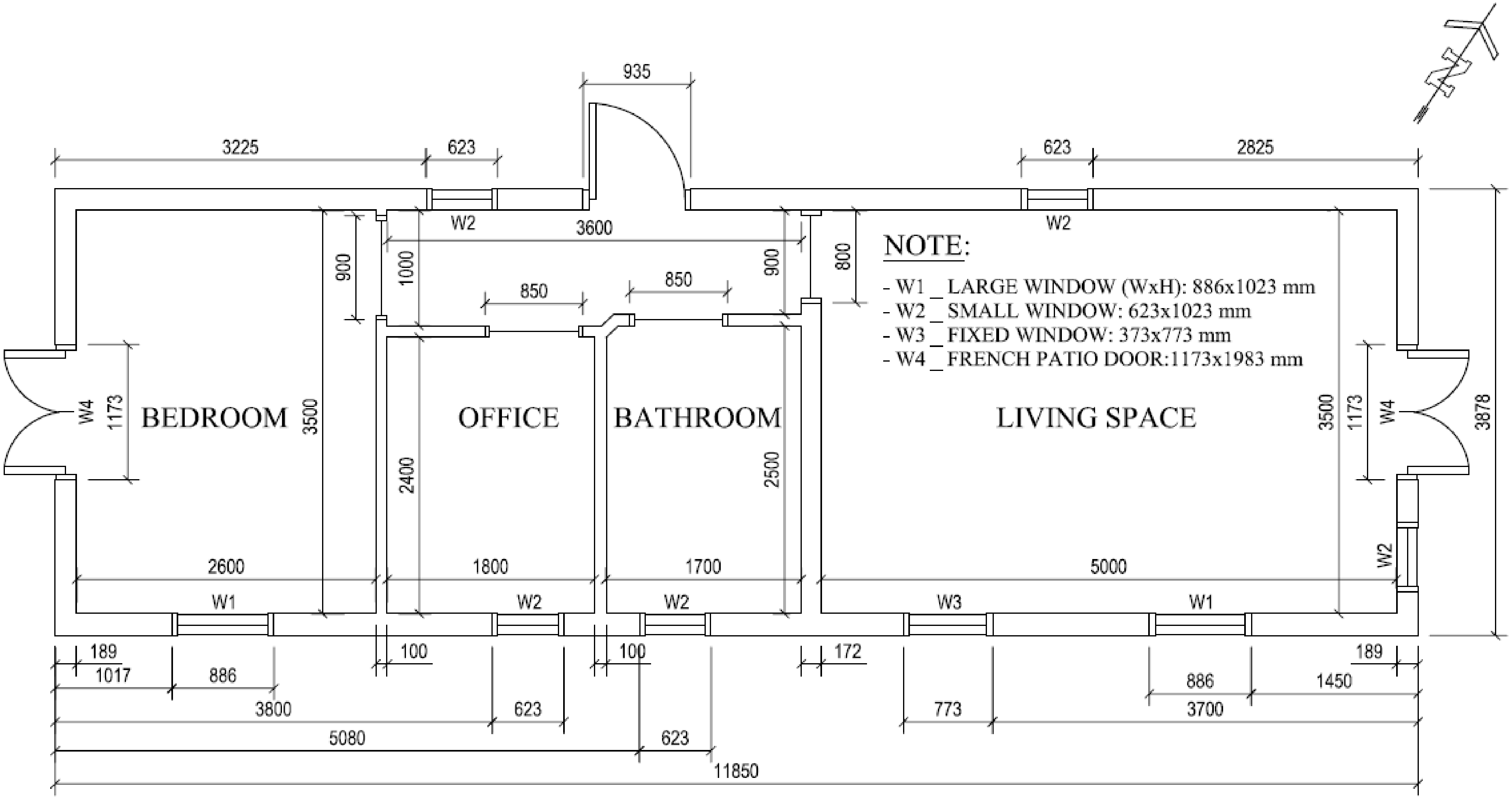


Figure 4-3: Plan ErgoHome test building

### 4.2.1 Constructional information

SIP system composed of Oriented Strand Boards, “multi-layered board mainly made from strands of wood together with a binder”, OSB/3 (which are classified as load bearing boards for use in humid conditions) (BSI, 2006) facings with a rigid insulation core. It is manufactured by injecting a precise blend of chemical polyurethane foam (PU) under high pressure between the OSB faces. This creates autohesive bonds the OSB and the foam core together as the chemical reaction occurs, resulting in superior bond strength compared to lamination techniques, and guarantees a continuous bond across the entire surface area of the panel (SIPCO, 2009). There is slightly difference in SIP composition between wall, roof and floor structures (see Table 4.1).

Table 4-1: Constructional information

| **Building element/** | **Details of layers in external – internal order** |
|---|---|
| External wall | Cedar timber (6 -22 mm); ventilated air cavity with batten support (25 mm); OSB/3 (11mm); polyurethane foam (103 mm); OSB/3 (11mm); unventilated air cavity with batten support (12.5 mm); gypsum paper-faced board (12.5 mm) |
| Ground floor | OSB/3 (11 mm); polyurethane foam (103 mm); OSB/3 (11mm); polystyrene (PS) (18 mm); black PS (30 mm) with PS balls (3mm) thermally modified; oak radial (oak spruce: 11 mm and oak: 4 mm) |
| Pitched roof (15°) | Aluminium corrugated with air ventilated; building membrane; OSB/3 (15mm); polyurethane foam (120 mm); OSB/3 (15mm); plasterboard (12.5 mm) |
| Internal partition | Plasterboard (12.5 mm); rock wool sound insulation (63 mm) with timber studs; plasterboard (12.5 mm); |
| Window | Double glazed: outside pane: clear float and inside pane: “iplus DK” (low e-coating), argon filled (93%) whilst ignoring frame effect |

The test unit utilises windows of VELFAC 200 system. They are to be a unitised composite aluminium/wood system (VELFAC, 2009). There is no shading device and trickle ventilator of 40 $cm^2$ each are equipped in small and large window types so as to provide controllable ventilation source.

Table 4-2: Information of glazing elements

<table>
<tr><th>Windows</th><th colspan="6">Descriptions</th></tr>
<tr><td>**Glass**</td><td colspan="2">**Element details**</td><td colspan="2">**Light**</td><td>**Solar heat**</td><td>**U-value, W/m$^2$K**</td></tr>
<tr><td>4|16|: 4</td><td colspan="2">Outside pane: float</td><td colspan="2">Light transmittance $L_T = 0.8$</td><td>Solar heat factor: $S_G = 0.62$</td><td rowspan="3">1.11</td></tr>
<tr><td rowspan="2">Calculation method respect BS EN ISO 673 and 410 (BSI, 1998 and 2007b)</td><td colspan="2">Cavity is filled with argon (filling degree: 93% )</td><td colspan="2" rowspan="2">Light reflectance (both pane) = 12%</td><td rowspan="2">Transmittance = 54%;<br>Reflectance = 27%;<br>Absorptance = 11% / 8%</td></tr>
<tr><td colspan="2">Inside pane: iplus DK, which is double silver coating at inner side</td></tr>
<tr><td>**Frame/sash**</td><td colspan="6">- Depth of unit 124 mm from this 90 mm frame<br>- The external aluminium sash must be polyester powder-coated in compliance with BS 6496, BS 6497, GSB and DIN 50939, in RAL colour to gloss level 77% and a primary coating thickness of between 60-120 µm.</td></tr>
<tr><td>**Type**</td><td>**Quantities**</td><td colspan="2">**Dimension (WxH), mm**</td><td>**Sash area, m$^2$**</td><td>**Glazed area, m$^2$**</td><td>**U-value , W/m$^2$K**</td></tr>
<tr><td>Large window</td><td>4</td><td colspan="2">886 x 1023</td><td>0.207</td><td>0.71</td><td>1.71</td></tr>
<tr><td>Small window</td><td>10</td><td colspan="2">623 x 1023</td><td>0.18</td><td>0.47</td><td>1.83</td></tr>
<tr><td>Fixed window</td><td>2</td><td colspan="2">373 x 773</td><td>0.123</td><td>0.18</td><td>2.17</td></tr>
<tr><td>French patio door</td><td>4</td><td colspan="2">1173 x 1983</td><td>0.686</td><td>1.66</td><td>1.82</td></tr>
<tr><td>Entrance door</td><td>2</td><td colspan="2">914 x 2013</td><td>1.84</td><td>0.09</td><td>0.92</td></tr>
</table>

### 4.2.2 Thermal properties of the fabric of building envelope

With the building constructional information given in the previous section, the thermal properties of the building envelop were determined thus enabled development of computer simulation modelling. Summarised calculated parameters are given in Table 4-3 (next page), and detailed calculations can be found in Appendix B Section B.1.1 and Section B.1.2.

Several passive design principles and techniques employed in the test building to achieve energy efficient perspectives are listed below:

- SIPs are the main construction of the test building. Polyurethane is used as the insulation layer and possesses higher R-value than current insulation materials (EPS or XPS) and being close cell foam helps reduce condensation risk. For example, a 114mm thick of the insulation layer, R-value of PUR SIPs can reach up to 4.58 $m^2K/W$ (U-value = 0.21 $W/m^2K$) while XPS SIPs possess lower R-value of 3.34 $m^2K/W$ (e.g. U-value = 0.30 $W/m^2K$) and EPS SIPs provides lowest R-value among 3 types with R-value of 2.82$m^2K/W$ (e.g. U-value = 0.36 $W/m^2K$) (The Murus Company Inc, 2009).

- Opening area of test unit is designed in accordance with recommendations for natural ventilation requirements. It is stated that ventilation openings with total area of at least 1/20 of the floor area of the space are (DCLG, 2010b).Hence, window area = 10.96 $m^2 > 1/20*44.96 = 2.25$ $m^2$. Additionally, trickle ventilator of 40 $cm^2$ each are equipped on a range of large and small windows to satisfy the requirement of background ventilation (DCLG, 2010b).

- The test building employs high energy efficient windows with improved U-values down to between 1.71 and 1.82 $W/m^2K$ (See Appendix B Section B.1.1.1.6). In order to achieve this, the window design is based on minimising the frame/glass ratio. Double glazing with low e-coating on internal pane as well as argon filled cavity with warm-edge spacer has been used (VELFAC, 2009).

- Solar panel on south facing slope roof and mechanical heat recovery ventilation system are available for further design development but were not included in the research project regarding its scope of considering building thermal performance alone.

Table 4-3: Summary of calculated thermal parameters for building components

| **Element** | **Construction information** | **Transmittance** | **Admittance** | | **Decrement factor** | | **Surface factor** | |
|---|---|---|---|---|---|---|---|---|
| | External – internal order | U, W/m$^2$K | Y, W/m$^2$K | ω, h | f, - | ø, h | F, - | ψ, h |
| External wall | Cedar timber (6 - 22 mm); Ventilated air cavity of 25mm; SIP 125: OSB/3- PU-OSB/3 (11-103-11mm); Unventilated air cavity with batten support (12.5 mm); Gypsum paper-faced board (12.5 mm). | 0.24 | 0.92 | 4.38 | 0.91 | -2.90 | 0.96 | -0.44 |
| Pitched roof (15°) | Aluminium corrugated with air ventilated space and building membrane; SIP 150: OSB/3 - PU - OSB/3 (15-120-15mm); Plasterboard (12.5 mm). | 0.22 | 1.20 | 4.60 | 0.94 | -3.05 | 0.96 | -0.58 |
| Ground floor | SIP 150: OSB/3 - PU - OSB/3 (11-128-11 mm); Polystyrene (PS) (18 mm); Black PS (30 mm); Oak spruce (11 mm). | 0.16 | 0.95 | 4.27 | 0.79 | -6.45 | 0.95 | -3.61 |
| Internal partition | Plasterboard (12.5mm), rock wool insulation (75mm), plasterboard (12.5mm) | 0.49 | 0.79 | 7.64 | 1 | -1.06 | 0.92 | -0.85 |
| Window | Glazing (4\|16\|: 4) Outside pane: clear float; Cavity is filled with argon (filling degree: 93%); Inside pane: iplus DK, which is double silver coating at the inner side.<br>- Windows with different percentage of frame fraction f | 1.1 (glazing only); | 1.26 | 1.79 | 1 | -0.36 | 0.86 | -0.33 |

## *4.3 BUILDING SIMULATION*

The house was simulated in its current construction. The simulation software which is used to simulate the house was tested and calibrated against the field readings as was discussed earlier in this chapter. Several assumptions were made to provide a full representation of the house. Firstly, analytical tests were performed throughout a range of comparison of some selected thermal parameters (i.e. U-value, Y-value, g-value) and simplified calculation methods including Steady State Heat Loss (e.g. using CIBSE Simple Model) and CIBSE admittance method (using CIBSE cyclic model). These provide a quick check of the model accuracy by comparing the simulation results with a known solution. Model assumptions and detailed calculation methodologies are included Appendix B.1. <VE> simulation suite application has ApacheCal tool performs heat loss and heat gain calculations. Heat Loss utility applies CIBSE Simple Model to perform steady-state heat losses calculation and Heat Gain program employs CIBSE Cyclic Simple Model to predict peak temperature in hot days.

The CIBSE steady state methods in use for analytical verification include Simple Model and Cyclic Model which are simplifications to facilitate manual calculation. The calculated results using these two models were compared with IES<VE> results driven from ApacheCal tool which employs the same assumption and calculation methods. The Simple Model calculates the maximum heating load at a fix design condition including the given external design air temperature and internal air or operative temperature. The Cyclic Model utilises idealised (sinusoidal) weather and thermal response factor (e.g. admittance value, decrement factor and time lag) that are based on 24 hours frequency. It is used to predict the thermal capacity of the building envelope whilst determining the peak internal temperature during summer period and the associated maximum cooling load. However, the methods only provide one hour of winter and/or summer design condition while lack of integrated design solutions such as use of natural ventilation, mix mode operation (i.e. combined use of mechanical and natural ventilation), real climatic conditions and encountering other impacts like duration of high/low temperature, period of occupancy (i.e. use in weekend is different to use in weekdays).

### 4.3.1 Analytical verification using CIBSE Simple Model

CIBSE Simple Model is developed for building designer to size emitters in order to achieve a specified operative temperature. The design scenario was that the dwelling was heated to an operative temperature of 20ºC and the external design temperature as in winter was selected at -5ºC. For simplification in manual calculation using the climatic data in CIBSE Guide J (CIBSE, 2002), the long sided wall with higher glazing area faces due south while in reality the building orientation onsite is 33º due South.

With the given building geometry, layout and constructional information, the simulation model of the test building was conducted using CIBSE Simple Model allowing numerical verification of the model as can be seen in Table 4-4. Inside air temperature and mean surface temperature are then calculated in correspondence with these assumptions and analysis. Model assumptions and detailed calculation methodologies are included in Appendix B Section B1.1 and B.1.3. IES<VE> simulation suite application has ApacheCal tool performs heat loss and heat gain calculations. Heat Loss utility applies CIBSE Simple Model to perform steady-state heat losses calculation and Heat Gain program employs CIBSE Cyclic Simple Model to predict peak temperature in hot days. Table 4-4 shows comparison of calculation data and IES<VE> outputs for Steady State Heat Loss in five thermal zones. Details calculation can be found in Appendix B Section B.1.3.1.

Table 4-4: Comparison of heat loss results utilising CIBSE Simple Model

| **Thermal zone** | **Thermal analyses** | **Calculation results** | **<VE> outputs** | **Percentage of difference (%)** |
|---|---|---|---|---|
| Living space | Heat loss (kW) | 1.125 | 1.094 | -2.4 |
| | Air temperature (°C) | 19.57 | 19.44 | -0.4 |
| Bedroom 1 | Heat loss (kW) | 0.459 | 0.441 | -2.73 |
| | Air temperature (°C) | 19.44 | 19.57 | -0.5 |
| Office | Heat loss (kW) | 0.227 | 0.231 | 1.8 |
| | Air temperature (°C) | 19.30 | 19.45 | 1.8 |
| Bathroom | Heat loss (kW) | 0.221 | 0.225 | 1.8 |
| | Air temperature (°C) | 19.30 | 19.45 | 1.8 |
| Hall entrance | Heat loss (kW) | 0.27 | 0.243 | -2.4 |
| | Air temperature (°C) | 19.45 | 19.75 | 0.5 |
| EH unit | Total heat loss (kW) | 2.502 | 2.454 | 1.8 |

### 4.3.2 Analytical verification using CIBSE Cyclic model

The cyclic model in which analysis is carried out uses a sequence of identical days for which, the external conditions vary on a chosen 24 hour basis (CIBSE, 2006a). The calculation sequence starts with an assessment of whether a building needs to be cooled down, by calculation of summertime peak temperature (e.g. CIBSE admittance method).

Short-wave solar radiation reaches the building envelope surface and is absorbed at the external surface. After a delay due to thermal storage capacity (known as thermal mass), the external temperature of external surface receiving short-wave radiation increases. Different temperatures on both sides of a building element results in heat flow (or long wave radiation) through this element and into the room by convective heat transfer (CIBSE, 2006a). Thus the summertime peak temperature is determined at the time when the peak solar radiation occurs together with thermal response of building envelope to short-wave radiation.

The results of analytical verification using CIBSE Cyclic Model are shown in Table 4-5, predicting cooling load and peak in room air temperature in a hot summer day with the peak in solar radiation. Detailed calculations for calculated results can be found in Appendix B Section B.1.3.2 with the thermodynamic values of building envelope previously calculated in Appendix B. Section B.1.2.2.

Table 4-5: Comparison of cooling results using CIBSE Cyclic Model

| **Thermal zone** | **Thermal analyses** | **Time peak** | **Calculation results** | **<VE> output** | **Percentage of error (%)** |
|---|---|---|---|---|---|
| Living space | Peak air temperature (°C) | 9:00 | 35.89 | 35.15 | - 2.1% |
| | Peak solar gain (kW) | | 1.072 | 0.971 | - 9.4% |
| | Cooling load (kW) | | 0.882 | 0.881 | -0.1% |
| Bedroom | Peak air temperature (°C) | 14:00 | 43.04 | 42.45 | -0.9% |
| | Peak solar gain (kW) | | 0.478 | 0.510 | 6.7% |
| | Cooling load (kW) | | 0.772 | 0.779 | 0.9% |
| Study room | Peak air temperature (°C) | 12:00 | 34.37 | 34.04 | -0.9% |
| | Peak solar gain (kW) | | 0.174 | 0.178 | 1.1% |
| | Cooling load (kW) | | 0.144 | 0.159 | -4.2% |
| Bathroom | Peak air temperature (°C) | 12:00 | 34.47 | 34.11 | -1.4% |
| | Peak solar gain (kW) | | 0.174 | 0.178 | 1.1% |
| | Cooling load (kW) | | 0.144 | 0.143 | -1.8% |
| Hall entrance | Peak air temperature (°C) | 13:00 | 25.79 | 25.84 | 0.3% |
| | Peak solar gain (kW) | | 0.084 | 0.088 | 4.8% |
| | Cooling load (kW) | | 0.078 | 0.079 | 1.3% |

## *4.4 TESTING AND MONITORING*

Based on the available budget and equipment to the research work, the airtightness testing was conducted twice and the monitoring procedure was summarised in this section.

### 4.4.1 Air leakage testing

A blower door test is used to determine the leakage rate so as to assess the airtightness of the building envelope. By using a calibrated fan and metering equipment, airflow can be measured at a variety of pressure differences up to 50 Pascal. The worst acceptable building air permeability performance criteria as defined in Section 2 of the Building Regulations 2000 (as amended), Part L1A Conservation of Fuel and Power in New Dwellings is $10m^3/(h.m^2)$ @ 50Pa (DCLG, 2010a). The envelope air tightness test was carried out in line with the ATTMA TS1 Issue 2 - Measuring Air Permeability of Building Envelopes.

One air depressurisation test was conducted on 3rd November 2010 with support from Dr Colin Oram from the University of Warwick in an attempt to get leakage rate result for develop simulation. As it was a homemade test, the equipment consisted of an axial fan attached on wooden door sealed to main entrance door, polythene tube and a pressure gauge for pressure difference readings (See Figure 4-4). The fan capacity offered limited pressurisation, up to 40 Pa only, and the measured air permeability obtained from two test depressurisation carried out between 16:00 and 17:00, scaled up for 50 Pascal pressure were 1.65 and 1.54 $m^3/h.m^2$. The test was conducted by BSRIA Ltd, on 29th June 2011 between 10:00 and 10:30 and the measured air permeability at the pressurisation test of 50 Pa is 1.82 $m^3/h.m^2$.

During the test period, all trickle ventilators, drainage traps, ventilation supplies and extracts were temporarily sealed in compliance with Building Regulations part L1A (DCLG, 2010a). It was interesting to find out that a simple kit could provide good reliable data for research study, whilst comparing the airtightness results between the two tests.

Figure 4-4: Axial fan fixed on portable timber door mounted at the door way and pressure gauge

### 4.4.2 Long term monitoring

With regards to the monitoring strategy developed from Chapter 4 Section 4.3 measuring equipment were set up within the monitored space. The requirements to validate the simulation model are the data from monitoring the unoccupied experimental building rather than complex occupied ones (CIBSE, 1998). The ErgoHome test building is located at the University of Birmingham for a 3 year period for construction, completion then thermal monitoring taken place. The monitoring has been operating at one test building unit since March 18th 2010 that allows collecting data to investigate and analyse the building thermal performance. Table 4-7 (next page) provides a summary of data collection and interruption events during the period when the instrument was installed.

#### *4.4.2.1* Data monitoring at initial stage

At the initial stage, the measuring equipment was located with regards to monitoring strategy as discussed in Chapter 3 Section 3.3.2.The built-in temperature and humidity sensors GC-10 are in use with accuracy of ±0.4ºC within the temperature measurement range from -30 to +40ºC and of ±2% (10 to 90%RH.) for relative humidity (Omni Instrument, 2009).

The operative temperature is also measured to provide a quick check of comfort level as it reflects how humans sense comfort. The black bulb sensor model TT-915 is in use. It consists of a black bulb of 40mm diameter which is reported as providing the same thermal exchange as a human body with the surrounding environment  The accuracy of this device is of  ±0.15ºC for the measurement range from 0 to 100ºC (Omni Instrument, 2009). The same model of data logger is used in the test buildings. Data loggers model RX250AL allows mobile utilisation because it does not require the permanent connection with a standby computer and its built in battery enhances uninterrupted logging are in use to receive data from both weather station and the modular construction

Air temperature and relative humidity sensors were placed in the room centre at different height levels above the floor (0.1m, 0.6m, 1.1m and 1.7m in living space as shown in Figure 4-5

Table 4-6 Measuring parameters over monitoring period

| **Date** | **Data from weather station**<br>Location: On the roof of the building of School of Civil Engineering at University of Birmingham | **Data from the ErgoHome building** | **Location of thermal monitoring equipment installed at the ErgoHome building** |
|---|---|---|---|
| 18/03 – 16/06/2010 | Dry-bulb temperature, relative humidity, wind speed and wind direction, atmospheric pressure and global solar irradiation on horizontal plane | Air temperature and relative humidity | At the centre at 0.1, 0.6, 1.1 and 1.7m height above floor level in living space and at 0.1, 0.6 and 1.1 m height in bedroom |
| 17/06 – 13/07/2010 | No data available. | | Change of location for testing |
| 14/07 – 22/08/2010 | Available | Air temperature, relative humidity and operative temperature | At 1.1m height above floor level at the centre of the south east wall in living space and 0.6m in the corner between SE and SW walls in bedroom |
| 22/08 – 10/09/2010 | No data available. | | |
| 10/09 – 07/10/2010 | No data available. | No data available. | |
| 07/10 – 19/11/2010 | Available | No data available. | |
| 19/11/2010 – present | Available (The weather station were still in use by the time the research work were written up for collecting climatic data for use of other research studies at the University) | Air temperature, relative humidity and operative temperature, | Same as above. In addition, a temperature and relative humidity sensor was installed under the EH stair to record local outdoor conditions for comparison, between 19th November 2010 and 29th August 2012 (the ErgoHome building moved out from site on 3rd ) |

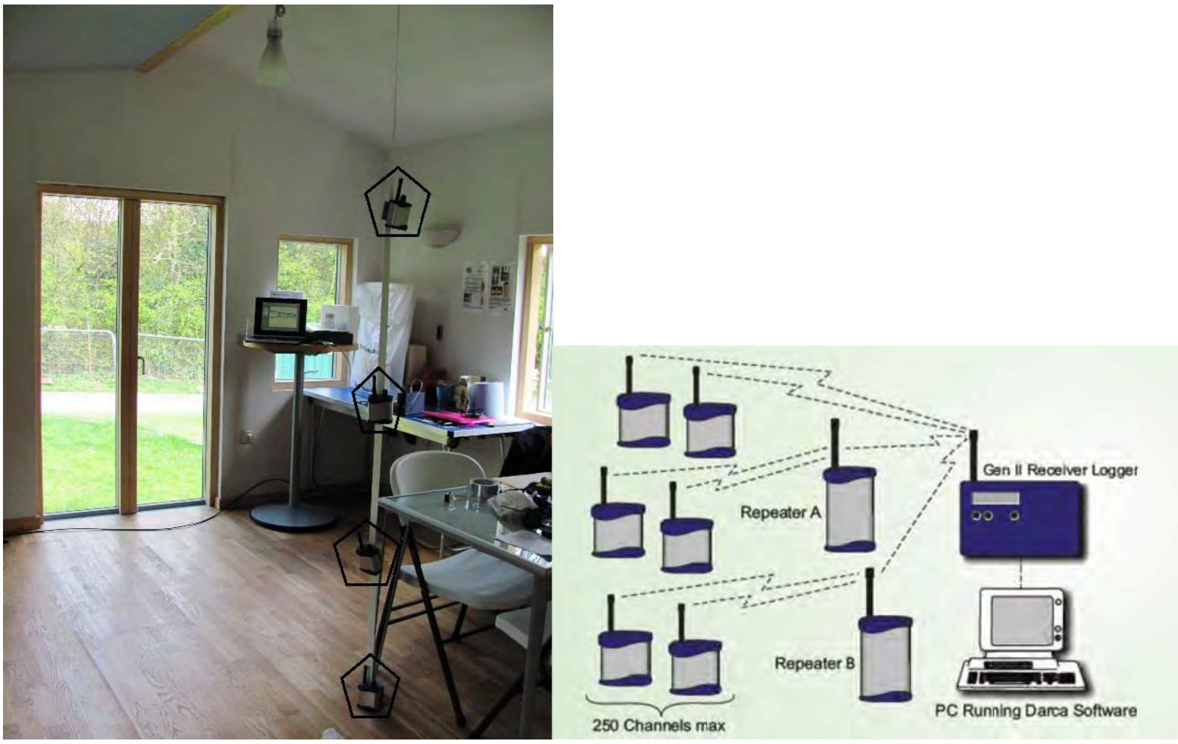
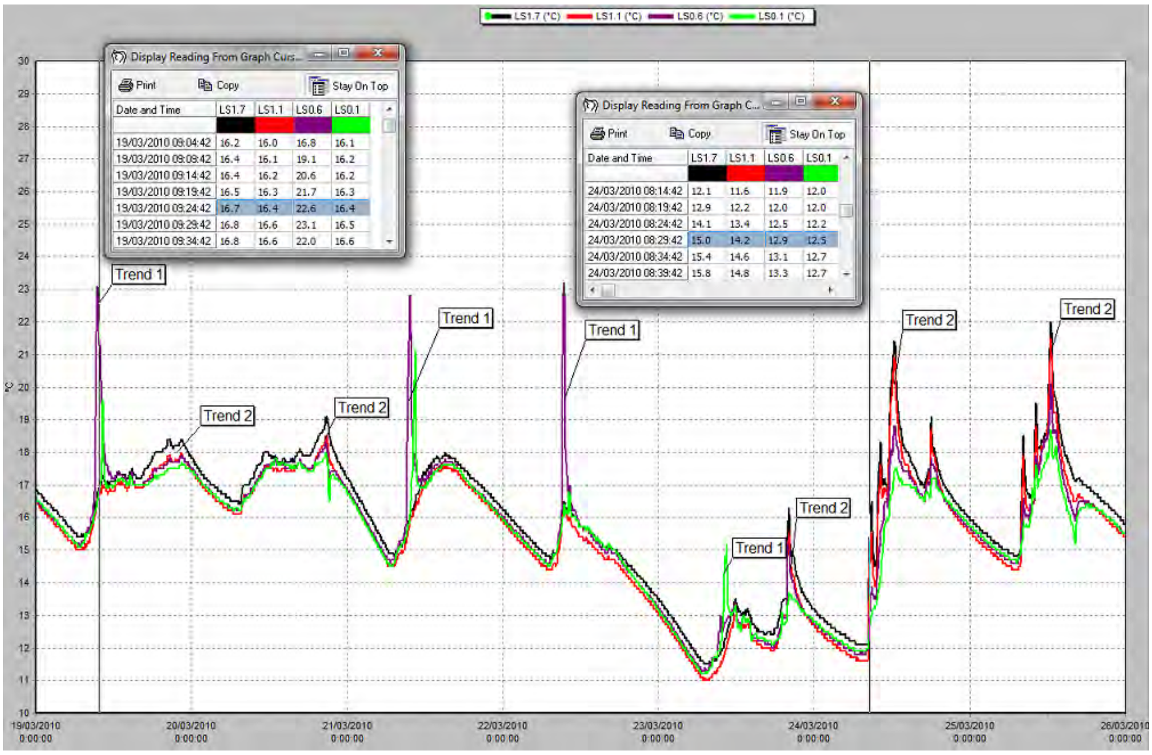


Figure 4-5: Built in temperature and humidity sensors in living space

It is observed in Figure 4-6, the chart of indoor air temperature at different height levels, that there are sudden rises in temperature in a short period of time and they can be classified into 2 trends. The first one is the increase in temperature at lower height level (e.g. at 0.1 and 0.6 metres height above floor) that further exceed the recording temperature at highest level (e.g. at 1.7 metres) and the second one is the increase in temperature at higher level (clearer for readings at 1.7 and 1.1 metres then 0.6 metres height above floor and 0.1 metres in order.

Recording data was explored to find out the causes that might affect readings. The first error trend could be explained as error readings caused by solar irradiation. It is then confirmed by employing SunCast image tool to verify the position and original source (See Figure 4-7). Also, when the solar radiation transmits heat through large glazing window and heats directly the temperature and humidity measuring instrument, it results in fake readings (i.e. excessively high air temperature and low relative humidity).

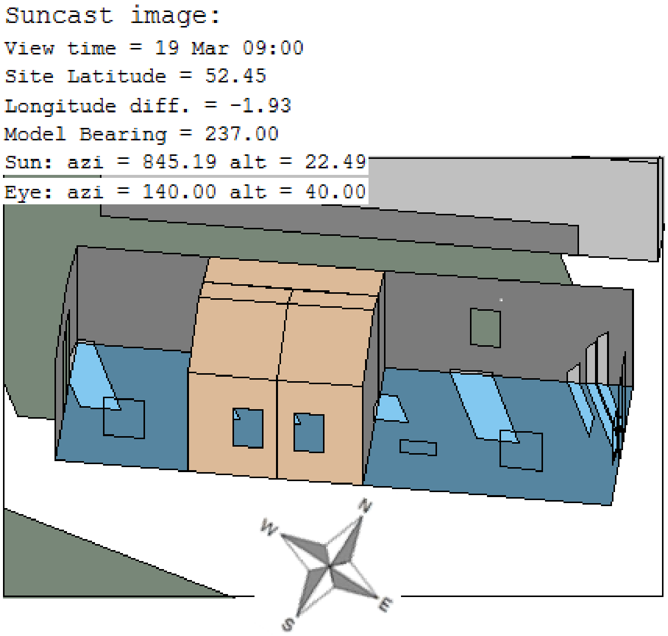
The second error trend (See Figure 4-6) relating to sudden increase in recording temperature at higher location level was mostly influenced by the use of a small fan heater of the building owner in order to generate a warm environment to work. This fan was switched on and off manually in accordance to how the owner felt about his environment so the time in operation is random. The use of fan heater leads to a significant increase in readings at 1.7 and 1.1 metres (black and red lines) than those at 0.6 and 0.1 metres (red and green lines) as a result of warm air rises up as seen in Figure 4-6. Besides, fluctuated temperature curves as shown in Figure 4-5 were due to interaction within the building via opening and closing door/window for a significant amount of time.



| Date and Time | LS1.7 | LS1.1 | LS0.6 | LS0.1 |
|---|---|---|---|---|
| | ⬛ | 🟥 | 🟪 | 🟩 |
| 19/03/2010 09:04:42 | 16.2 | 16.0 | 16.8 | 16.1 |
| 19/03/2010 09:09:42 | 16.4 | 16.1 | 19.1 | 16.2 |
| 19/03/2010 09:14:42 | 16.4 | 16.2 | 20.6 | 16.2 |
| 19/03/2010 09:19:42 | 16.5 | 16.3 | 21.7 | 16.3 |
| 19/03/2010 09:24:42 | 16.7 | 16.4 | 22.6 | 16.4 |
| 19/03/2010 09:29:42 | 16.8 | 16.6 | 23.1 | 16.5 |
| 19/03/2010 09:34:42 | 16.8 | 16.6 | 22.0 | 16.6 |

| Date and Time | LS1.7 | LS1.1 | LS0.6 | LS0.1 |
|---|---|---|---|---|
| | ⬛ | 🟥 | 🟪 | 🟩 |
| 24/03/2010 08:14:42 | 12.1 | 11.6 | 11.9 | 12.0 |
| 24/03/2010 08:19:42 | 12.9 | 12.2 | 12.0 | 12.0 |
| 24/03/2010 08:24:42 | 14.1 | 13.4 | 12.5 | 12.2 |
| 24/03/2010 08:29:42 | 15.0 | 14.2 | 12.9 | 12.5 |
| 24/03/2010 08:34:42 | 15.4 | 14.6 | 13.1 | 12.7 |
| 24/03/2010 08:39:42 | 15.8 | 14.8 | 13.3 | 12.7 |

Figure 4-6: Temperature profiles at the living space during 19th and 25th March 2010 (occupied occasionally)



```
Suncast image:
View time = 19 Mar 09:00
Site Latitude = 52.45
Longitude diff. = -1.93
Model Bearing = 237.00
Sun: azi = 845.19 alt = 22.49
Eye: azi = 140.00 alt = 40.00
```

Figure 4-7: Solar access within indoor space (IES screenshot)

### *4.4.2.2* Monitoring with equipment at new locations

Instruments were placed in the shaded area (i.e. out of reach of direct solar radiation) and no interference of occupant. The location selection was made as advised from <VE> SunCast analysis over every midmonth within a year in order to make sure of the location of the instruments out of direct sunlight.

Figure 4-8 describes the temperature profile during 7 days continuous (from 26th June to 3rd July 2010 without any interference of the building owner. From this, all curves of temperature profile at different height levels above floor predict the similar trend. It is observed that the difference in readings between 1.7 and 0.1 metres height above floor level is steadily not significant (e.g. less than 0.2°C difference). The maximum difference recorded between those levels of around 0.4°C might result reflected radiation. Whilst taking account of accuracy of measuring sensor of ± 0.1°C, the steady difference in readings can be ignored.

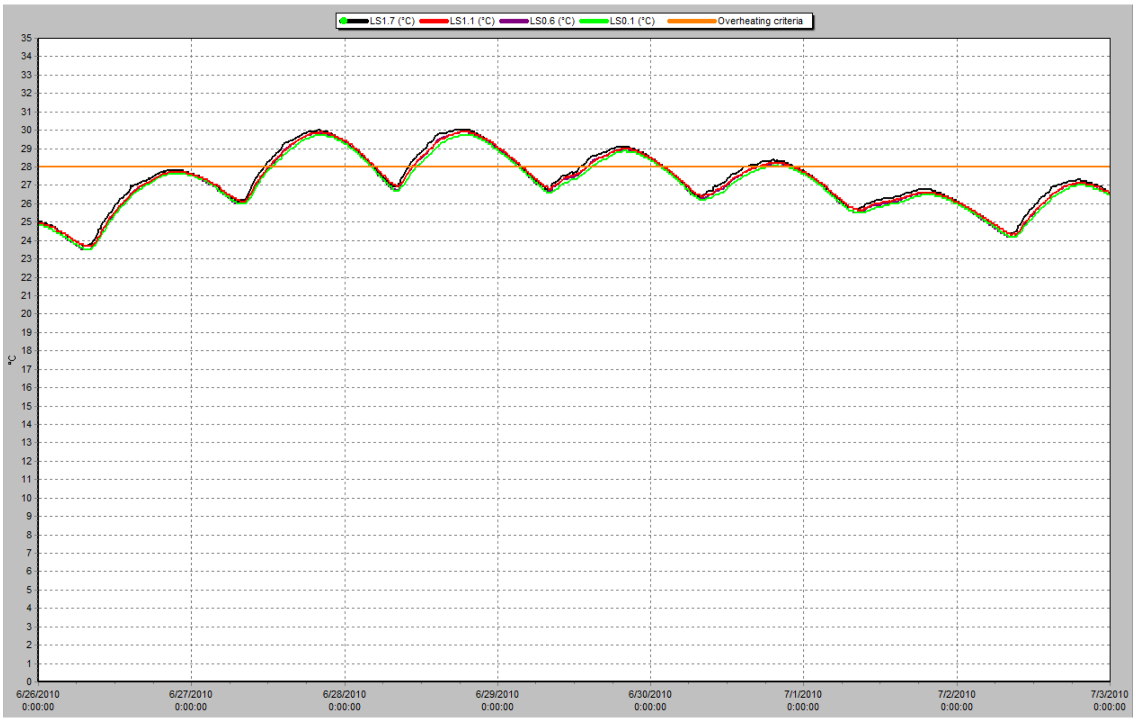


Figure 4-8: Temperature profile in the living space at test location without any occupancy interference during 26th June to 3rd July 2010.

Also, in the monitoring literature review, the aim of locating temperature sensors at different height levels is to study the local thermal discomfort which requires that the temperature difference between the head and the ankle height (at 0.1 and 1.1 m for seating occupant and 0.1 and 1.7m for standing occupants) does not exceed 0.6°C. The temperature curves in Figure 4-8 could confirm the good thermal performance of building envelope that assures local thermal comfort. From these reasons above, the number of measuring instruments during the monitoring at EH1 could be reduced to one sensor per each room.

+ From 14th July to present: Measuring instruments located opposite to the south east wall at 1.1 metres height above the floor level in the living space (see Figure 4-9) and at 0.6 metres height in the corner between south west and south-east walls of the bedroom.

Two black bulb sensors were installed since 14th July 2010 in order to provide readings of operative temperature for comfort study.

Figure 4-9: Black bulb sensor and built-in temperature and humidity sensor at 1.1m above floor level in the living space at EH

#### *4.4.2.3* Weather station and data treatment

Vaisala weather transmitter WTX520 was selected as the weather station for the project research as it applies all modern and recent techniques available for reliable weather data measurement as well as user friendly in operation and maintenance. This weather transmitter offers measurement of 6 basic weather data: barometric pressure, temperature, humidity, wind speed and direction and rainfall in just one compact instrument of particular advantage are the ease in which modules can be changed. The global solar radiation on the horizontal plane is measured by a pyranometer CMP3 manufactured by Kipp & Zonnen.

With respect to the installing requirement for weather station and pyranometer from the manufacture guidance as well as site security, the weather station cannot be located at the building site as for data set requirement in previous section. The weather transmitter and pyranometer were installed on the roof of School of Civil Engineering building at University of Birmingham which is of 1km radius distance from the construction site.

Figure 4-10: Weather station on the roof of the building of School of Civil Engineering

The data logging system relies on radio telemetry which offers a cost-effective, flexible and practical alternative to hard-wired one (Omni Instruments, 2009). The data from a range of sensors located at selected locations in ErgoHome test units are sent to Squirrel receiver logger and this logger transfers all the logging data to a personal computer (PC) by the use of a USB cable.

## *4.5 EMPERICAL CALIBRATION*

The weather file used in IES<VE> has the “file name”.fwt which can be exported to Excel allowing manually input of recording climatic data, then can be imported back to run the simulation using the customised weather conditions. The selected periods of time for empirical calibration were when the building was unoccupied for more than one week. It is necessary to mention that the building is still in progress at the finishing stage that is slowed down by the owner. The unit is interfered at reasonably high frequency of three days stay a week, excluding annual vacation.

Because the construction is lightweight thus it could be back at the “normal” state after a reasonable amount of time, says 1- 2 days during summertime. Because the influence on room thermal conditions from the act of occupant’s opening/closing windows does not last too long. Figure 4-11 to 4-12 show the variation in hourly temperature data between the measured air ambient temperatures, room air temperatures and the simulated results. The study was conducted where the modellers had no knowledge of the measured building performance. The measured indoor air temperatures followed the changing pattern of outdoor temperatures, with the slightly delay of about two hours in peak temperature. The simulated air and operative temperatures showed good agreement with measurements during the unoccupied period, the maximum difference is 0.7°C.

Additional validation work as shown in Figure 4-13 and 4-14 was required as there was some changes on the building envelope. The window blinds were added in the test building after summer 2010 to enhance privacy for the owner. The blinds also reduced heat gain from solar radiation and higher outdoor air temperatures that the differences between the peaks in indoor and outdoor air temperatures during the selected days were smaller, as shown in Figure 4-13, in comparing with those in Figure 4-11. Besides, the test building owner was doing the finishing work that affected the building envelope itself. For example, during August 2010, the cement board was built within the long sided external wall or the hole of 100mm diameter on bathroom floor was made for water excavation in October or mechanical ventilation heat recovery system was being built over November and December 2010. It was necessary to note that the first stage validation used the airtightness test result conducted by the researcher, the building test owner under support and supervision of Dr Colin Oram from the University of Warwick. An official airtightness test conducted by 3rd party (BSRIA Ltd) was undertaken after some interference within the building envelope as mentioned above. These modifications were taken into account in the simulation work.

The following reasons are to be determined as resulting in errors:

- Inaccuracy of the simulation tool itself (not to be discussed in the project).

- Error from assumption and approach: It is very important to bear in mind that the simulation is an attempt to reflect the reality. For example, thermal transmittance for each building element was calculated by the assumption of one dimensional heat flow, constructional layers were planar and heat path forms as the perpendicular to the surface and internal/external surface temperature was uniform within the surface.

- Inaccuracy of measuring instruments: The equipments in use to measure indoor air temperature possessed a significant inaccuracy range of ±0.1°C.

- Error from location: The climatic data inputted into the simulation were collected from a place of 1.1 miles distance to the test site which has slightly difference in external conditions. For example, it was observed that the temperature difference varying within (-0.57°C to 1.32°C) between air temperature from the weather station and outside the test building over a period from 7th to 12th October 2010. And the instruments measuring air temperature located opposing the wall instead of at the room centre because the readings had been affected by solar radiation.

Figure 4-15 illustrates the coldest period last winter (December 2010) when the outdoor dry-bulb temperature was within the range of (-12ºC to 5ºC). It was observed that the difference in hourly air temperatures between measurement and simulation that the simulation results follows the air ambient temperature whilst the reading deters with at nearly 8ºC difference at 00:00 on 15th December. It was because the occupant utilised a small fan heater in order to generate a warm space for working indoors hence the thermal conditions were affected. It accounted for the cool down of the building unit when the owner left the building at 20:00 on 14th December 2010. The indoor air temperature decreases slowly with the combined effect of remaining heat indoor and fluctuated outdoor air temperature as can be seen from day 1 to day 3. The validated model simulation ran through this period and illustrates that it takes around 5.5 days that the building lost totally the heat generated during the occupancy period. That might be a potential key performance of the ErgoHome in saving energy because the ability of maintaining the warmth can improve the use of heating device in term of intermittent operation. Also, on the right hand side of the graph, there was a sudden rise in temperature readings when the building started to be occupied at 10 am on 21st December 2010.

Figure 4-16 is the graph showing readings of outdoor and indoor air temperatures and the heating energy was used for the test building. However, there was not a comparison of whole house energy consumption between simulation results and measurement. It was due to the amount of work loads for simulation and field data work to validate the simulation model of heating system which could go beyond the timeframe of research work. Several studies: Lomas et al. (1997), Judkoff and Neymark (1995), Broomfield 1999) and Strachan (2005) showed significant amount of work and reasonably high uncertainties in errors between simulation and measurements. For instance, the case study: Lisses House collaborated between BRE and EDF reported that the comparison of whole-house energy consumption over the complete experimental period (more than two winter months) revealed errors ranging from -4% to +26% (Broomfield, 1999).

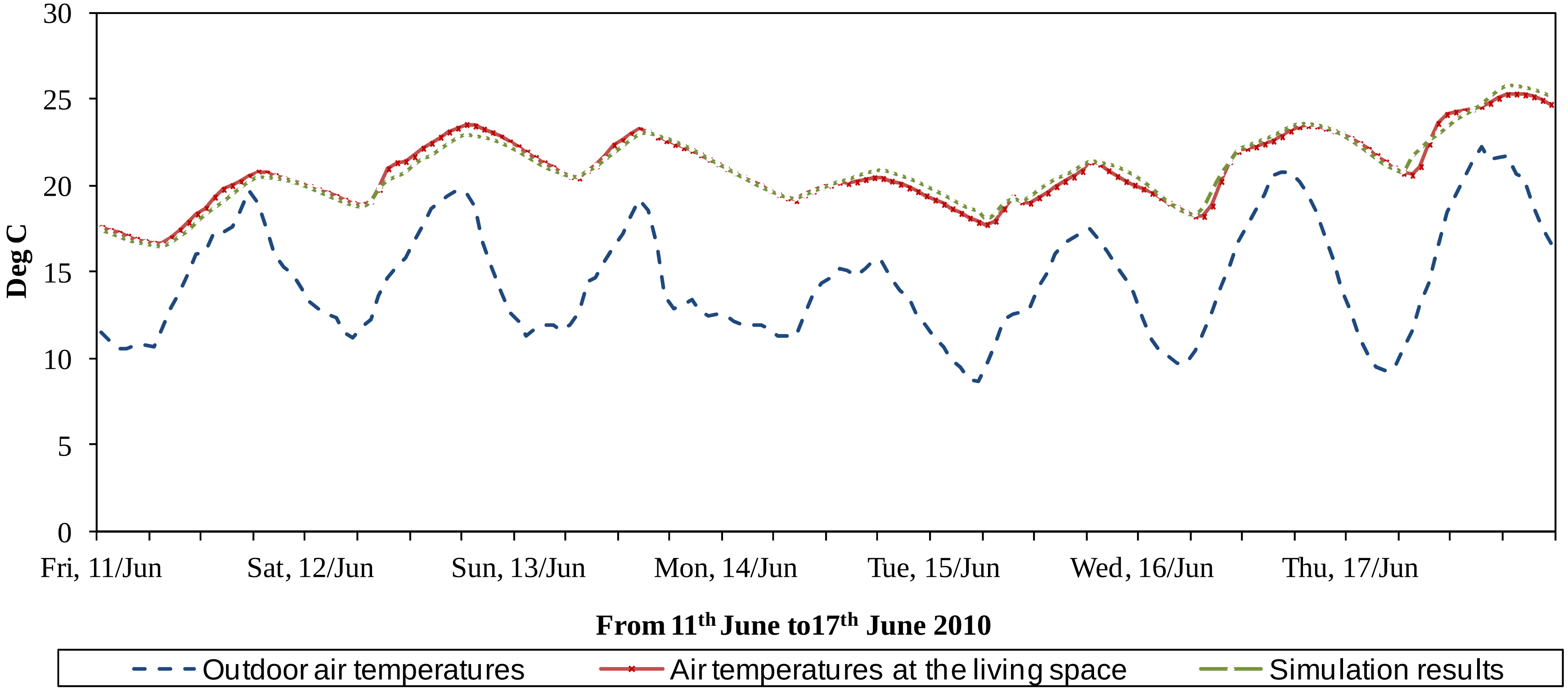


Figure 4-11: Comparison of hourly air temperature over a selected hot period in summer 2010

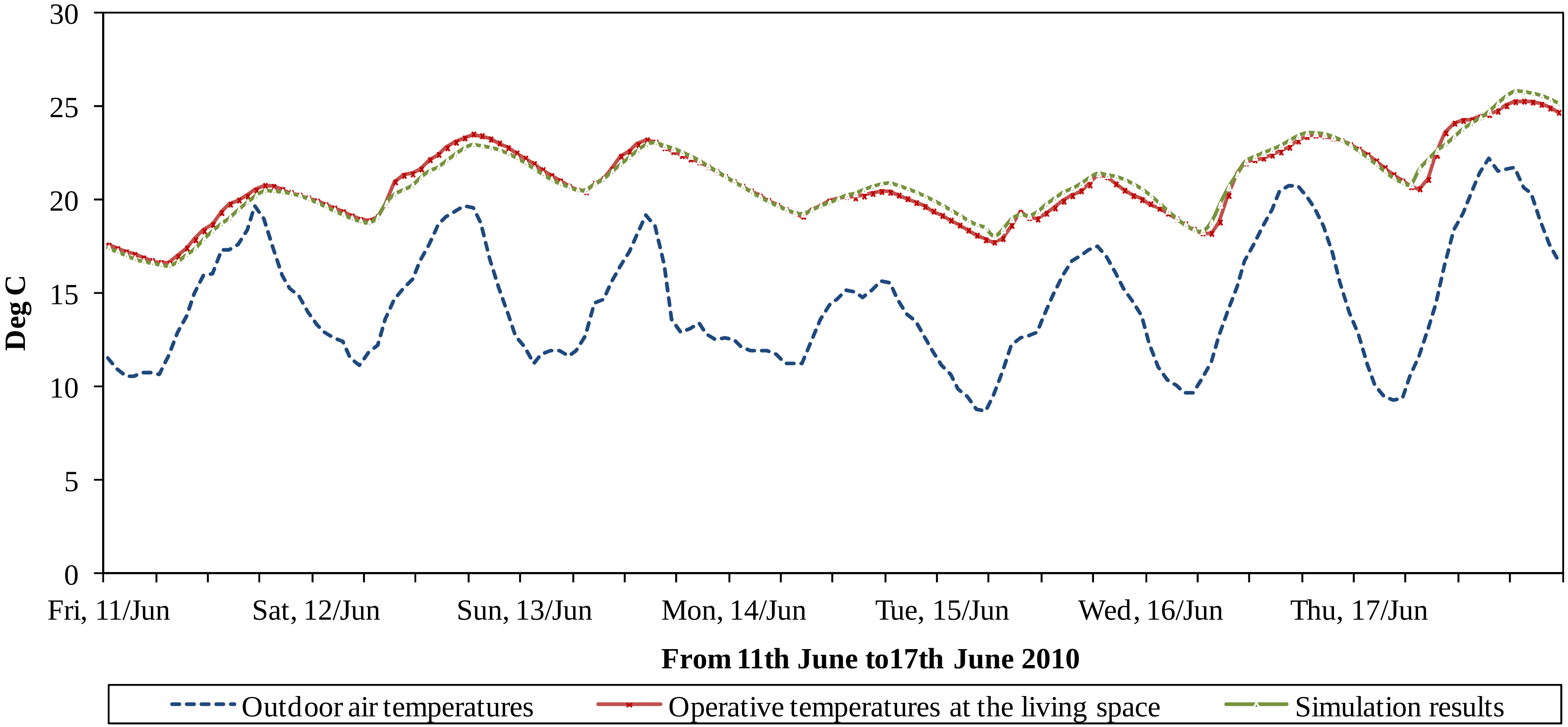


Figure 4-12: Comparison of hourly operative temperature at the living space during the selected hot week in summer 2010

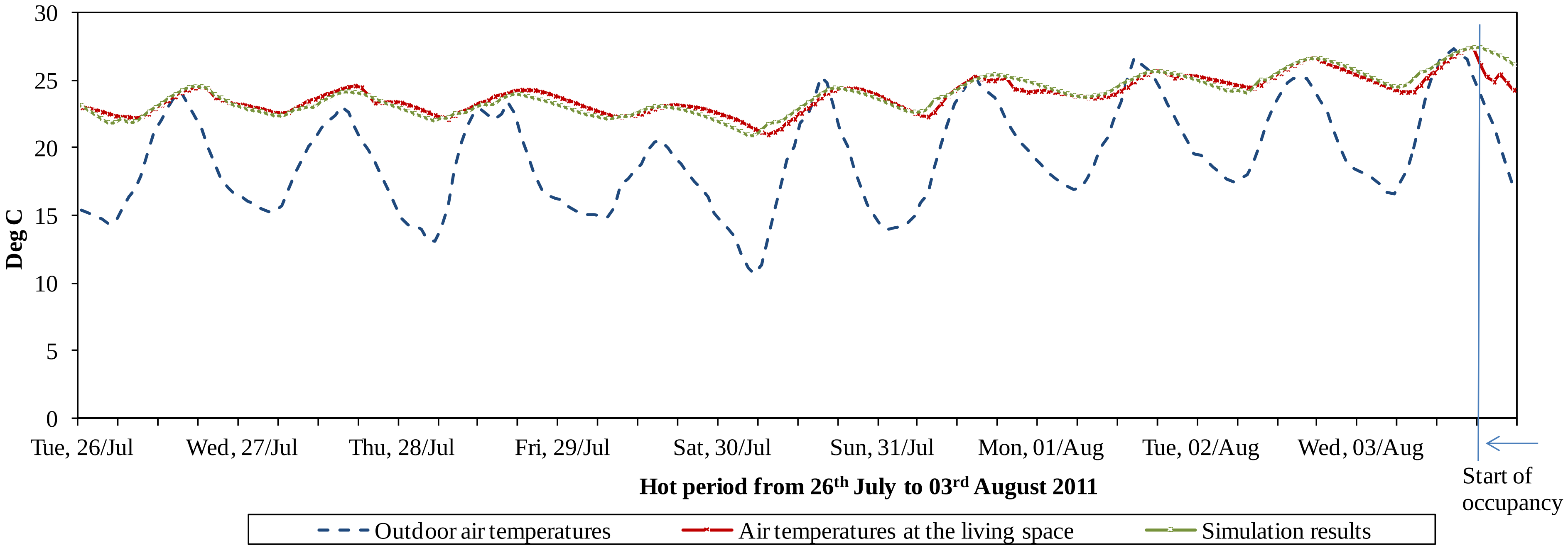


Figure 4-13: Comparison of hourly air temperature at the living space in a selected period in summer 2011

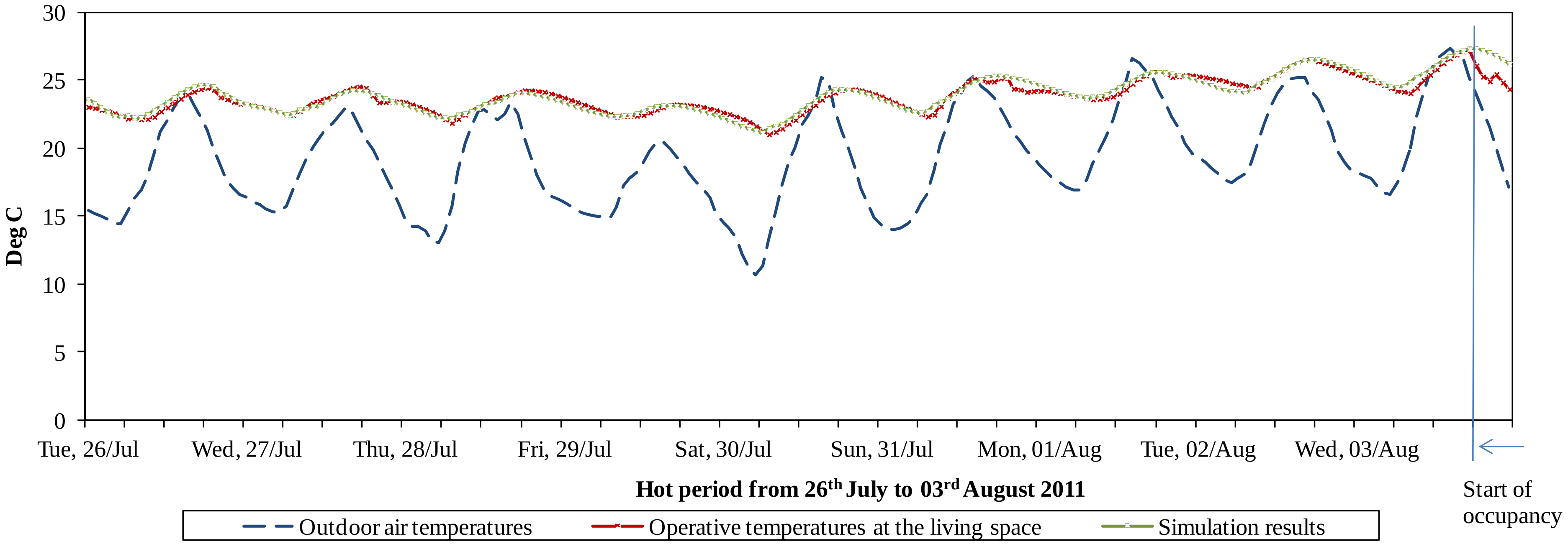


Figure 4-14: Comparison of operative temperature in the living space with installed internal blinds to prevent solar heat gain

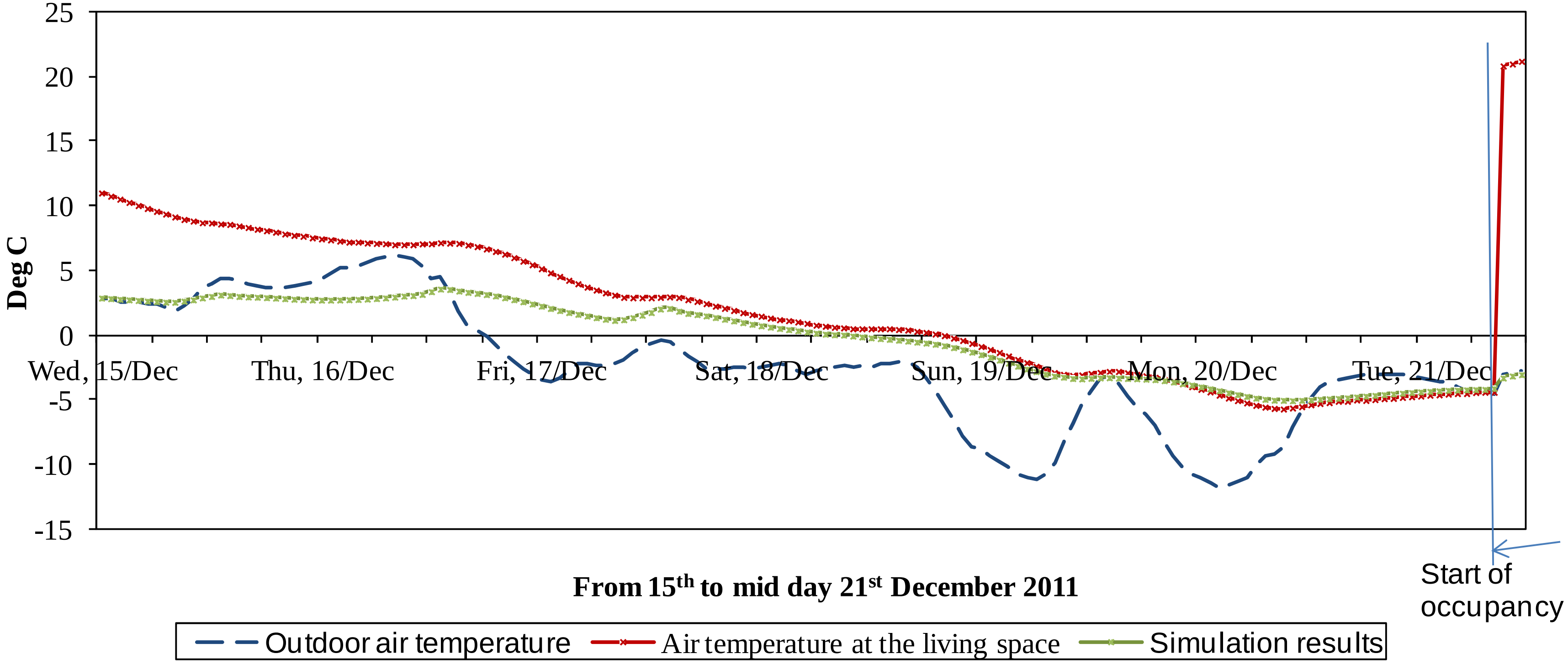


Figure 4-15: Comparison of hourly air temperature at the living space in winter 2011

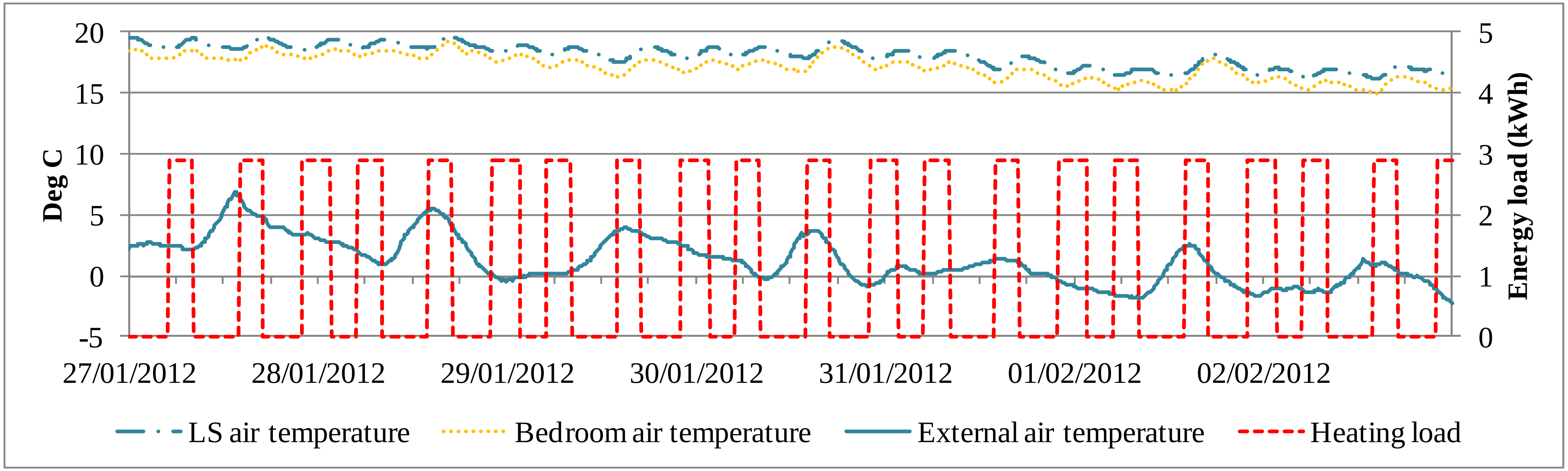


Figure 4-16: Monitored air temperatures when the test unit is heated by immersion heater, winter 2012.

## 4.6 SUMMARY

The field data from monitoring process shows that the indoor temperature changes steadily, around one fifth compared to the fluctuation of air ambient. The capability of maintaining a consistent indoor air temperature/operative temperature of the SIPs unit can be understood as improved thermal comfort. This is achieved by high level of insulation and airtightness of the building envelope. During the warm period, a small amount of heat might be required to achieve desired comfort level because the unit loses heat very slowly during the night, it picks up heat quickly by solar gain through its glazing fenestration and trapped this useful heat to maintain the warmth indoors. However, in summer 2010 overheating occurs inside the EH unit with the bedroom experienced the highest level amongst the rest due to the room volume and its high glazing areal facade facing the west. This issue was then solved by installation of internal shading devices of solar screen blind offered by Intelliglaze Ltd for summer 2011. It appears that the overheating risk is eliminated despite of the increase in the warmth this summer compared to last one (peak outdoor air temperature was up to 25ºC in end of July and last week in September 2011). Because it is shown in the field monitoring data that during the peak of external temperature the peak in internal temperature was delayed and equal or less than the outdoor level. However, during the daytime, the room remains gloomy that light bulbs are required if allowing working task taking place. With regards to ventilation performance that natural ventilation strategy is sought to apply in passive design strategy, it is shown that by opening the windows, the room temperature is cooled down to meet outdoor air temperature level very quickly, revealed by 10 minutes readings. Opening the French patio door will allow an effective and urge cool down if peak temperature indoors is undesired. During heating period, it was recorded of such severe condition in winter 2011, when outdoor air temperatures falls down to -12ºC, the indoor temperature varied amongst -5ºC. The two previous days of this coldest day, the outdoor temperature varies between -5 to 0 ºC and the indoor temperature varies between 0 and 5 ºC. The owner while occupying the EH unit used a fan heater to provide warmth during his working and it was recorded that it took 3 days air temperatures logging at the living space are closer to the simulation results. This can be interpreted as resulting in saving heating energy through shorter operation period and higher intermittent for the heater device, and in improved thermal comfort within the space.

Validation of simulation model includes analytical verification at the first stage to evaluate the accuracy of building model by empirical values or known calculated solutions. The simulation is then validated by empirical comparison that comparing hourly data or shorter interval between simulation results and monitoring of the unoccupied experimented building with the real weather data collected at the nearest to the construction site. The validated model simulation allows further development for integrated design solutions where passive design strategies are sought through and verified to be effective or not.

# Chapter 5: **SIMULATION DEVELOPMENT**

Building performance simulation aims to emulate the real physical conditions in a building by creating a model that ideally represents all energy flow paths in a building as well as their interactions (Clarke, 2001). The use of integrated simulation tool in building design process allows assessment of building thermal performance and predicts energy consumptions and emissions. Feedback from simulation results could be used for evaluating building environmental impacts and identifying rooms for improvement with regards to environmental impacts, budget and building type, available technologies and site planning.

A validated simulation model of the modular dwelling unit used in this study was presented in Chapter 4. This described the building performance without any interaction of real life activities and any interference from the installed building systems under real weather conditions in Birmingham during the monitoring period between 2010 and 2011. When the building is in use, the interactions between the occupants and building includes their interference with shading devices, ventilation (opening windows or activating the mechanical ventilation system), their usage of household appliances as well as their occupied period together with indoor activities. These factors vary differently between buildings, individuals and building systems and an example of occupancy profile was developed to predict the thermal performance and consumption of the dwelling construction unit in operation stage.

In order to illustrate the stage of building in use, a generalised pattern of occupancy profile including period of occupancy, activities taken place and level of consumption in response to everyday need (e.g. water consumption and electricity usage for electronic devices) was established. Input data for developing the occupancy profile were driven from Approved Document by the Building Regulations, CIBSE guidance documents, reliable resources of national statistics and published finding and reports in the research public.

External conditions in term of climatic data and site location used for developing the simulations are presented in Section 5.1. Occupant profile related to number of tenants, assumed daily living activities at home, the usage of household appliances and lighting as well as the heating and hot water in demand are discussed in Section 5.2. Section 5.3 shows the IES<VE> results of the predicted building performance regarding thermal, ventilation and lighting as well as the operational energy consumption. The last section is concerned with developing simulation scenarios for heating and cooling performance improvement applying passive design strategies.

## *5.1 WEATHER DATA*

Weather file data in use for building simulation was Chartered Institution of Building Services Engineers (CIBSE) test reference year (TRY) and the design summer year (DSY) for Birmingham location. In the UK, these reference years were developed by CIBSE for 14 locations from a set of measured weather data during 23 years between 1983 and 2005 to combine into single years of reference weather data (Kershaw et al., 2010). The TRY dataset contained 12 separate months of data, each of which was the most average month from 23 years data collection and its usage in building simulation to predict energy consumption and potential carbon emissions. The DSY reference year was said to be the year with the third hottest April to September period though it differed to extreme summer conditions (Kershaw et al., 2010). Therefore, the predicted thermal performance and consumption level derived from the study could showcase how the building operates under a certain circumstance regarding site location, building owner and usage pattern.

A medium condition of site exposure was assumed for simulations. Terrain type which determines the vertically variation of the wind speed and was assigned as suburb (range between city and country site) and wind exposure was selected as sheltered type. Such selection was made with regards to the design purpose of considering the overheating issue which would occur in lightweight construction like the building in the study. As it was indicated in IES<VE> guidance that the peak summertime conditions would occur for a sheltered site (IES, 2012a).

In order to assess the effectiveness of passive solar design, four main orientations where the main building facade faces south, north, east and west were main themes of simulation scenarios for variety of heating and cooling interventions. Because the work focused on assessing the performance of the building envelope, the obstruction on site was excluded at the development stage. This meant no surrounding buildings or trees were taken into account which allows evaluation with full solar receipt through building glazed fenestrations.

The simulations took site location into account by considering. However for study and obstruction free refers to no for a full solar receipt The main facade is designated as the long side external wall with more windows as illustrated in Figure 5-1. In case where the main building façade faces due south (S) the high glazing area on short façade in living space and bedroom faces due east and west (denoted as E and W) was herein denoted as south case and similar denotation for the three other orientations.

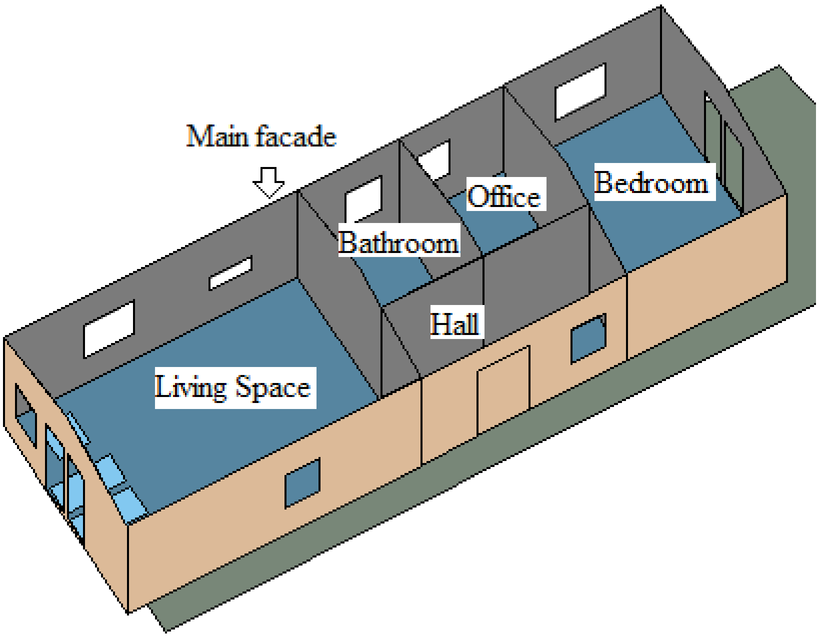


Figure 5-1: Designated indoor space and main building facade indication

## 5.2 *OCCUPANCY FACTOR*

In order to carry out suitable simulation of thermal spaces both quantitative and of variation profile, five different thermal zones were separated to reflect different purposed usage per each room in domestic building as illustrated in Figure 5-1.These includes the period of occupancy and main activity taken place in each room, equipment in use, required lighting to maintain illuminance for different tasks. Domestic hot water was supplied in kitchen space and bathroom for cooking, washing, and showering/bathing need. Natural ventilation was intended to be the main strategy for cooling performance though mechanical ventilation could be considered to supplement the ventilation later in development in case overheating risk wasn't resolved by natural ventilation. Space heating was maintained by the use of central heating system which is controlled by occupancy period and room temperatures.

Human behaviour could be understood in the whole spectrum of behaviour habits, and actions performed by the occupants at homes varying in individuals and depending on cultural, social and physiological. In building energy study, it refers to occupant's behaviour and interaction with the building in relation with energy consumption: heating and hot water, lighting, household appliances, cooling by natural ventilation.

There is adaptive approach towards comfort indoors, and individuals respond differently to the surrounding environment due to sex, health and activities (See Appendix A Section A.4.3.2). In order to predict the energy consumption demand for the given building, this section discusses about the occupancy period and assumed activities taken place in different zones in the dwelling, electricity consumption related to lighting and household appliance usage for daily activities, as well as heating and hot water demand. If the occupant does not feel comfortable with the prevailing indoor temperature, he will try to modify it, for instance, if it is too cold, he might turn on the heating device or if it is too warm, he might open window (s).

### 5.2.1 Occupancy profile

As previously discussed in Chapter 2 Section 2.1, the one person households increase significantly compared to other sizes of household, a two third of the total increase in households. With regards to the building size of the construction unit and the trend of single household demand, the occupant profile was taken as one person, as a working employee. Thus occupancy during weekdays was taken from 17:30 to 8:30. For weekends, the occupation was taken to be up to 70% of the time between 8:30 and 17:30 in addition to the weekdays' profile. This percentage followed the overheating purposed assessment suggested by CIBSE as it is important conditions for domestic building design with the presence of the occupant during the potentially high temperature during the daytime (CIBSE, 2006d). Thus, the assumption of occupancy distribution to five thermal spaces is shown in Table 5-1.

With the occupation in a space, the human body adds an amount of metabolic heat rate in the form of sensible and latent heat gain (Appendix A Section A.4.1.). They are denoted as SHG for sensible heat gain and LHG for latent heat gain. Whilst taking account of the main occupant activity pattern per each, the representative values of heat emission rates derived from Table 6.3 in (CIBSE, 2006a)) were used (See Table 5.1). These values which take account of mixture between males and females are for stated activity level in dwelling type. A value of 0.7 describes an occupation of 70% of the time in the living space. The hall was considered as circulation area therefore it could be used anytime when the occupant stay inside the building to pass from one room to other. Thus the occupation value was estimated to be very low, for instance a 5% from 7:00 to 8:30 could equate to 5 minutes long the occupant spent in the hall in a weekday morning.

Table 5-1: Space distribution and heat rate value given off by the occupant

| **Room** | **Rate of heat emission from the occupant** | **Time of the day during which the room is occupied**<br>*Occupancy density |
|---|---|---|
| Living space | SHG=75W and LHG=55W. | Weekday: 7:30 – 8:30 and 17:30 – 20:30.<br>Weekend: 7:30 – 17:30 (0.7)* and 17:30 – 20:30 (1.0)*. |
| Bedroom | SHG = 60W and LHG = 40W. | 23:00 – 7:00. |
| Office | SHG=75W and LHG=55W. | 21:00 – 23:00. |
| Bathroom | SHG = 75W and LHG = 70W. | 7:00 – 7:30 and 20:30 – 21:00. |
| Hall | SHG = 75W and LHG = 70W. | Weekday: 7:00 – 8:30 and 17:30 – 23:00 (0.05 and 0.02 respectively )*<br>Weekend: 7:00 – 23:00 (0.01)*. |

### 5.2.2 Household appliance profile

It is observed from UK National Statistics Publication Hub that statistic reports on annual electricity consumption in domestic sectors is often based on average values (DECC, 2012b). For example, energy statics show the average electricity consumption for dwelling in the UK is at 4411 kWh (DECC, 2009). This figure includes the electricity consumed for household appliances as well as space heating and domestic hot water (except for buildings with natural gas water boiler and heater).

A monitoring study of the electricity consumption of 72 UK domestic buildings suggests that an average consumption during the first year of the study was only 3100 kWh and this slightly increased in the second year to 3241 kWh (Firth et al., 2008). The rise in consumption compared to the first year was resulted from increases in consumption from continuous, standby and active appliances. In fact, monitored data of this study depicted an increase in electricity consumption of continuous and standby appliances by an average of 10.2% against first year usage and by 4.7% of rise for active appliances usage (Firth et al., 2008).

This study also investigated the responsibility of energy users on the overall increase in electricity consumption in the 72 monitored UK houses thus dividing into 3 groups as high, medium and low energy user based on their consumption. The ranges of electricity consumption are between the low energy user group with consumption of 1964 kWh, the medium group of 2670 kWh and the high energy user group consumed 5088 kWh per year (Firth et al., 2008). These findings agrees with recent published values provided by Ofgem UK, which classified the typical low consumption values for electricity is 2100 kWh and typical high consumption of 5100 kWh (Ofgem, 2007). Lastly, the study concluded by suggesting that the determining factor in household electricity consumption would relate to number of occupants, number and type of appliances, and occupancy patterns may be more relevant rather than the built form of dwellings (Firth et al., 2008).

In addition, a research of household electricity consumption conducted at the University of Strathclyde also suggests 3 examples of consumption level related to number of occupants: like a working couple consumes around 4117 kWh electricity, a family with 2 children (parents working and children at school) consumes 5480 kWh electricity and a single person will consume around 3084 kWh electricity (Currie et al., 2002). With reference to these data, the profile of household appliances for a single occupant can be established and this is shown in Table 5-2 and Table 5-3. The power consumptions of the household appliances were selected based on  data provided from Table 5.6 – 5.8 in CIBSE TM37 - Design for improved solar shading control (CIBSE, 2006d), based on research by the University of Strathclyde (Currie et al., 2002) and online data from Carbon Footprint Ltd (Carbon Footprint Ltd, 2011).

The electricity consumption rates of the household appliances were also taken into account as internal heat gain load in a space. The consumption rate established for activities in living space were distributed when the living space was occupied (e.g. 7:30 – 8:30 and 17:30 – 20:30). Main cooking activities were assumed to take place between 18:30 – 19:30. However, simulations neglected the heat gain emitted from cooking activities taking place in the kitchen area with an assumption that all the amount of heat from cooking would be completely removed. In practice, extract fans are used to exhaust polluted, moist and hot air from cooking to maintain indoor quality in most case or in some other cases, occupants will open windows to provide purge ventilation. Therefore, internal gain was formed by appliance loads of the living space, cold appliance like fridge-freezer on continuous mode and an additional heat load from breakfast by using toaster and coffee maker.

Table 5-2: Energy consumption and usage pattern for living space

| **Household appliance** | **Device power consumption** | **Average hours of use per day** | **Days of use per week** | **Quantities** | **Average energy usage per day** |
|---|---|---|---|---|---|
| | Watts | Hours | Days | - | kWh |
| **Living space** | | | | | |
| TV Plasma 34-37inch | 263.9 | 6.5 | 7 | 1 | 1.72 |
| Video Games (not inc. TV) | 195 | 1 | 1 | 1 | 0.03 |
| Wireless router | 7 | 6.5 | 7 | 1 | 0.05 |
| Satellite dish | 70 | 6.5 | 1 | 1 | 0.07 |
| CD/DVD Player | 50 | 2 | 1 | 1 | 0.01 |
| Portable Stereo | 60 | 2 | 2 | 1 | 0.03 |
| Vacuum cleaner | 600 | 0.5 | 1 | 1 | 0.04 |
| Electric Iron | 1400 | 0.5 | 2 | 1 | 0.20 |
| Total kWh per day | | | | | 2.15 |
| **Kitchen area** | | | | | |
| Fridge Freezer (408 kWh per | 46.5 | 24 | 7 | 1 | 1.12 |
| Toaster (2 Slice) | 1200 | 0.25 | 2 | 1 | 0.09 |
| Coffee Maker | 1200 | 0.15 | 2 | 1 | 0.05 |
| Extract Fan | 500 | 0.5 | 7 | 1 | 0.250 |
| | Watts per use | Number of use per year | | | |
| Washing Machine | 630 | 187 | | 1 | 0.32 |
| Electric kettle | 110 | 1542 | | 1 | 0.46 |
| Microwave | 945 | 96 | | 1 | 0.25 |
| Electric oven | 1560 | 135.1 | | 1 | 0.58 |
| Electric hob | 710 | 424 | | 1 | 0.82 |
| Dishwasher | 1440 | 135 | | 1 | 0.53 |
| Total kWh per day | | | | | 4.47 |

Table 5-3: Energy consumption and usage pattern for office space and bathroom

| **Household appliance** | **Device power consumption** | **Average hours of use per day** | **Days of use per week** | **Quantities** | **Average energy consumption per day** |
|---|---|---|---|---|---|
| | Watts | Hours | Days | - | kWh |
| **Office** | | | | | |
| Computer - CPU unit (without | 120 | 2 | 7 | 1 | 0.24 |
| Monitor 14" | 150 | 2 | 7 | 1 | 0.3 |
| Printer | 45 | 2 | 7 | 1 | 0.09 |
| Cellphone charger | 10 | 2 | 7 | 1 | 0.02 |
| Total kWh per day | | | | | 0.65 |
| **Bathroom** | | | | | |
| Electric Toothbrush | 5 | 0.08 | 7 | 1 | 0.0004 |
| Electric shower | 7500 | 0.17 | 7 | 1 | 1.25 |
| Extractor Fan | 500 | 0.5 | 7 | 1 | 0.250 |
| Total kWh per day | | | | | 1.50 |
| **Hall** | | | | | |
| Alarm/Security | 5 | 24 | 7 | 1 | 0.12 |
| Total kWh per day | | | | | 0.12 |

Total annual energy consumption calculated from total averaged consumption per day in Table 5-2 and 5-3 are: 365 x (2.15 + 4.47 + 0.65 + 1.5 + 0.12) = 3245 (kWh). This figure excludes the lighting power consumption which will be discussed in Section 5.2.3)

### 5.2.3 Lighting profile

Design guidelines recommended the provision of daylight in a space by employing the term daylight factor which was first proposed in the UK in early 1900s and included in building standards over fifty years ago (Hopkinson, 1963). The CIE overcast sky developed by The Commission Internationale de L‘Éclairage (CIE) which quite well models the completely cloudy skies in temperate climate such as the UK and western Europe are used in many daylight calculations (CISBE, 1999). The daylight factor is used to quantify the amount of diffuse daylight in a space and is measured at the height of working plane. This refers to the ratio of ratio of internal illuminance to unobstructed horizontal illuminance under standard CIE overcast sky conditions (i.e. 100% cloud cover), expressed as a percentage. A space is said to be dimly lit with a mean daylight factor of less than 2% and between 2 and 5% is considered to be well lit and it will require little or no electric lighting during daytime (BSI, 2008). Meanwhile, it is suggested for dwelling space that the required average daylight factor is 2% for kitchen, 1.5% for living space and 1% for bedroom (BSI, 2008). Minimum daylight factors for these spaces are respectively 0.6, 0.5 and 0.3 determined as an estimation obtained by dividing the average daylight factor by 2.3 (CISBE, 1999). The average daylight factor could either be calculated by the formula given in (CISBE, 1999) or determined by simulation results. The IES<VE> FlucDL tool was used to provide day lighting analysis regarding daylight factor and daylight illuminance results. In such sky condition, the daylight will refer to the diffuse light from a whole overcast sky. The worst case for natural daylight is likely to be a completely cloudy sky in mid-winter and it could be improved under a partly cloudy or clear sky with sunlight. Mid-winter design date as the 21st December with CIE overcast sky condition was selected for determining values of average daylight factors of different rooms. The mid-day (i.e. 12:00) of 21st December under CIE overcast sky condition was selected to calculate average daylight illuminance levels on the working plane at 0.85 meters height above the floor level in five different spaces as the lowest illuminance levels as given in Table 5-4. For the design purposes, the working plane is defined at 0.85m above the floor level in industry and domestic buildings or 0.7m in office like a desktop height (CISBE, 1999). These daylight results were in comparison with the recommended maintained illuminance level (Table 1.5 in CIBSE, 2006a) which could be fulfilled either by daylight or artificial lighting or both with dimming option available for electric lighting for the purpose of lighting energy savings.

The comparison of the results in Table 5-4 and the required average daylight factor confirms that the clear glazed fenestrations of the building unit are well lit for their purposes and no artificial lighting is needed during the daytime. Thus, it was supposed that there is no need of artificial lighting in the premise during the daytime in weekends/holidays.

Table 5-4: Daylight illuminance on the 21stDecember, CIE Overcast sky

| **Room** | **Average daylight factor, %** | **Average daylight illuminance, lux** | **Recommended maintained illuminance, lux** |
|---|---|---|---|
| Living space | 3.9 | 161 | 150 - 300 (kitchen area);<br>50 – 300 (lounge) |
| Bedroom | 4 | 166 | 100 |
| Hall | 1.7 | 71 | 100 |
| Bathroom | 2.1 | 88 | 150 |
| Office | 2 | 83 | 300 |

Whilst considering the recommended range for maintained illuminance of the living space (See Table 5-4), an average illuminance level of 161 lux was deems reasonable since the day lighting level will be improved under partly cloudy sky or clear sky with the sun. Higher illuminance level would be preferable for kitchen area which could be fulfilled by the use of electric lighting. Also, the cooking activities was developed in occupancy profile to take place between18:30 and 19:30 daily during this period of time, the daylight maybe still available during summer time but not in winter time thus electric lighting is required. The same argument can be applied with the use of artificial lighting in the office during the occupied period between 21:00 and 23:00 and the bathroom between 7:00 – 7:30 and 20:30 – 21:00. For the bedroom, lighting was switched on for half an hour at night and another half an hour in the morning to ensure illuminance for personal preparation before and after bedtime. During these times, the room was either dark or dim so electric light was an obvious use. As shown in Table 5-4, the illuminance in the hall was below the recommended value thus the electric light might be required during the daytime in the weekend. However, whilst considering the occupation time assumed for the hall and the length of this circulation area, is was reasonable to assume electric light to be off between 8:30 and 17:30.

In order to specify sensible lighting gain as well as power consumption, if the required illuminance level is known, the parameter “installed power density” is employed. The installed power density per 100 lux is the power needed per square metre of floor area to achieve 100 lux of the average maintained illuminance on a horizontal working plane (IES, 2011a). Lighting power consumption in Watts was calculated by a multiple of lighting power density value (W/m$^2$ per 100lux), the maintained illuminance (lux) and floor area (m$^2$) as shown in Table 6-5. The 2010 Approved Document part L for new dwelling requires 75% of the fitted luminaires to be low energy that provide luminous efficacy of 45 lumens per watt (lm/W) (DCLG, 2010a). For this requirement to be applied, taking the living space as an example, to achieve the required illuminance of 200 lux (i.e.200 lumen per $m^2$), the lighting power consumption to illuminate the floor area of 20.43 $m^2$ is 90.8 watts.

Meanwhile, a research study conducted by Centre of Energy and the Environment at University of Exeter showed that the installed lighting density of the notional building (as discussed in 2010 Approved Document part L) ranged between 2.2 - 2.4 W/$m^2$ per 100 lux. This finding was derived from the graph presented in the study showing the installed density lighting as a function of room geometry.(CEE, 2011). The lighting power consumption for the living space ranged between 90 and 98W. This agreed with previous calculation by using the installed power density of 2.2W/$m^2$ per 100 lux and was used to determine lighting power consumption for five rooms in the building unit (See Table 5-5). The hall was considered as the circulation area thus the presence of the building occupant was at low density and random time (see Section 5.2.1). When the day lighting is not available, electric lighting in the hall should be switched on and off in accordance to save energy. An assumption of lighting in use was as half as the occupancy time as stated in the table below.

Table 5-5: Lighting power consumption and usage pattern

| Room | Installed power density, W/($m^2$100 lux) | Maintained illuminance, lux (See Table 6-4) | Floor area, $m^2$ | Lighting power consumption, W | Period of time lighting in use, 00:00 – 23:59 |
|---|---|---|---|---|---|
| Living space | 2.2 | 200 | 20.43 | 90 | 7:30 – 8:30 &<br>17:30 – 20:30 |
| Bedroom | 2.2 | 100 | 10.98 | 24 | 7:00 – 7:30 &<br>22:30 – 23:00 |
| Office | 2.2 | 300 | 5 | 33 | 21:00 – 23:00 |
| Bathroom | 2.2 | 150 | 4.9 | 16 | 7:00 – 7:30 &<br>20:30 – 21:00 |
| Hall | 2.2 | 100 | 4.6 | 10 | 7:00 – 8:30 &<br>17:30 – 23:00 |

### 5.2.4 Heating profile

It is generally accepted in the UK that if the average outdoor air temperature is higher than the “base temperature” at 15.5°C, the building will not need to be heated. (CIBSE, 2006c). Figure 5-2 depicts the outdoor air temperatures over a year from the CIBSE TRY weather file. By using the base temperature reference as threshold value, the heating period is selected between the months of October and May during which the outdoor air temperature is below 15.5°C.

The comfort range in domestic buildings is designed such that the operative temperatures are between 19 and 25°C (See Appendix A, Section A.4.3.1). In comparison with this criterion, the operative temperatures in the living space (e.g. grey line shown in Figure 5-2) were lower than the recommended level during the months between October and mid-April. This result would be higher as it excluded internal heat gains, thus the heating period might be shorter.

From this observation, the heating period was determined based on room operative temperatures during the time the room was occupied rather than based on generic outdoor temperatures threshold value (e.g. base temperature). This could be explained that the base temperature was a historical convention applied for UK conventional dwelling materials (e.g. concrete blocks or stones). New dwellings with good insulation reduces significant amount of heat loss whilst receiving additional heat gain through effective solar passive design that helps maintaining a warmer indoor conditions.

It is stated that The Fuel and Electricity (Heating) (Control) Order 1974 and The Fuel and Electricity (Heating) (Control) (Amendment) Order 1980 prohibit the use of fuels or electricity to heat premise above 19°C (CIBSE, 2006a). Hence, the room operative temperature was heated up to 19°C by a heating device though the comfort would be enhanced by additional heat sources from solar radiation and internal heat gain. A central heating system with time and thermostat control per room was assumed for the simulation development. This meant that the heating profile was established that the heating system in operation only if the room operative temperature was below 19°C and the occupant was at home. From the energy saving point of view, there was no need for heating during the bedtime so the heating was switched off at 23:00. Timer set was then at between 6:30 to 8:30 and 17:00 to 23:00 during weekdays and 6:30 – 23:00 in the weekend.

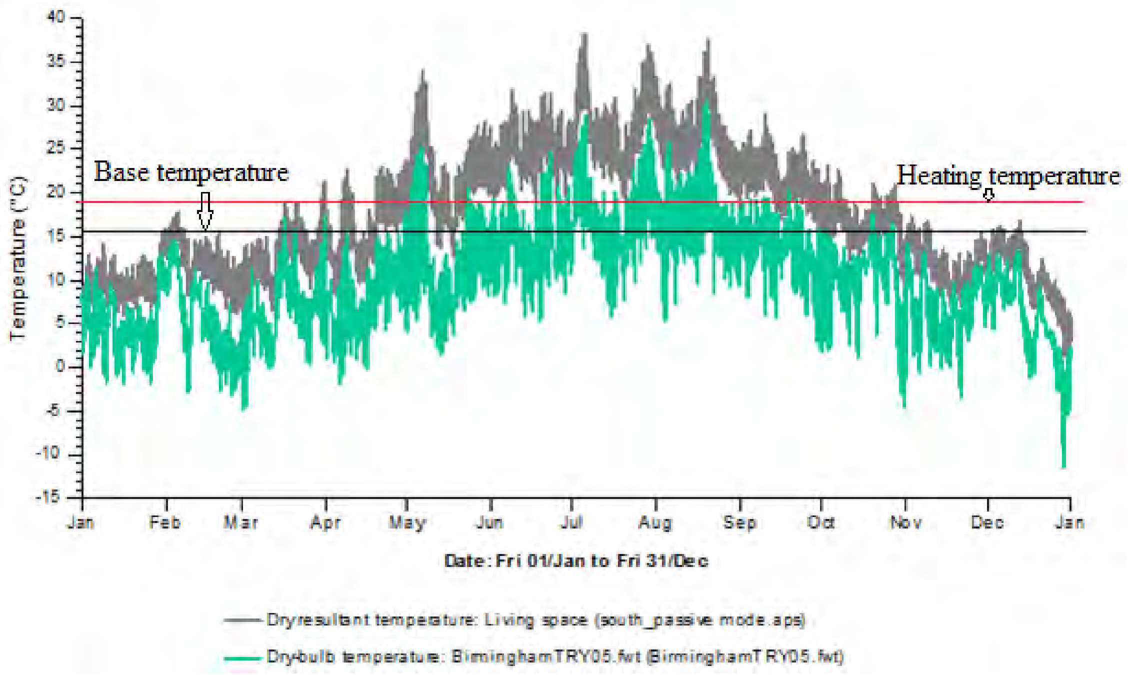


Figure 5-2: External air temperature and operative temperatures in main area

### 5.2.5 Domestic Hot Water consumption

Hot water in residential buildings is used for different purposes such as bath/shower, hand washing, clothes washing and dish washing (by hand or machine). According to English House Condition Survey data of consumed hot water for different usage levels for each appliance, a total average usage is of 49 litres of hot water per person per day. Where, the average consumption of hot water across all households is 4 litres per person per day for washing machines and 35 litres per person per day for baths and showers. An additional 10 litres of hot water is used for the cleaning of dishes at the sink and for hand and face washing (BIS, 2005).

Domestic hot water (DHW) consumption profile in litres/hour per person established in the model is of 6.65 litres/ hour per person for the living space during 4 hours occupied and 26.4 litres/ hour per person for shower and hand washing with 1 hours of use in total.

## *5.3 PREDICTED BUILDING PERFORMANCE*

This section discusses about the simulation results from the input information developed from the previous sections. It includes ventilation performance in two aspects providing whole building ventilation to assure indoor air quality and cooling performance by passive ventilation, human comfort and availability of daylight in the space.

### 5.3.1 Trickle ventilator performance

The adopted ventilation strategy for the dwelling unit is the combination of naturally ventilation (e.g. whole building ventilation or background ventilation is provided by trickle ventilators and purge ventilation for reduce overheating risk through opening windows) and mechanical ventilation system (e.g. intermittent extracting fan). This is known as “mixed-mode ventilation” or hybrid ventilation (DCLG, 2010b). It is suggested in Approved Document part F - Ventilation that for the air supply to the habitable spaces in a dwelling that the whole dwelling ventilation rate is more than 13 l/s as for a dwelling with one bedroom (Table 5.1 in (DCLG, 2010b)). Additionally, it requires that the minimum ventilation rate per each room is not less than 0.3 l/s per $m^2$ internal floor (DCLG, 2010b). Applying these requirements, the ventilation rates in different zones in the building unit are calculated as shown in Table 5-6.

Table 5-6 : Required ventilation rate per floor area

| | **Living space** | **Bedroom** | **Office** | **Bathroom** | **Hall** | **Whole building** |
|---|---|---|---|---|---|---|
| Floor area ($m^2$) | 20.43 | 10.98 | 5 | 4.86 | 4.6 | 45.87 |
| Ventilation (l/s) | 6.13 | 3.29 | 1.5 | 1.46` | 1.38 | 13.76 |

An approximate annual air infiltration rate was determined through the known value from the airtightness test given as one twentieth of the measured number of air changes per hour at the pressure difference of 50Pa using empirical values in CIBSE technical memoranda about testing buildings for air leakage rate (CIBSE, 2000). The airtightness results were presented in the previous chapter (See Chapter 4, Section 4.4.1), with the number of air change per hour at 50Pa noted as n50 = 2.1 ac/h (Air leakage test result shows $Q_{50}$ = 283 $m^3$/h and building volume V = 135 $m^3$) thus air leakage rate is 0.1 ach, equating to 1.67 l/s with the volume of the living space. By comparing the required ventilation rate indicated in Table 6-6 whilst accounting of the air leakage rate of 1.67 l/s (or 0.1ac/h), the required ventilation rate for the living space is then equal to 4.46 l/s.

In addition, the term “equivalent area” was introduced to replace the “free area” when sizing the background of ventilator (i.e. trickle ventilators). “Free area” is defined as the physical size of the aperture of the ventilator while “equivalent area” reflects the air flow performance that the trickle ventilator will achieve (DCLG, 2010b). Trickle ventilators installed on large and small windows of the building unit were supplied by the VELFAC Ltd manufacture. The manufacture statement indicated that the product in use namely click vent of 40 $cm^2$ free area possessed the equivalent area of 27.6 $cm^2$ (VELFAC, 2009). Seven windows with click vents could make up to 7 x 27.6 = 193.2 $cm^2$ or 19320 $mm^2$. This is below the guidance for background ventilators as indicated in Table 1.2a in Approved Document part F - Ventilation of the Building Regulations 2000. For a one bedroom single storey dwelling above the ground level with more than one exposed facade, the total "equivalent area” for the total floor area of less than 50 $m^2$ should not be less than 25,000 $mm^2$ (DCLG, 2010b). Regarding building background ventilation performance as a whole, the current numbers of trickle ventilators in the building unit were below the guidance. Additionally, it is worth notify that in order to provide minimum ventilation, trickle ventilator maybe oversized for the more common external conditions and this could lead to draughts and wasted energy in heating the coming air ((White and Perera, 1998). Therefore, the simulation results regarding ventilation performance by trickle ventilators in providing air exchange rate would be looked at closely in both heating load and the required air flow rate.

Assumption that the required background ventilation was maintained during occupancy period, 2 simulation scenarios were developed. The first case employed air flow model reflecting click vents on windows that are active while in the second case, a fixed rate equivalent to 13 l/s was assigned to the model. In fact, a value of 0.27 ac/h was used which added to the infiltration rate of 0.1 ac/h to make up 0.37 ac/h equating to 13 l/s. In the two simulation scenarios, the ventilation profile was available during occupancy period. In the second case, the air exchange is at the fixed value on continuous basis that could be supplied from the mechanical ventilation system or mechanical ventilation with heat recovery which will be discussed in Chapter 6-Section 6.3.1. Figure 5-3 shows the predicted energy consumption for heating in these two cases.

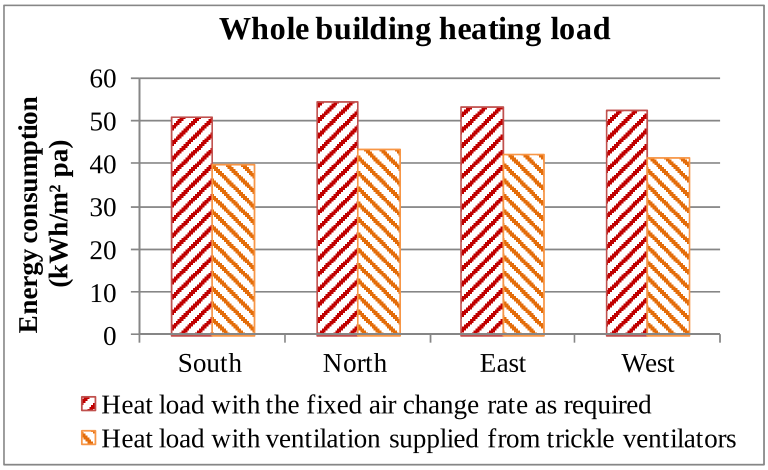


Figure 5-3: Heating energy consumption for 2 cases, one with fixed air exchange rate and another with operated trickle ventilators.

It is observed from Figure 5-3 that the heating requirements of the second case that assigning a fixed air exchange rate is significantly higher than that of the first case which modelled trickle ventilators in use. Taking the living space as an example, Figure 6-4 shows the air flow rate supplied by operating trickle ventilators built within the simulation modelling. It was assumed that the trickle ventilators were used since the start of the occupancy period and closed when the building was unoccupied by occupant's manual control. This flow rate profile driven by wind and stack effect, already included the air infiltration rate. The recommended background ventilation was not met by the provision of air exchange rate through the three trickle ventilators on 3 external facades of the living space as shown in Figure 5-4.

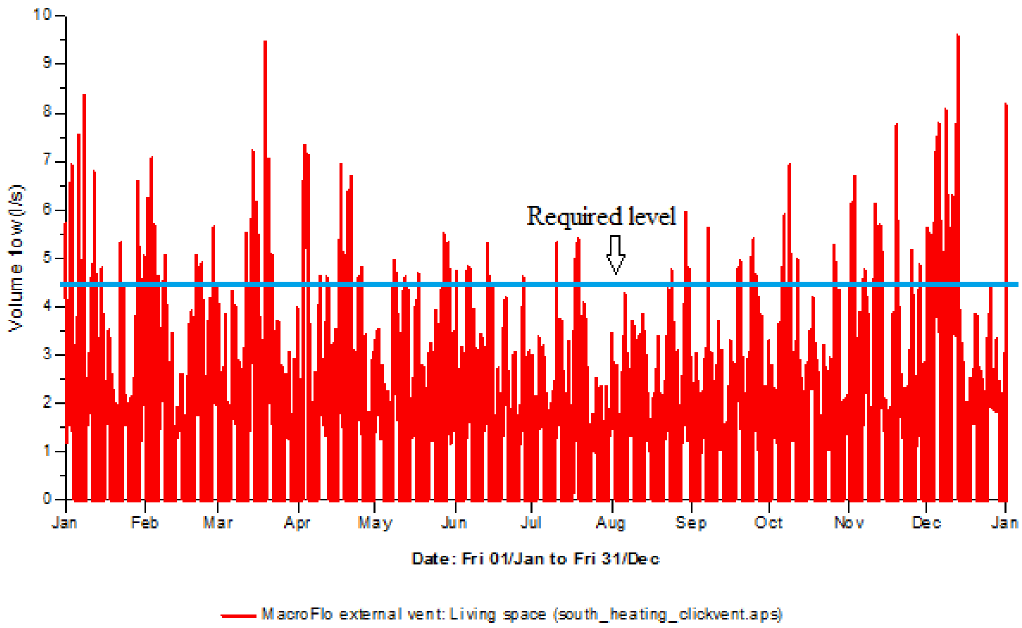


Figure 5-4: Air exchange rate in litre per second supplied from three trickle ventilators on three exposed facades of the living space

By resizing the trickle ventilators in order to provide adequate ventilation (e.g. the total equivalent area of 25,000 mm$^2$), the equivalent area of each trickle ventilator is 25000/7 = 3571 mm$^2$ or 35.71 cm$^2$. As the ventilation performance of trickle ventilators in dwelling was not the main focus in the study, therefore it was impossible to address the use of trickle ventilators in supplying adequate background ventilation or improving indoor air quality. For this reason, the fixed air exchange rate to maintain background ventilation during occupancy period was assumed for simulations. The difference in heating energy demands in these two cases as shown in Figure 5-3 could be illustrative for the effect of heat loss by ventilation. A much higher heating consumption would be expected if relying on opening windows to provide fresh air into room during winter months.

### 5.3.2 Thermal performance

The simulation outputs are presented in graph showing predicted energy required for heating demand and overheating analyses. This facilitated the evaluation of efficacy of each design strategy in term of thermal performance (both heating and cooling demand) because each of building design elements (form, shape, fabric, shading device, and ventilation) has had a significant impact on the whole building thermal performance. The cooling strategy in domestic buildings mostly relies on natural ventilation through trickle ventilation or through openings when overheating occurs. In case of higher cooling demand, mix-mode ventilation can be applied where mechanical ventilation supplements natural ventilation.

The overheating degree hour was used to express the severity of overheating risk (See Appendix A Section A.4.3.3). By using the threshold temperature for living rooms as active spaces (e.g. living space, bathroom, hall entrance, office) at 28°C and 26°C for bedroom, the cooling performance are described in Figure 5-5. It is necessary to mention that the heating performance was assessed by using CIBSE TRY weather file and the cooling performance was assessed by using warmer conditions of CIBSE DSY weather file. The initial state of building refers to current construction of the building unit to differentiate with other changes made onto the building envelope at simulation development stage in the next sections.

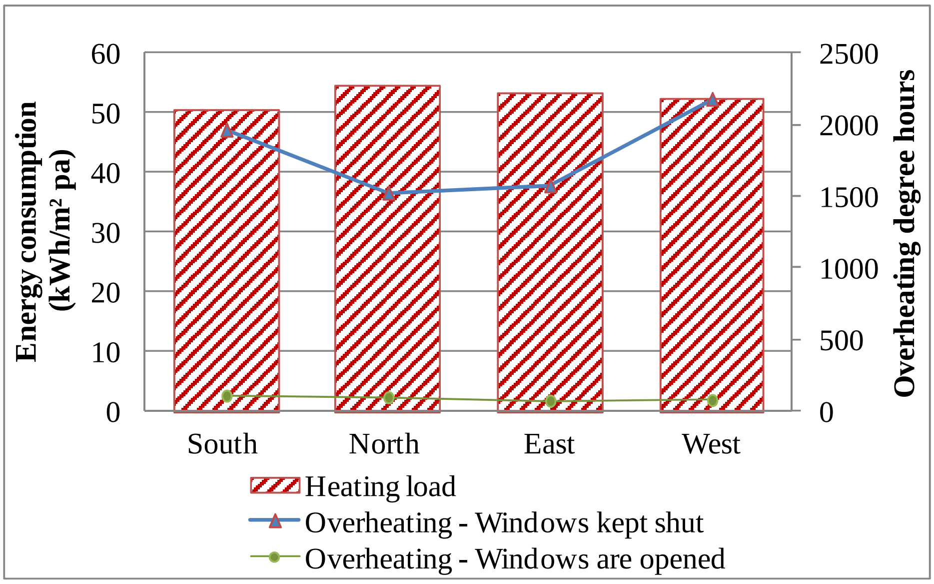


Figure 5-5: Predicted heating demand and overheating severity5

As shown in Figure 5-5, the differences in total space loads (in kWh/m$^2$ per annum) within 4 main orientations are not significant with the lowest consumption for south case of 62 and the highest consumption is for the north case with 64.3, that equates to 3.7% more in demand. Amongst four cases, heating energy demand is lowest in south case and highest for the north case while cooling energy demand is lowest in the east and highest in the west. These figures would also suggest that site orientation contributes a very little in the thermal performance of highly insulated building envelope, the order in site orientation to go for is south, west, east then north.

The cooling performance is detailed by the temperature profiles shown in Figure 5-6 for the scenario if opening windows is not permitted. For all the four orientations, the room temperatures are always above the overheating benchmark with the bedroom temperature higher than 26°C and the other spaces above 28°C. Without opening windows, mechanical ventilation or air conditioning are required. To compliment this, passive ventilation will be discussed in the following section

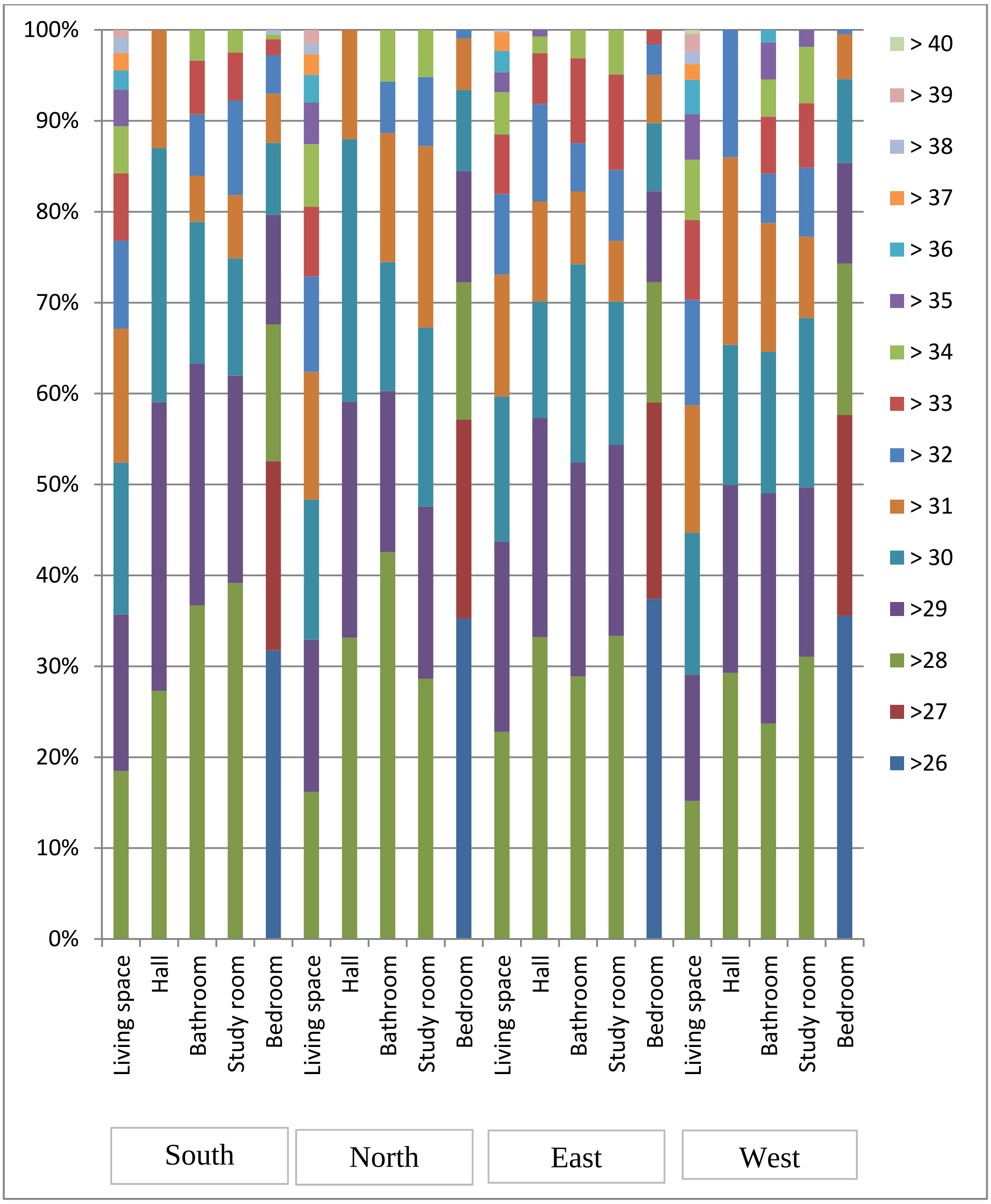


Figure 5-6: The temperature in different rooms via four orientations during cooling period

### 5.3.3 Ventilation performance

The test thermal performance of the building unit during cooling months provides reasonable potential keys for passive cooling design. Passive cooling design starts with a high performance of building envelope in order to reduce unwanted heat gain to internal spaces hence minimising cooling load.

In order to assess cooling performance by passive ventilation, simulation scenarios were developed for 3 cases:

(1) When all building fenestrations are kept shut.

(2) When windows start to open during the time that the building is occupied (closed at 23:00 for security reason) when indoor operative temperature reaches to 25°C and outdoor air temperatures are lower than indoor ones. This threshold value was based on observation that occupant starts to feel hot when operative temperature exceeds 25°C (CIBSE, 2006a).

(3) When French patio doors in the living space and the bedroom are open in addition to opening of windows to provide higher air exchange rate to remove heat quicker hence the space is cooled down quicker. This opening profile restricts with occupancy period and the closure at 23:00 when occupant goes to sleep.

#### *5.3.3.1* Overheating risk assessment

Simulation results from the first case could provide assessment of overheating risk of the dwelling unit in case that it is impossible to apply natural ventilation strategy.. Mechanical ventilation, air conditioning or other cooling technologies are required to be alleviate overheat indoors. The second scenario simulated windows opening at the threshold temperature to reduce overheating risk and the third one which simulated opening of French patio doors in the living spaces and bedroom to test the efficacy of the increased air flow rates supplied by all the building fenestrations when the building is overheated. The overheating risk assessment based on CIBSE guide A criterion of less than 1% of the percentage of annual occupied hours when operative temperature exceeds a threshold benchmark at 28°C for living spaces and 26°C for bedrooms (CIBSE, 2006a). The simulation results of the percentage of annual occupied hours that operative temperatures in five different spaces exceeds the overheating benchmark are shown in Figure 5-7 for 4 main orientations.

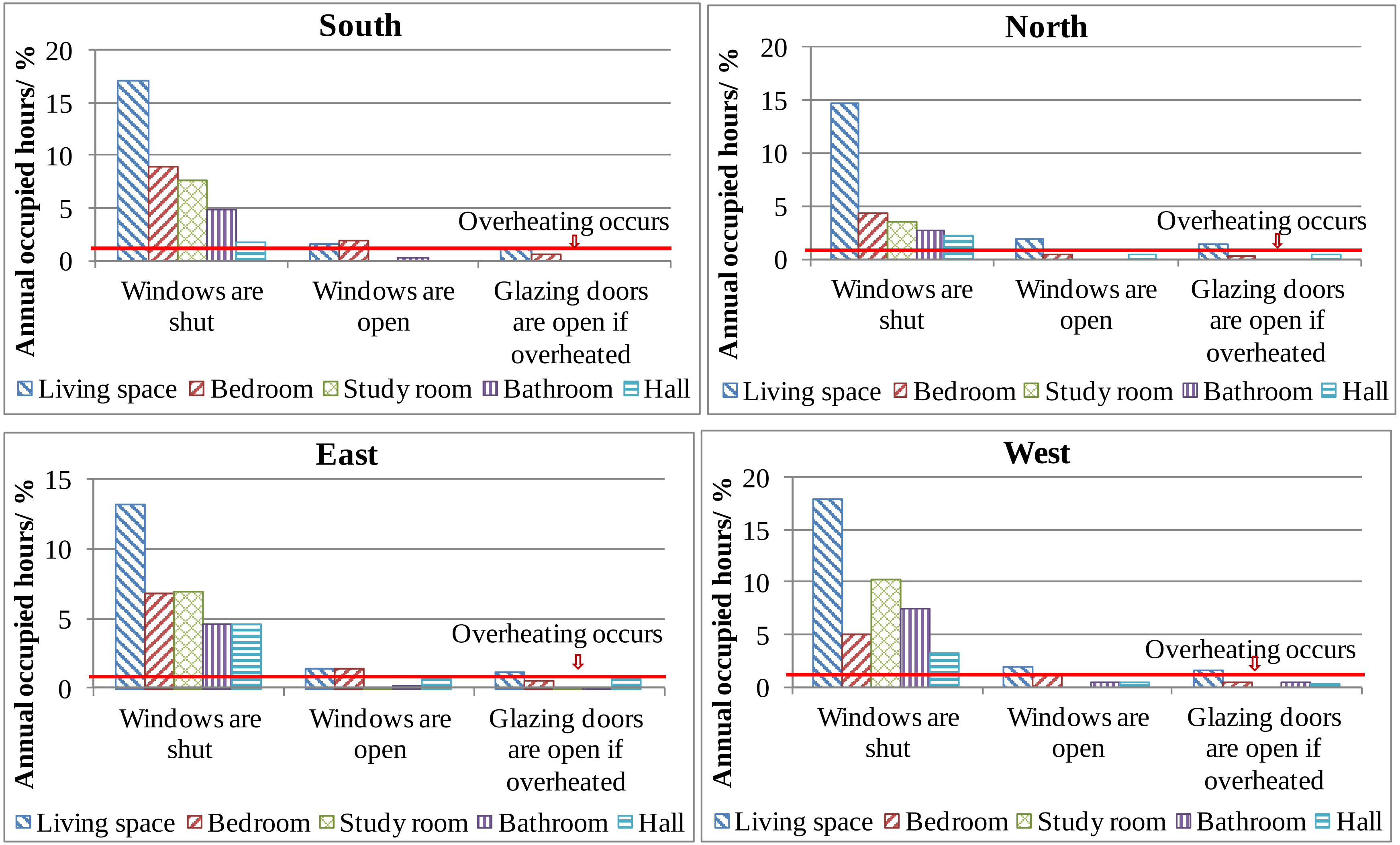


Figure 5-7: Overheating risk assessment via four orientations, 1% annual occupied hours when room temperatures above 28°C (26°C for bedroom)

Depending on the occupancy period that a 1% of annual occupied hours of overheating risk in different thermal spaces vary differently. In the case study with assumed occupancy profile, it equates to 25 hours for living space, 30 hours for bedroom, 7 hours for office or 4 hours for bathroom. When all windows, glazed doors are kept shut, the overheating risk expressed in term of percentage of annual occupied hours against 1% allowance vary between 13.2 (east case) and 17.9% (west case) in living space, between 4.3% (north) and 9% (south) in bedroom, between 3.5% (north) and 10.2% (west) in office room. The bathroom which possessed similar volume space and glazing area as the office space but was assigned different occupancy pattern and load, the overheating risk varies between 2.7% (north) and 7.5% (west). Overheating risk in the hall with the glazed surface on the opposite side of the main facade ranges between 1.7 (south) and 4.6% (east). By opening windows (as in the second scenario), overheating risk in office, bathroom and hall disappears in all four orientations. For the living space, a slight variation in overheating risk assessment between 1.4 (east) and 2% (west) against 1% criterion via 4 orientations. For the bedroom, there no risk of overheating in north case, but varies from 1.3% (west) to 1.9% (east). The overheating risk in bedroom eliminated when opening the French door patio in additional as simulated for the third scenario. However, opening the French glazed door in addition to windows in the living space only reduces the overheating risk between 1.2% (east) to 1.6 (west).

If considering adaptive method as discussed in Appendix A Section A.4.3.2, such remaining overheating risk would be attenuated by changing lighter clothes, taking shower or having cold drinks. Or the overheating issue can be resolved by integrating other interventions into the current state in complementing to natural ventilation to mitigate indoor environment (see Chapter 6 Section 6.1). The assessment of overheating risk as discussed above leads to an initial conclusion that passive ventilation works well in reducing overheating risk in this lightweight modular dwelling unit.

#### *5.3.3.2* Comfort benchmark for natural ventilated building

In addition to the overheating risk criteria, a comfort benchmark for natural ventilated building set out in CIBSE guidance J (CIBSE, 2002) requires a limit of 5% of the annual occupied hours when room operative temperature does not exceed 25°C (See Appendix A Section A.4.3.3). Also, the acceptable summer comfort temperature for free mode buildings set in CIBSE guide A set 25°C for living areas but 23°C for bedroom with the possibility of impair sleeping arising from above 24°C (Table 1.7 in (CIBSE, 2006a)). There is not yet a recommended length of occupied period for the bedroom (i.e. percentage of annual occupied hours). The percentage of annual occupied hours when the operative temperature in the bedroom exceeds 24°C was determined to assure comfort in bedroom by seeking effective cooling strategy that minimises this percentage. Because the benchmark temperature set for comfort at 25°C was also the threshold temperature for opening windows, it would be useful to test the effectiveness of opening windows before the operative temperatures reached to this level (23°C). Figure 5-8 briefly describes simulation results of annual occupied hours that room operative temperatures in different spaces exceeds the comfort benchmark.

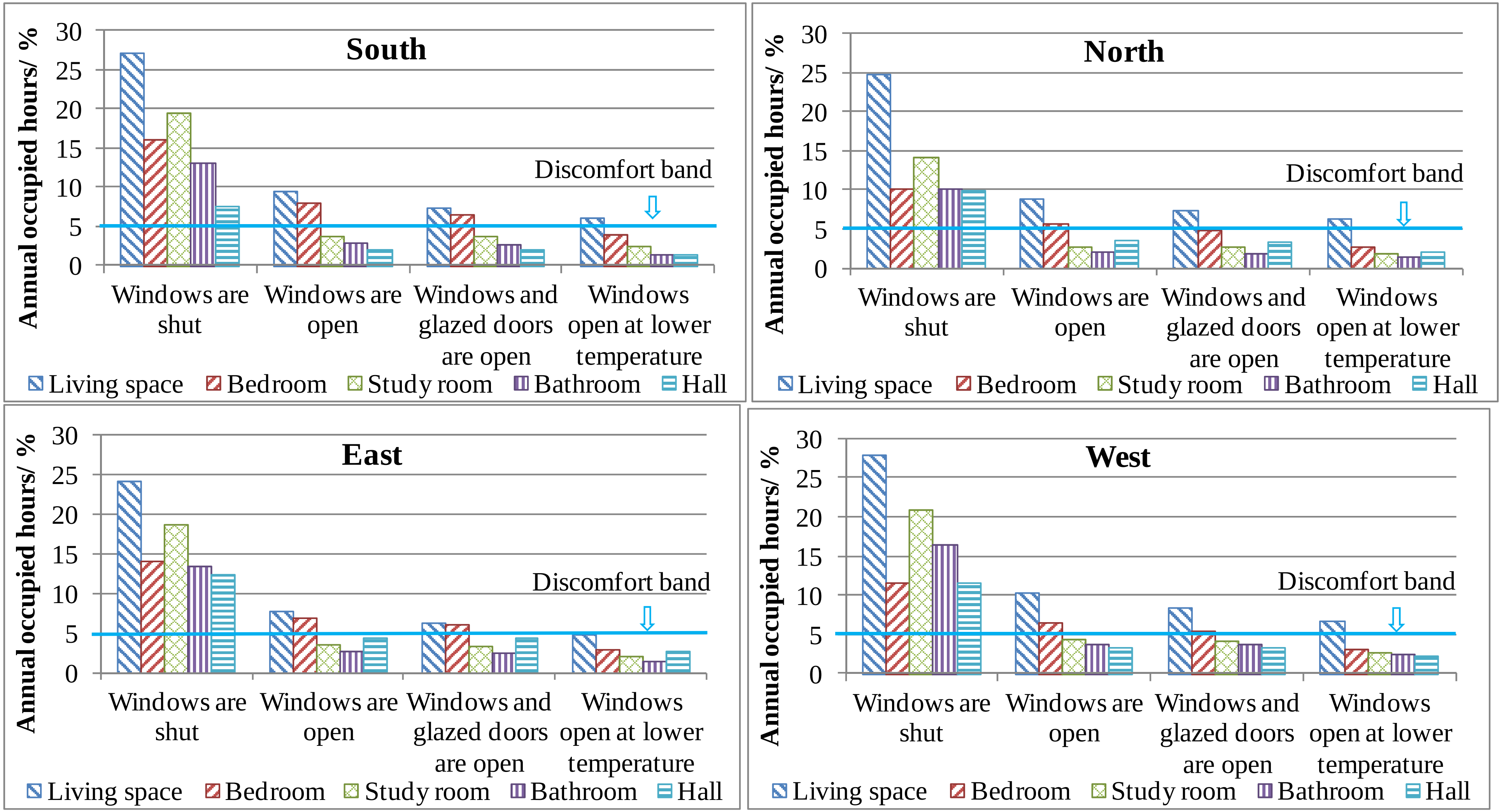


Figure 5-8: Comfort assessment via four orientations using the benchmark of 5% annual occupied hours when room temperatures above 25°C

When all windows are kept shut, the comfort benchmark criteria are exceeded from twice to three times for such space like bathroom and hall, but is worst at five times higher in the living space (at 27.8% in west case), or range between three and four times higher in the office. When windows are open, the discomfort is mitigated, with the living space of 7.8 to 10.1% against 5% requirement while the rest of the space satisfies the criterion. The length of discomfort in the living space reduces gradually in respective of order from opening the windows, opening glazed doors in addition to increase air exchange rate to opening windows at lower temperature compared to the threshold one.

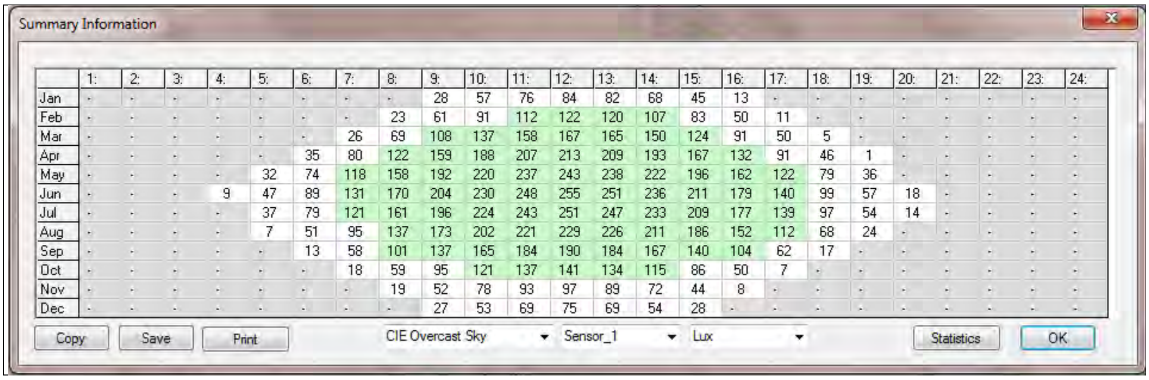
For the bedroom, the risk of impaired sleep was expressed in the study by the percentage of occupied hours that operative temperature exceeds 24°C. The criterion for this does not need to be as low as 1% like the overheating risk with threshold temperature at 26°C but should not be too high to affect the sleeping quality. Regarding this criterion, it ranges between 10.2% (north) and 16% (south) when windows are closed and from 5.4% (west) or 5.6% (north to 8% (south) when windows are opened. Opening glazed doors in addition to the windows does not significantly reduce this risk in comparison with opening windows at lower temperature, (i.e. lower than the threshold temperature of assessing the risk).

Such range of discomfort in the living space could be acceptable considering adaptive approach though this could not be applied for the bedroom due to inactive/unconscious activities. A small quiet fan running during night time or windows could be partially open depending on site security where the dwelling locates. Or it could be achieved by opening windows at lower temperature (23°C) in the early evening could mitigate bedroom temperature. Otherwise, several design strategies will be investigated to provide improved performance (See Section 5.4).

### 5.3.4 Lighting performance

A good daylight design could maintain indoor living activities during the daytime when the sun is available. Designing building glazed fenestration for daylight requires considering its impact on visual and thermal comfort, thermal performance, energy consumption and emissions. It is because over glazing for good daylight may cause significant heat loss or overheating issue, thus higher energy consumption and emissions are required to maintain thermal comfort in a space.

The approach to assess sufficient daylight provision through building fenestration is to consider the worst case scenario under overcast sky conditions. The required light level for domestic building is that the illuminance range between 100 and 300 lux for the lounge, from 150 to 300 lux for kitchen, 150 lux for bathroom (CIBSE, 1999). IES<VE> Radiance tool was used to predict daylight level in the living space, with the sensor located at the centre of the space in the modelling. The living space was selected regarding its occupancy profile of use during weekend daytime, the daylight illuminance readings under overcast sky condition over a year as shown in Figure 5-9.



CIE Overcast Sky

Sensor_1

Lux

| | 1: | 2: | 3: | 4: | 5: | 6: | 7: | 8: | 9: | 10: | 11: | 12: | 13: | 14: | 15: | 16: | 17: | 18: | 19: | 20: | 21: | 22: | 23: | 24: |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | - | - | - | - | - | - | - | - | 28 | 57 | 76 | 84 | 82 | 68 | 45 | 13 | - | - | - | - | - | - | - | - |
| Feb | - | - | - | - | - | - | - | 23 | 61 | 91 | 112 | 122 | 120 | 107 | 83 | 50 | 11 | - | - | - | - | - | - | - |
| Mar | - | - | - | - | - | - | 26 | 69 | 108 | 137 | 158 | 167 | 165 | 150 | 124 | 91 | 50 | 5 | - | - | - | - | - | - |
| Apr | - | - | - | - | - | 35 | 80 | 122 | 159 | 188 | 207 | 213 | 209 | 193 | 167 | 132 | 91 | 46 | 1 | - | - | - | - | - |
| May | - | - | - | - | 32 | 74 | 118 | 158 | 192 | 220 | 237 | 243 | 238 | 222 | 196 | 162 | 122 | 79 | 36 | - | - | - | - | - |
| Jun | - | - | - | 9 | 47 | 89 | 131 | 170 | 204 | 230 | 248 | 255 | 251 | 236 | 211 | 179 | 140 | 99 | 57 | 18 | - | - | - | - |
| Jul | - | - | - | - | 37 | 79 | 121 | 161 | 196 | 224 | 243 | 251 | 247 | 233 | 209 | 177 | 139 | 97 | 54 | 14 | - | - | - | - |
| Aug | - | - | - | - | 7 | 51 | 95 | 137 | 173 | 202 | 221 | 229 | 226 | 211 | 186 | 152 | 112 | 68 | 24 | - | - | - | - | - |
| Sep | - | - | - | - | - | 13 | 58 | 101 | 137 | 165 | 184 | 190 | 184 | 167 | 140 | 104 | 62 | 17 | - | - | - | - | - | - |
| Oct | - | - | - | - | - | - | 18 | 59 | 95 | 121 | 137 | 141 | 134 | 115 | 86 | 50 | 7 | - | - | - | - | - | - | - |
| Nov | - | - | - | - | - | - | - | 19 | 52 | 78 | 93 | 97 | 89 | 72 | 44 | 8 | - | - | - | - | - | - | - | - |
| Dec | - | - | - | - | - | - | - | - | 27 | 53 | 69 | 75 | 69 | 54 | 28 | - | - | - | - | - | - | - | - | - |

Figure 5-9: Illuminance performance in the living space.

The illuminance outputs under overcast sky are within the required lighting design for the space, and improved daylight level can be expected under partially cloudy sky or clear sky with the sun. It can be then concluded that the living space is well day lit during the period when it is occupied (including daytime in the weekend).

In order to quantify illumiance level of the room, the average daylight factor becomes a poor representation in spaces under overcast sky conditions as there are high daylight levels near windows and very low at the rear, especially for deep rooms. The daylight illuminance level depends on glazing area, its location in a space and orientation (i.e. solar access) as well as transmittance value of the glass. The daylight illuminance values in five rooms of the building unit via four different orientations were determined by the use of IES<VE> Gaia tool. This was because the IES<VE> FlucsDL using a radially symmetric overcast sky thus changing building orientation does not have any effect on daylight illuminance. Simulation results of average daylight factor, illuminance uniformity (calculated as minimum illuminance value divided by the average illuminance value) under CIE overcast sky condition for the design date as 21st September for four different orientations are shown in Table 5-7. The design date was selected as a date half way (i.e. 21st of September) between mid-summer, the 21st June and mid-winter, the 21st December which gives maximum and minimum levels of daylight (Ward, 1992). A solar noon time (i.e. the time when the sun is at its highest due south) was selected, it could be considered as 12:00 in this case study as for its location. It also includes illuminance values for three different sky conditions in correspondence with the design time and date.

Table 5-7: Daylight analysis of the building unit under CIE overcast sky conditions

| Cases | Rooms | Mean daylight factor,% | Illuminance uniformity | Illuminance (lux) at 12:00 on September 21$^{st}$. |
|---|---|---|---|---|
| South | Living space | 6.7 | 0.09 | 640 |
| | Bedroom | 7.1 | 0.14 | 674 |
| | Office | 4.8 | 0.19 | 453 |
| | Bathroom | 5.1 | 0.22 | 485 |
| | Hall | 1.3 | 0.02 | 120 |
| North | Living space | 4.8 | 0.09 | 454 |
| | Bedroom | 3.7 | 0.12 | 350 |
| | Office | 1.5 | 0.23 | 143 |
| | Bathroom | 1.6 | 0.24 | 148 |
| | Hall | 3.7 | 0.01 | 354 |
| East | Living space | 3.9 | 0.11 | 370 |
| | Bedroom | 7.5 | 0.06 | 714 |
| | Office | 2 | 0.16 | 192 |
| | Bathroom | 2.4 | 0.17 | 227 |
| | Hall | 2.3 | 0.04 | 218 |
| West | Living space | 7.3 | 0.15 | 693 |
| | Bedroom | 3.7 | 0.13 | 355 |
| | Office | 2.4 | 0.18 | 231 |
| | Bathroom | 3.7 | 0.15 | 208 |
| | Hall | 1.8 | 0.02 | 169 |

Visual discomfort (glare) caused by excessive brightness contrast could be annoying or even causes pain however in domestic building it would not be the main issue. It is because the occupant can flexibly move away from the glare or using the blind/shutter to prevent glare.

## *5.4 SUMMARY*

The previous section discussed about heating, cooling, ventilation and lighting when the dwelling was occupied. The space heat load was predicted to be highest on north case at 2495 kWh (or 54.4 kWh/m$^2$ pa). This is lower than the requirements for new built dwellings from 2010 and 2016 onwards for similar floor area at 5400 kWh per year for 2010 built and 4000 kWh per year from 2016 (NERA, 2010). Further development for heating improvement will be investigated to explore the potential heating energy savings.

Opening windows as mean of natural ventilation was effective in alleviating overheating problem with reduction in the percentage of annual occupied hours regarding overheating risk criteria for the living space at 1.4 - 2 (%) from 13.2 - 17.9 (%) or bedroom to the level of 0.5 - 1.9 (%) from 4.3 - 9 (%). Natural ventilation supply adequate air change in eliminate overheating risk in the rest of the building. By opening glazed doors to increase air exchange rate, overheating risk disappears in the bedroom but still slightly remains within 1.3 - 1.6 (%). in the living space. In addition, regarding comfort criteria for natural ventilated living spaces of 5% annual occupied hours when the room operative temperature exceeds 25°C, the living space of the building unit does not meet this criteria and the bedroom only meets this when main building facades faces due east or when windows open at lower temperature than the threshold temperature (25°C is acceptable summertime and when it increases, occupant starts to feel hot). Therefore, interventions for cooling design are sought to reduce overheating risk by controlling solar access with different type of shading devices or by increasing thermal mass of the building envelope combined with effective ventilation strategy. Such development offers opportunities for improved cooling performance to reduce the frequency in window opening or to take account of warmer climate at other locations or under climate change context. Furthermore, it is unlikely that air exchange rate supplied by trickle ventilators could meet the requirement of whole building background ventilation. In summertime this could be easily met by opening windows to enhance ventilation; however it becomes critical in wintertime resulting in ventilation heat loss and draught. Thus, ventilation strategy to provide adequate ventilation rate needs to be sought through. Current building fenestrations ensure the building is well lit for building occupant to work and live in daily activities.

# Chapter 6: **INVESTIGATION FOR IMPROVEMENT**

The chapter starts with establishing strategies for further development in improving heating and cooling performance. The predicted building performance and energy consumption developed in Chapter 5 was as base case or initial design to facilitate comparison between initial design and implemented solution for improvement. Without any specific building location, the climatic conditions and location information were kept the same as described in previous chapter. Development stage focuses on two main improvement heating and cooling performances. Regarding improved heating interventions, it includes the installation of mechanical ventilation with heat recovery system and increased thermal insulation (Section 6.2). Interventions for reducing cooling demand includes solar access control via shading options, solar control glass and reduced glazing areas as well as increased thermal mass by the use of phase change material (PCM) with effective ventilation strategy (Section 6.3). It continues with further simulation development combining best heating performance strategy and best cooling performance strategy as presented in Section 6.4. The chapter finishes by initial findings and comment drawn from simulation development work.

## *6.1 SIMULATION DEVELOPMENT STRATEGIES*

Thermal space loads measured in MWh were then converted into kWh/m$^2$ to facilitate the comparison with building design guideline or with other dwelling types of different size. As discussed in previous chapter, the dwelling unit is likely to be overheated except excessive windows opening applied in some period of time. Because natural ventilation appears effective in reducing overheating risk in the studied building, there is no need of installation of mechanical ventilation or air conditioning for cooling purpose. Therefore, cooling energy demand is not applicable though it is important to notify that energy use to operate extract fan for dehumidification in wet rooms (e.g. kitchen and bathroom) is accounted in utilities consumption.

In order to reduce the length of overheating experience indoors, shading design and phase change materials are considered as they prove to be suitable options for prefabricated lightweight construction, as a quick fixed tool from the author’s point of view. Importantly, the current indoor conditions exceed approximately five times the length of benchmarking comfortable conditions (e.g. 5% of annual occupied hours that the operative temperature exceeds 25°C).

A range of case studies where several selected designed strategies were integrated to the building model were conducted to provide quantitative data to evaluate the efficacy of each designed strategy on building performance and consumption.

By denoting the initial construction state as X, heating and cooling options are Y and Z as shown in Figure 6-1. It is important to note that the installation of mechanical ventilation heat recovery system (MVHR) aims to improve heating performance. Its operation in warm season is assumed to provide background ventilation when windows are kept shut. This agrees with the assumed air change rate for healthy environment indoors as discussed in Chapter 5 Section 5.3.1. When the indoor temperature exceeds the threshold temperature of comfort benchmark, natural ventilation achieved by opening windows provide cooling and background ventilation. It is assumed that MVHR stops working when a window is open with respect to the energy saving purpose. Besides, the presence of phase-change material within the space, as part of cooling strategies, does not increase heating load as the material absorbs and store heat. It is based on assumption that heating load is used for heating the room up to 20°C though the room temperature could be higher than 20°C by other gains like solar heat gain and internal gain. Because the melting point or switching temperature of the selected phase-change material is at 21.7°C thus the material is not supposed to absorb heat from internal air when the indoor conditions and PCM temperature is below 21.7°C (Norris, 2011). Thus it is important to keep the PCM out of reach from solar radiation to avoid PCM is heated and exceeds its melting point. Table 6-1 lists the simulation scenarios according to the development strategies in Figure 6-1.

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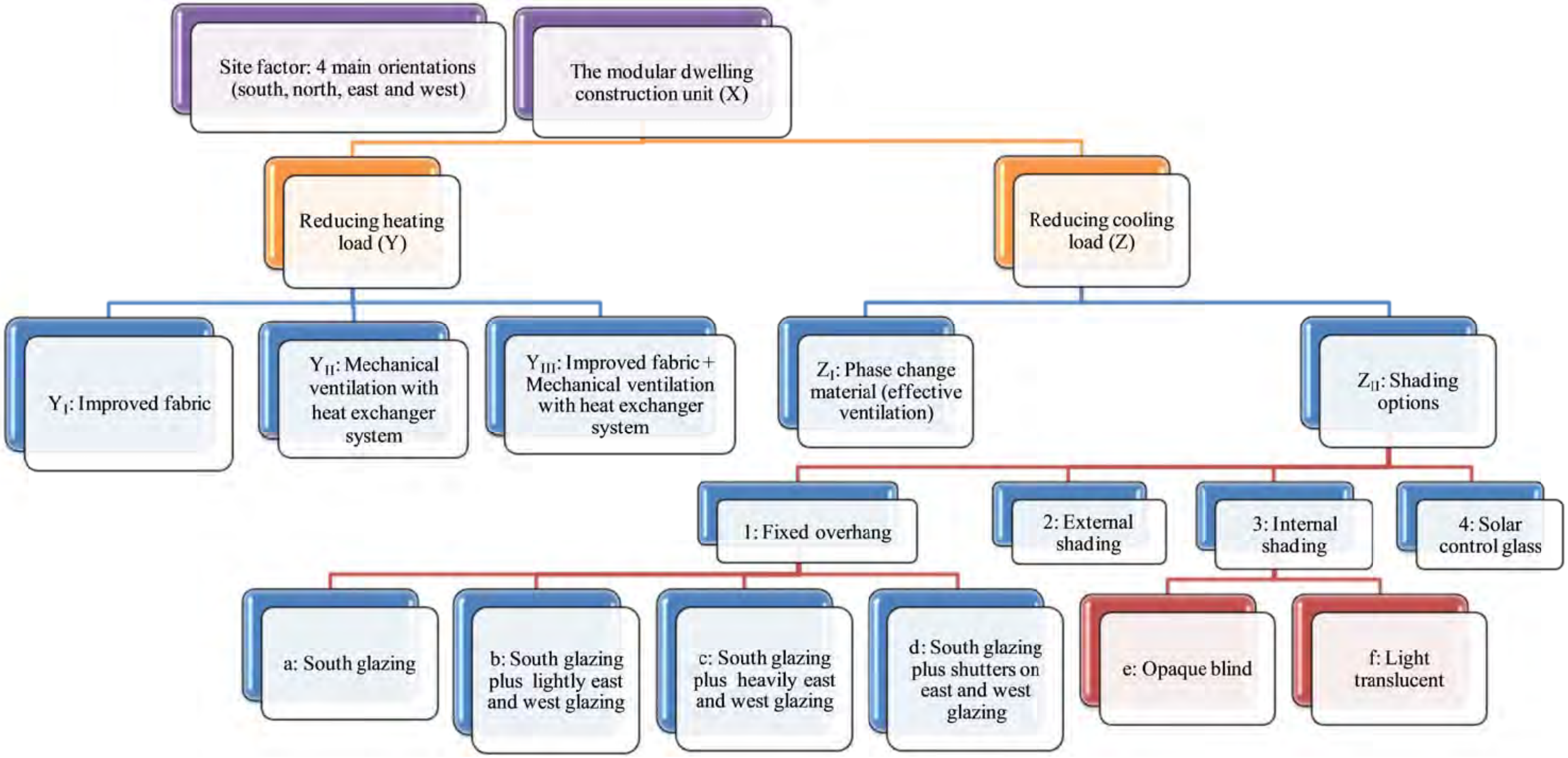


Figure 6-1: Diagram of scenarios for simulation development

Table 6-1: List of simulations and output information

| | | MVHR - $Y_{II}$ | Shading options - $Z_{II}$ | | | |
|---|---|---|---|---|---|---|
| **Change of fabric** | | | Fixed overhang – 1[a, b, c, d] | External shading - 2 | Internal shading - 3 [e, f] | Solar control glass - 4 |
| | Initial state - X | $XY_{II}$ | $X Z_{II}$ 1<br>[a, b, c, d] | $XZ_{II}2$ | $XZ_{II}3$[e, f] | $XZ_{II}4$ |
| | Improved fabric - $Y_I$ | $Y_IY_{II}$ | $Y_I Z_{II}1$<br>[a, b, c, d] | $Y_IZ_{II}2$ | $Y_IZ_{II}3$[e, f] | $Y_IZ_{II}4$ |
| | PCM ($Z_I$) impregnated into the initial construction - $XZ_I$ | $XY_{II}Z_I$ | $XZ_IZ_{II}1$<br>[a, b, c, d] | $XZ_IZ_{II}2$ | $XZ_IZ_{II}3$<br>[e, f] | $XZ_IZ_{II}4$ |
| | PCM ($Z_I$) impregnated into improved fabric - $Y_I Z_I$ | $Y_IZ_IY_{II}$ | $Y_IZ_IZ_{II}1$<br>[a, b, c, d] | $Y_IZ_IZ_{II}2$ | $Y_IZ_IZ_{II}3$<br>[e, f] | $Y_IZ_IZ_{II}4$ |

With X is the base case of building design, whilst considering change of building fabric, the improved fabric is concerned with using SIP 250 instead of SIP 125 thus it is denoted as $Y_I$ referring to the new building envelope. However, PCM option was to add a PCM board behind the plasterboard of the current building envelope so it is denoted as $XZ_I$ to reflect this change (i.e. adding but not replacing).

## *6.2 INTERVENTIONS FOR REDUCING COOLING LOAD*

This section discusses interventions including shading devices and phase change material with regards to reducing cooling energy demand for a comfortable environment. First alternative is to control solar access to the overheated spaces. This allows low angles solar radiation reaches inner space in heating months for free heat gain but also blocks unwanted solar gain in summer when the lightweight structure is overheated. The study explored different shading design options listed as fixed overhang above windows, external shutters, internal blind and solar control glass. The overhang option is fixed within the building envelope, independent to occupant's interaction and requires lower maintenance work and cost. It requires careful design and also compromising acceptance as reducing solar gain are active anytime of the year useful solar gain in heating months will be affected. Meanwhile, external and internal shadings offer occupants flexibility in use from no effect to partially or fully shading but they require occupant interaction which might be disturbing sometimes. Solar control glass was also included in shading options whilst considering their effectiveness in reducing solar heat gain within a space. The second alternative is to apply thermal mass on the building envelope in order to alleviate internal comfort, reduce overheating risk by increasing thermal storage capacity of building fabric

### 6.2.1 Shading devices

The shading devices are an important solar control alternative in order to reduce solar radiation reaching the space hence it reduces overheating risk and cooling demand for the building. The use of shading devices is also known for providing security, privacy as well as distributing lighting thus eliminates glare. The design of shading devicew as part of building fenestration system depends on local climatic conditions and the use of building (e.g. building type: school, office or domestic and occupant’s pattern: occupancy period, electrical devices, etc.). For example, in hot climates with mild winter and for an office type building that indoor environment is adequately warm enough that full shading might be required to reject solar gain all year around. Or for cold climate that solar gain in summertime is also beneficial that designing the fenestration system of domestic building requires full solar access all year around.

The shading devices in domestic buildings should be designed to reject most of direct sunlight during summertime but have no effect on receiving it during wintertime when free solar gain is desired. Type of shading device as well as their shape, position and characteristics are to be considered and designed carefully to meet these goals. The shading devices reduce the sunlight reaching to the space by reflecting and absorbing short wave solar radiation. In most case, the effectiveness in reducing solar heat gain of shading devices decreases by their location within the glazed area. The internal shading devices are least effective at reducing solar heat gain because they block radiation when it has already entered the space and some amount of heat absorbed by internal blinds will be passed into the room by means of convective and radiant heat transfer. The mid-pane blinds refer to type of devices where the blinds are between the 2 glass panes. Their efficacy in solar control is somewhere in between internal and external shading devices. In fact, solar radiation enters the cavity between two glass panels, heating it up then some of the heat will be transferred through the mid pane blind and the inside glass panel to reach the room. The external shading devices could be most effective amongst these three systems as they prevent the solar radiation before it reaches the glazing surfaces hence least amount of heat could reach the room. However, such system is relatively more expensive and as being exposed to the weather, it does require higher maintenance (e.g. wooden shutter or metal roller blind), this excluding fixed overhang. Mid pane blinds could require least maintenance amongst the 3 systems but they might cause condensation in winter. Internal blinds as being exposed to internal space require regular cleaning though less maintenance cost than external system. Thus, for studying the effectiveness in reducing cooling demand at the building unit, external and internal shading systems are considered and mid pane blinds' efficacy could be assessed as an average or in between value.

#### *6.2.1.1* Fixed overhang

The fixed overhang is a simple external shading system to provide protection from direct sunlight to reduce overheating in a space. As the device is fixed to the outside of the window just above window's head, it reduces solar gains into the space without any occupant control. However, it does not offer other benefits like movable shading to adjust for changes in receipt receiving solar radiation intensity or security and privacy as well as glare control like other shading devices (Olbina, 2005). Even though, the strategy is still effective whilst blocking high angle summer sun during the hottest time of the day and allow low angle winter sun to pass directly into the dwelling. Fixed overhang design is the matter of compromising because this shading will not stop performing after a certain date (unless it's a moveable overhang) thus it will partially shade the window all year around. A wide overhang (heavily shading) which offers a fully shade window during summer time will block too much sunlight when solar heat gain is desired. Or a narrow overhang might be not effective in reducing solar gain when heating is not required. Regarding the building form and design, an overhang over the French patio door creating the balcony cover is more suitable than the vertical fins due to its presence causing space reduction and obstruction in the balcony. If there had not been a balcony in the initial design, then vertical fins would have been suggested for effective shading on east/west facades. The improvement when adding vertical fins lies between fixed overhang and shutter (external shading) so in the scope of illustration of different solar access control, the use of vertical fins was excluded.

*<u>Overhang design</u>*

The first step is to determine the cut-off date so as to determine the width of overhang that shades window in summer and allow direct sunlight in winter. It could be taken as the period of time during which the room experiences overheating thus full shading would be useful in reducing unwanted heat gain. As shown in Figure 6-3, if the cut-off date is based on overheating event occurs indoors then the selected cut-off date is 18th March and 24th September. An earlier date, 24th August is chosen for a higher solar altitude in order to provide the useful sunlight during March and early April. Therefore, the cut-off date for overhang design is 15th April and 24th August. The solar time to cut off can be based on peak cooling time in south, east and west zones. It can be based on previous result of analytical verifications for peak temperature and cooling load design (See Appendix B, Section B.3.2). If using that, the cut off time are below: 8:30 for east facade, 11:30 for south facade and 15:30 for west facade.

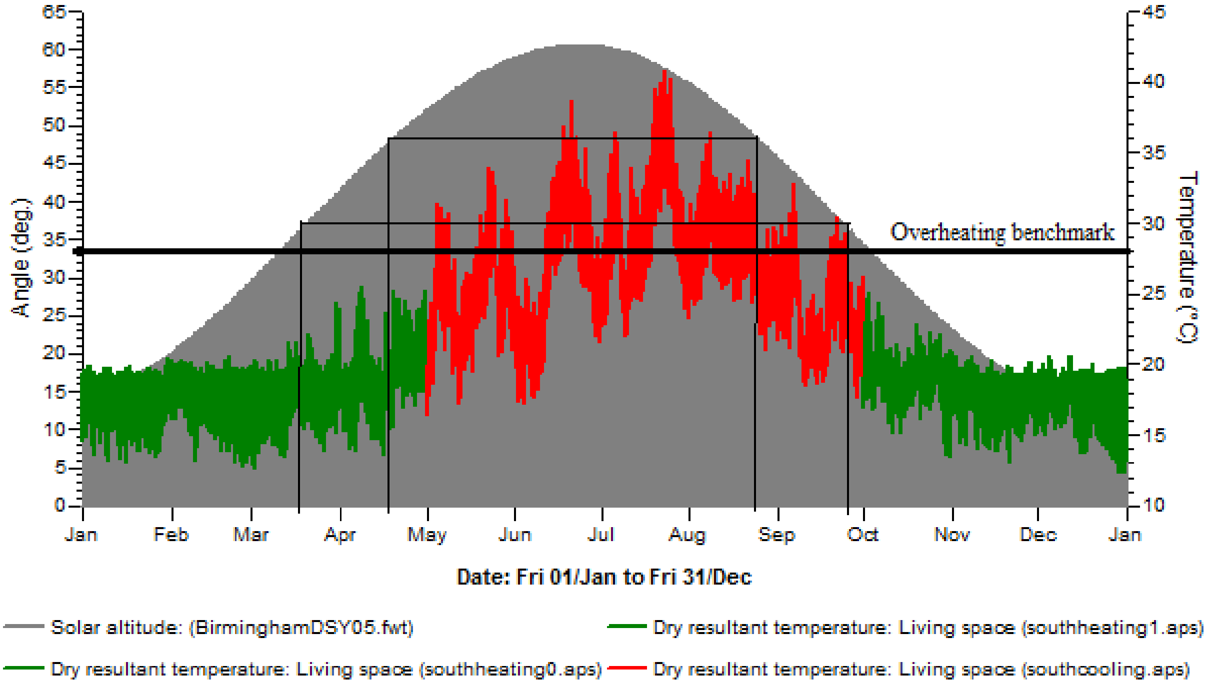


Figure 6-2: Solar altitude and operative temperature profiles for selection of cut-off date in IES<VE> graph

The dimension of the fixed overhang can be calculated using the following formula (Ballast, 1988)

h= [D x tan(solar altitude)] / cos{solar azimuth – window azimuth) (6-1)

Illustration of the dimension is shown in Figure 6-3. For sizing overhang for east or west window, a fin must be added for adequate shading, otherwise overhang can become unreasonably deep (Ballast, 1988).

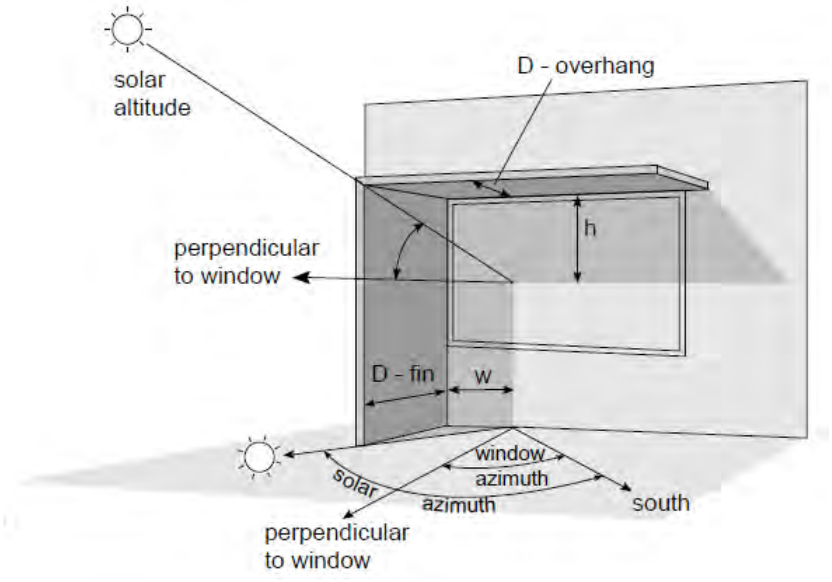


Figure 6-3: Solar position in reference with window (Olbina, 2005).

Solar positions for specific cut-off date and start and end time are determined by the use of weather data file in IES<VE> as shown in Table 6-2

Table 6-2: Solar positions for the selected cut-off date and time

| **Orientation** | **Time** | **Solar altitude (°)** | **Solar azimuth (°)** | **VSA in radian** |
|---|---|---|---|---|
| South glazing | 11:30 | 44.2 | 145 | 0.87 |
| East glazing | 8:30 | 30 | 112.3 | 0.56 |
| East glazing | 9:30 | 30 | 112.3 | 0.56 |
| East glazing | 10:30 | 37.9 | 127.3 | 0.78 |
| West glazing | 14:30 | 45.7 | 209 | 1.13 |
| West glazing | 15:30 | 40.1 | 227.6 | 0.85 |

The light or heavy case of overhang refers to the depth of the fixed overhang above windows in which the light case is selected for higher solar altitude and the heavy case is selected for the lower solar altitude. From the weather file data, the solar time is calculated at the mid hour range and the selected parameters of solar position for designing shading were listed in Table 6-2. On the cut-off date, the time of 10:30 was selected for designing fixed overhang glazing facing east and 14:30 was selected for west facing glazing area in the second case. While in the third case, designing a deeper fixed overhang, the time of 9:30 and 15:30 on the cut-off date were selected for glazed areas faces due east and west.

Table 6-3 lists the dimensions of fixed overhang designed with the selected cut-off date and time. However for the east case (main building façade faces due east), the fixed overhang above the glazed areas (both windows and French patio doors) designed at 9:30 were too heavy with 1.023 meters height windows, the overhang would be 1.64 m depth, or with 1.983m height glazing door, the required depth of the overhang would be 2 meters which seems unreasonable and could cause over shading that blocks useful sunlight in winter. So the later time was selected for designing overhang on east facade (i.e. 10:30 for the third case and 11:30 for the second case). Fixed overhang above the French patio door in the third case could be found in designing fabric awning or roof of a balcony as a solution. In this specific building and its fenestrations, the extent from each side of French patio door is longer the wall facade surface containing the overhang then this is designed to extend to cover the width of the façade (See Figure 6-4(b)).

The length of the overhang (L) was calculated by $L=2xW+W_{window}$ with W is the width of the overhang from each side of the window and $W_{window}$ is the width of windows (Olbina, 2005)

To provide a better representation of the severity of the overheating problem, the chart in Figure 6-3 show the number of degree hours over these comfort threshold temperatures for the occupied periods. Each 1°C beyond the threshold temperature (28°C living areas and 26°C for bedroom) for an hour equates to a degree hour overheating.

*<u>Simulation scenarios</u>*

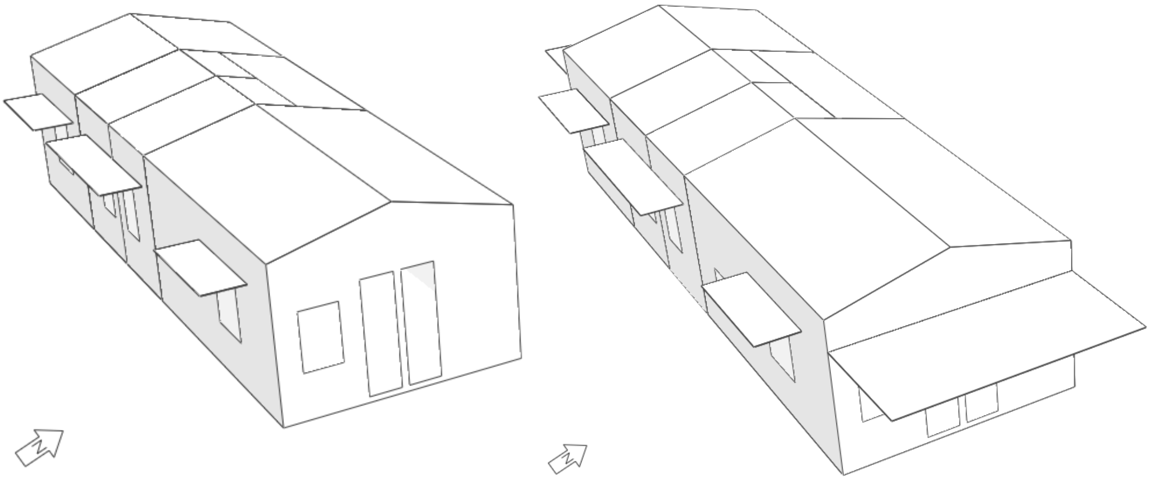
Several design scenarios:

- Case 0: Base case (shading free)
- Case 1: Fix overhang on south facade only, see Figure 6-4(a).
- Case 2: Overhang on all 3 facades: partially (light) overhang / awning on east and west facades, See Figure 6-2(b).
- Case 3: Overhang on all 3 facades: fully (heavy) overhang / awning on east and west facades (similar to Case 2 but deeper overhang)
- Case 4: Fix overhang on south facade and external shutter on east and west French facades.

Table 6-3: Dimensions of overhang for different windows on 3 main orientations

| Orientation | Glazing elements | Height x Width of glazing areas, m | Depth of overhang, m | Width of overhang (from each side), m | Depth x Length of overhang, m x m |
|---|---|---|---|---|---|
| South | Large windows | 1.023 x 0.886 | 0.86 | 0.6 | 0.86 x 2.09 |
| | Small windows | 1.023 x 0.623 | 0.86 | 0.6 | 0.86 x 1.82 |
| | French patio door | 1.983 x 1.173 | 1.67 | 1.17 | 1.67 x 3.88 |
| East | Large windows[2] | 1.023 x 0.886 | 0.6 | 0.86 | 0.6 x 2.61 |
| | Large windows[3] | 1.023 x 0.886 | 1.0 | 0.80 | 1.0 x 2.48 |
| | Small windows[2] | 1.023 x 0.623 | 0.6 | 0.86 | 0.6 x 2.34 |
| | Small windows[3] | 1.023 x 0.623 | 1.0 | 0.80 | 1.0 x 2.22 |
| | French patio door[2] | 1.983 x 1.173 | 1.17 | 1.67 | 1.17 x 3.88 |
| | French patio door[3] | 1.983 x 1.173 | 2.03 | 1.54 | 2.03 x 3.88 |
| West | Large windows[2] | 1.023 x 0.886 | 0.48 | 0.87 | 0.48 x 2.62 |
| | Large windows[3] | 1.023 x 0.886 | 0,90 | 0.82 | 0.9 x 2.53 |
| | Small windows[2] | 1.023 x 0.623 | 0.48 | 0.87 | 0.48 x 2.34 |
| | Small windows[3] | 1.023 x 0.623 | 0.9 | 0.82 | 0.9 x 2.23 |
| | French patio door[2] | 1.983 x 1.173 | 0.94 | 1.69 | 1.17 x 3.88 |
| | French patio door[3] | 1.983 x 1.173 | 1.74 | 1.54 | 1.74 x 3.88 |

Overhang shading design options were illustrated in the figure below:



( a) Fixed overhangs on south windows only (b) Fixed overhangs on 3 facades

Figure 6-4: Fixed overhang simulation model in the south case.

The simulation outputs of heating demand and overheating analysis for fixed overhang options were presented in Figure 6-5.

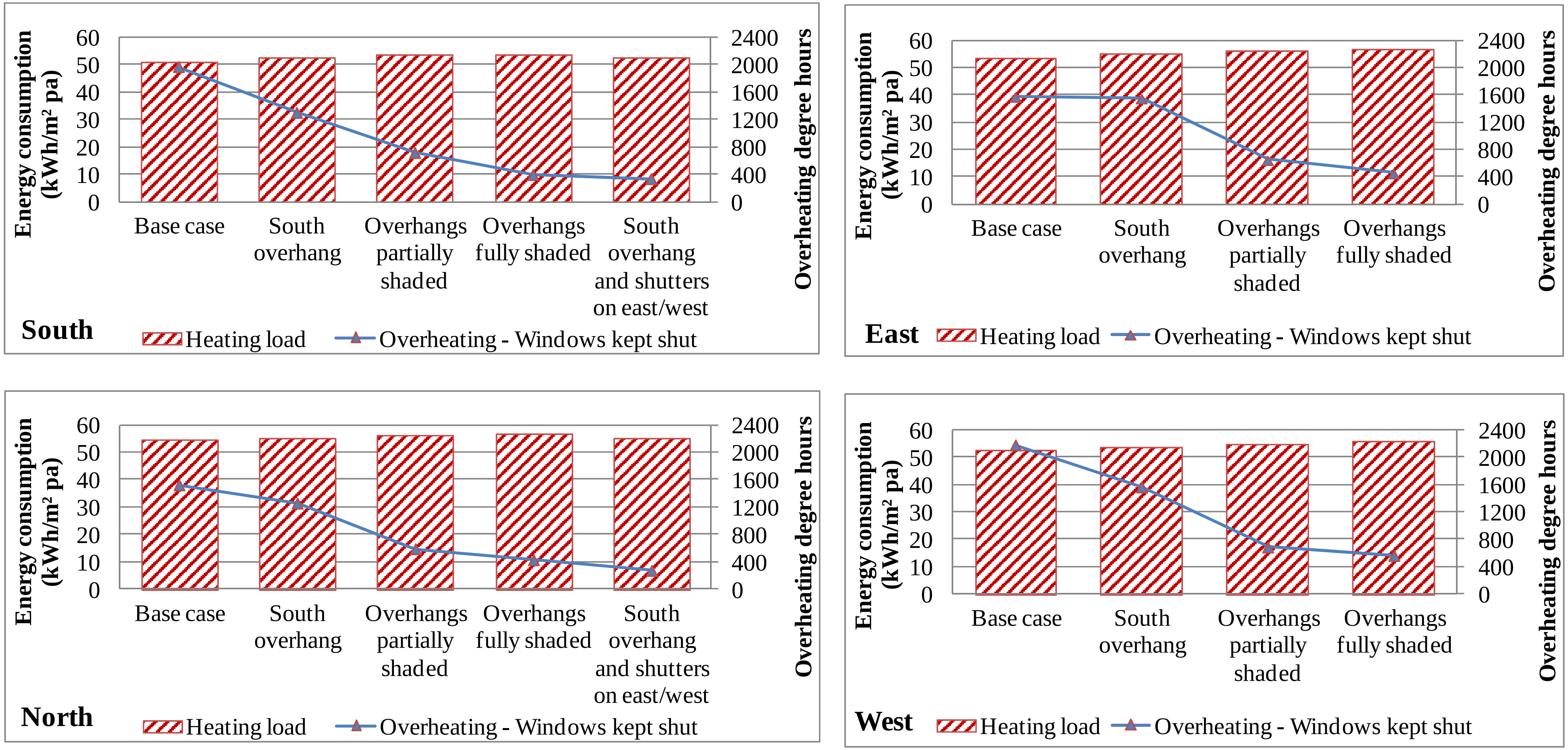


Figure 6-5: Heating load and overheating degree hours in different fixed overhang design options

### *6.2.1.2* External shutter

The blinds and shutters vary widely from country to country. They could be louvered shutters, venetian blind or curtain roller blind type and are made from different materials like plastic, wood, aluminium or curtain fabric. They are used for reasons of security, privacy, solar control and/or thermal insulation. Unlike fixed overhang, they require occupant control and restrict view when in use. For their best effective in solar control, the system is made from low heat storage materials with reflective finishing. This could reduce the amount of energy absorbed and stored within the system, thus less heat radiates back into the room. It is advisable to allow ventilation between the external shading system and glazing windows to remove remaining heat.

A full use of shading devices reduces the illuminance in the room causes requirement for artificial lightings during the occupancy. A trade off point in energy demand is raised as whether cooling energy savings from fully shaded windows in summer time could outperform lighting energy spent to maintain room’s illuminance. Whilst considering that people tend to welcome sunlight when it is available and prefer to be able to look outside the windows when they are active (quiet and dark room is preferred when resting and sleep), it is assumed that during the occupied period in summertime, a half lowered blind will be used.

The selected external roller shutter blind for the study allows limited ventilation and day lighting though it requires sash or inward opening windows. The profile of external shutter usage for modelling is half shaded describing that the roller blind is partially (i.e. half) lowered to let daylight enter internal space during the occupied period (i.e. weekend daytime). The simulation results of cooling load and overheating risk analysis and performance when the external shading is applied for 4 main orientations is shown in Figure 6-6 together with analysis of internal shading devices.

### *6.2.1.3* Internal shading device

Internal blinds are used to enhance privacy, reduce glare and heat loss via transparent glazing surfaces. Their use in solar control to resolve overheating issue is generally less effective due to the fact that solar radiation has already entered the room and the blind material tends to absorb heat and transfer it by mean of convective and radiant heat procedures. However it could be sufficient in some buildings where overheating is not too critical hence cooling demand is not too high or in some refurbished buildings or existing constraints does not allow external shading systems. The simulation modelling the use of internal shading devices provides numerical evidences for the efficacy of the internal system. Thus, for the integrated design process, it provides a mean to assess cooling performance and to combine with other cooling strategies so as to provide low cost and effective cooling strategies for the project.

A similar usage profile to the external shutter roller is applied to model the internal blind to be partially lowered (i.e. half shaded) allowing daylight entering the room. It is used for traditional curtain/blind with fabric materials. In term of using shading device to reduce solar heat gain but still receiving daylight, translucent blind was selected for the study. The solar characteristics of the shade use information given in Table 13G (ASHRAE, 2009) for light translucent that reflectance value is 60% and transmittance value is 25%.

Overheating analysis assessment for external and internal shading devices via four main orientations without opening windows to enhance passive ventilation is presented in Figure 6-6. The simulation results for overheating risk when windows are opening show that there is no risk of overheating in any room at any orientation. Regarding the comfort benchmark for natural ventilated spaces of 5% annual occupied hours that the room operative temperature is less than 25°C, both external and internal shading options are able to meet this criteria for every room.

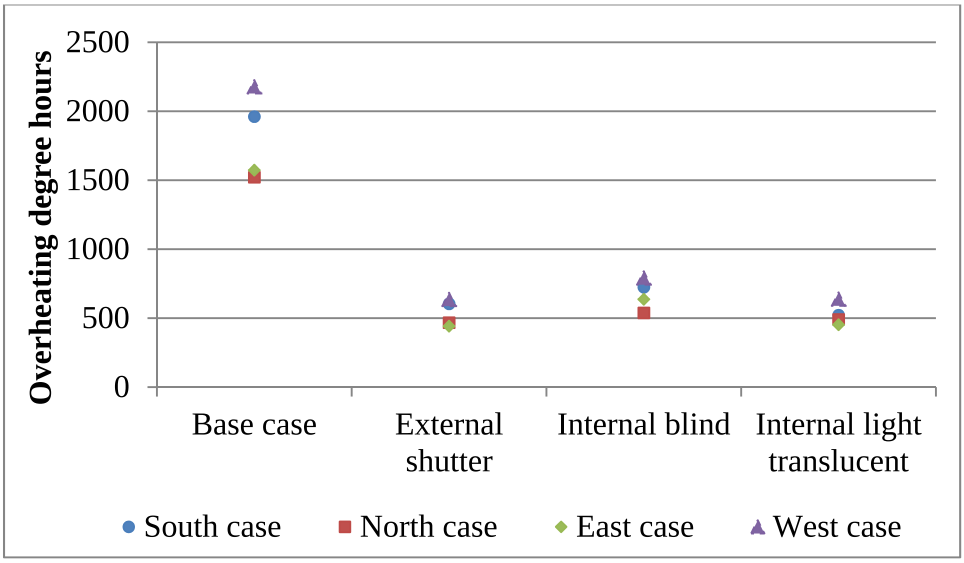


Figure 6-6: Overheating degree hours for external and internal shading devices via four main orientations

### *6.2.1.4* Solar control glass

Another effective way of reducing solar radiation is to employ reflective coated surface double glazed unit. Such type of coating will reflect incoming solar radiation hence alleviate overheating problem in light weight building construction. Though, the use of solar control glass causes an increase in heating demand as it rejects useful solar heat gain in winter time and low light transmittance through solar control glass unit could requires increased use of artificial lighting due to discomfort of occupants.

*Product description*

In order to provide a comparative study of the efficacy of solar control glass in cooling performance compared to initial design of low e-coating glass, the product selected for the study has the same U-value so still remains as double glazed unit with argon filled in the cavity to 93%. The reflective coating could be either on surface of external glass to the environment or internal surface within the cavity depending on "hard" or "soft" coating method. While the initial design, low emissivity coating surface is within the cavity, either on external or internal glass pane. Figure 6-7 illustrates solar characteristics through the double glazed unit with reflective coated surface, called as solar control glass.

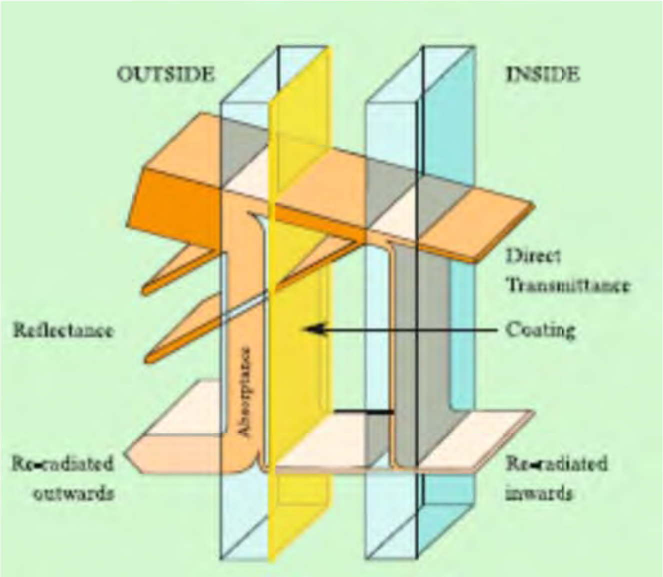


Figure 6-7: Solar control glass (Pilkington, 2010)

The product selected for the study is Pilkington Suncool™ glass. It incorporates a thin sputtered, metal oxide coating applied off-line on the internal surface of external pane (Pilkington, 2010). Offline coating refers to coatings applied after the glass was made whereas online coating which coatings applied during manufacture of the glass when it is still hot. Offline coating offers a range of properties hence this method gives more design options to ensure efficient use of light and heat. From the factsheet of this product (Product code 4C(30)-16Ar-4), U-value of the glass is the same as base case system of 1.1 W/m$^2$K, solar factor: g-value is 0.19 and lighting transmittance L= 0.31 (Pilkington, 2010).

*Simulation results*

Figure 6-8 shows total space loads for the building unit via four different orientations between the base case (i.e. low e coating glass) and the replacement by solar control glass, without opening windows for natural ventilation.. The use of solar control glass could be if the building utilizes electric heating system or when passive ventilation is limited due to outside noise/pollutions. However, whilst taking account of the central heating systems are fuelled by gas and passive ventilation is promoted in UK dwellings, the use of solar control glass is not significantly beneficial. It was reported in English House Condition Survey that 84% of the housing stock in the UK where most conventional central heating systems are fuelled by gas in 2007 (Nowak, 2009).

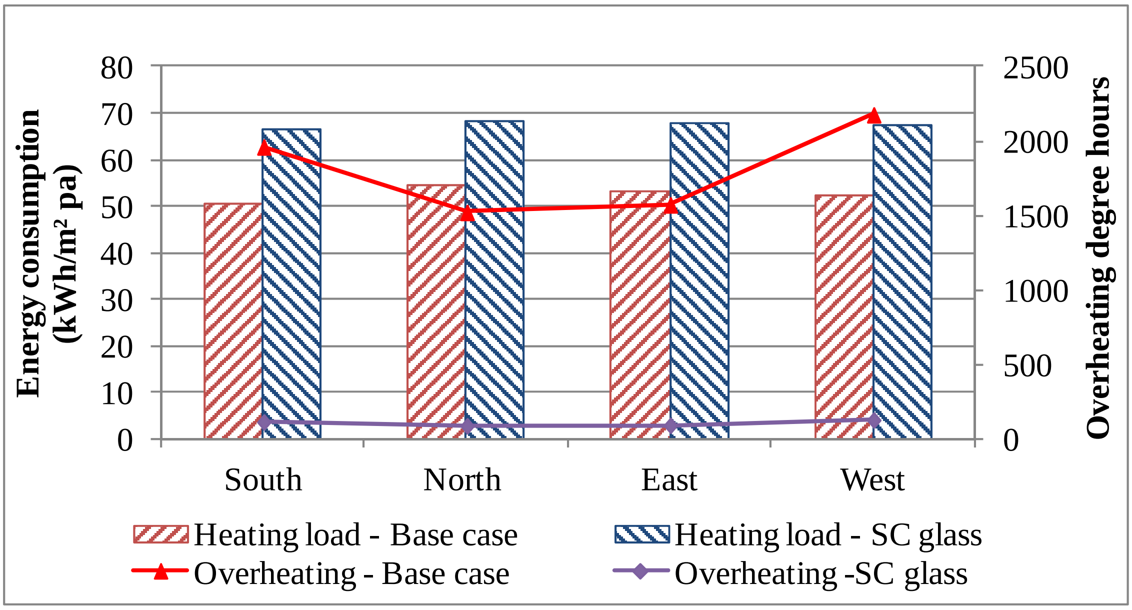


Figure 6-8 : Heating loads and overheating degree hours when replacing low e-coating, double glazing with solar control windows

### 6.2.2 Integrated thermal mass

Lightweight timber frame buildings, SIPs included, with modern construction method of prefabricated building elements has low level of mass compared to conventional brick and block buildings. Thermal mass related to admittance value as discussed in Appendix A Section A.3.1.2. Due to lack of thermal inertia, it results in rapid swings in the internal temperatures. In order to alleviate discomfort in summertime as well as reduce overheating risk in this lightweight building unit, it is suggested to add more mass into the building envelope. In practice, concrete either blocks or panels, precast or cast in-situ is the most practical and most common (The Concrete Centre, 2006). Thermal mass from medium to high level is provided from walls and floor construction with suitable finishes.

Phase change materials (PCMs), one of new alternative materials, have higher thermal energy storage capacities per unit mass than conventional building materials by storing energy in form of latent heat rather than sensible heat. PCMs outperform concrete, blocks or bricks from the aspect for the same heat storage capacity, the amount of mass required for PCMs is minimal as well as the required production energy (Kendrick and Walliman, 2007). For instance, in comparison with conventional thermal mass products, a 5 mm DuPont™ Energain® panel behaves approximately like 20 - 40 mm of concrete depending on the temperature. Typical heat storage capacity of DuPont™ Energain® panels 143 Wh/m², 18 - 24 °C (DuPont™Energain®, 2010) .

Thus, PCM is selected as an incentive of increasing mass for SIPs envelope. It is also suggested that the phase change temperature or melting point is close to the desired mean temperature of the room aims to provide effective thermal storage for both cooling and heating applications (Kendrick and Walliman, 2007).

Amongst PCMs, paraffin wax is seen as a particularly promising material for use in building components because of its cheapness and ready availability as well as flexibly adjustable properties (Demirbas, 2006). The study on the effect of fusion temperature on comfort concludes that the best overall performance could be expected with the use of PCM operating around the mid-point of the comfort range as the best compromise between cool morning and hot afternoon (Kendrick and Walliman, 2007). For an optimal range of comfort temperature in residential building, a PCM’s melting point around 22°C is suitable, taking 19°C as low extremity for heating desire and 25°C as high extremity for acceptable summer temperature from this band (25°C), people starts to feel hot.

#### *6.2.2.1* Production selection

The DuPont™ Energain® product was selected as an example to consider the effectiveness of thermal mass panel on building performance. The thermal mass panel is laminated to aluminium protective foils and the panel core is mixture between copolymer and paraffin wax. The product properties are given in Table 6-4.

Table 6-4: DuPont™ Energain® properties (DuPont™Energain®, 2010)

| Property | Description |
|---|---|
| Dimensions | Area: 1x1.198 (mxm) and thickness 5.26 mm |
| Area weight (Mass per unit area) | 4.5 kg/m$^2$ |
| Density | 810 kg/ m$^3$ |
| Melting point | 21.7 °C |
| Heat storage capacity | 515 kJ/m$^2$ (18 - 24°C) |
| Thermal conductivity liquid phase | 0.18 W/m K |
| Thermal conductivity solid phase | 0.17 W/m K |

The required amount of thermal mass depends on how severe overheating occurs in a room thus increasing the area in direct contact with internal air and the storage capacity. It is suggested that DuPont™ Energain® panels need to be placed in the warm side of the room and within the structure, located behind the insulation. If there is any cavity within the structure then it needs to be behind the thermal mass panel (Norris, 2011).The effect of Energain® panel on cooling performance is not influenced significantly when it is covered by the plasterboard as the finishing layer. A time lag of around 10 minutes was recorded in monitored buildings in which Energain® boards were installed (Norris, 2011). During heating period, installation of thermal mass helps to mitigate the indoor temperature at around the maintained comfort temperature by heating devices as room temperature is below the melting point of the phase change material. Considering this option with the current building envelop, the installation of DuPont™ Energain® will be between SIP and the internal plasterboards.

#### *6.2.2.2* Simulate PCM on building envelope

It is suggested that PCM panel was modelled as the air conditioned cavity zone in IES <VE> software tool (Kendrick and Walliman, 2007). The cavity was maintained at a set-point as related to the melting point of the selected PCM product and the latent heat capacity of PCM was the limited power capacity for the conditioned space. If the cumulated cooling load was higher than the total latent heat capacity of the selected PCM product, the air condition system would be switched off. This means that the air conditioning system in PCM cavity was turned on and off based on the maximum system power thus it allows the temperature of the conditioned space to pass beyond the set-point and rise in a normal manner. In brief, the principle to simulate melting phase was to use the nominal value of latent heat of the PCM material, average its maximum outputs over a period of time. It allows the temperature in the the Energain® board to increase and pass beyond the melting point of 21.7°C if the cumulated cooling load is higher than the total latent heat capacity of 515 kJ/m$^2$ (See Table 6-4). The same principle applies for the solidification at night so the cavity zone is heated to the set-point (i.e. 21.7°C for the Energain® board).

A research study of validating PCM model in IES<VE> suggested a simplification of phase change time would be 6 hours though this value can be adjusted in a subsequent research to better correlate to readings of the PCM sheet surface (Padovani et al., 2010). It is important to note that the energy consumption in the conditioned cavity was excluded from the energy consumption in building. The heating and cooling loads were to simulate the thermal behaviour of PCM. This is an ideal case scenario because the PCM does not always absorb its full heat storage capacity. Also effective night time ventilation is required to purge the heat remained in the thermal mass panel (Padovani et al., 2010).

Figure 6-9 depicts the thermal behaviour of the phase change materials by air conditioning the cavity zone at the set point of 21.7°C to simulate the melting process. A reverse process of solidification of the PCM occurs at night time when the cavity zone is heated at this set-point

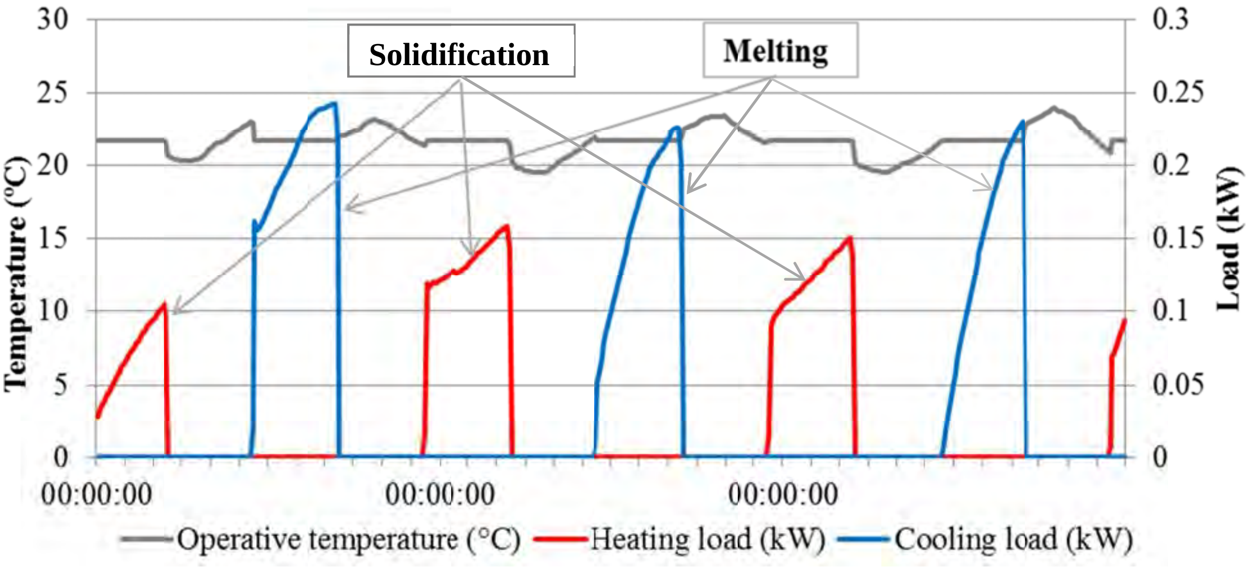


Figure 6-9: PCM thermal zone operative temperature and latent heat

Location for PCM within the building envelope could be either inner side of pitched ceiling or on wall locating behind the plasterboard. Three simulation scenarios were developed below:

(1) PCM on inner side of the pitched ceiling
(2) PCM on inner sides of external walls
(3) PCM on inner sides of the pitched ceiling and external walls

#### *6.2.2.3* Results of cooling performance PCM

By integrating PCM onto the building envelope, overheating risk diminishes in the bedroom and rest spaces except the living space. Figure 6-10 illustrates the overheating risk in the living space with different design solutions of incorporating PCM within the building envelope. It is important to note that for the PCM board to absorb by its full capacity, a careful ventilation design is required. Opening windows providing ventilation to purge out all the heat stored within the PCM board thus enable full capacity of absorb heat the following day. Night time ventilation by the use of mechanical ventilation or opening top hung windows should also be included to enhance the performance of PCM board.

With the scenario when windows are kept shut, the simulation method by air conditioning the air cavity zone still allow the heat absorptance to work in full capacity. Such scenario helps to test the effectiveness of PCM location and mass level within a space in reducing overheating risk via different orientations. The cooling effectiveness of each design strategy varies with orientation. It works best in the south case and worst in the north case. A remarkable overheating risk was reduced in the south case from 17.1% annual occupied hours down to 4.1% which equates to 325 hours of occupancy with PCM installed on the roof. It is less effective installing the PCM on ceiling than on external wall in all cases, taking account of more PCM to be installed to cover the surface area of external walls than the roof area in living space (See Figure 6-10). The overheating risk reduces but does not disappear when locating more PCM on both external walls and roof areas (i.e. 35.23 $m^2$ on the wall against 21.15 $m^2$ on the roof, See Table B-16). For all the three design options, there is no overheating risk with zero number of hours that operative temperature in living space exceeds 28°C when windows are open. Simulation results show that overheating risk diminishes in the rest of spaces like bedroom, office, bathroom and the hall.

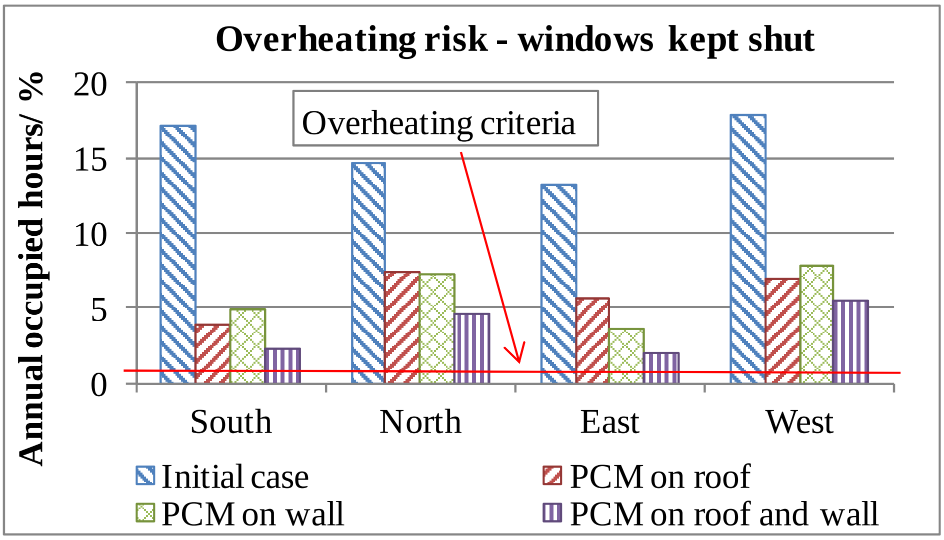


Figure 6-10: Overheating risk in the living space when PCM installed on the roof, the external walls or both within the building envelope via 4 main orientations.

Regarding the comfort benchmark for natural ventilated spaces, the presence of PCM board within the building envelope helps the percentage of annual occupied hours around the 5% benchmark for the living space and less than this level for other spaces. Such performance is valid as when windows kept shut that relies on background ventilation and the assumption of effective ventilation is provide to purge out the absorbed heat in the PCM board. It is impossible to indicate how much ventilation is required then when and how long the windows should be open to make sure the PCM works. It could be achieved just by continuous fresh air supply as background ventilation provided by mechanical ventilation system during occupancy/night time or a supplement of some more air exchanges to removing the heat during a short period of time.

## *6.3 INTERVENTIONS FOR REDUCING HEATING LOADS*

The key factors affecting heating performance are thermal insulation and airtightness of the building envelope. The thermal performance inside the building could then be improved by the use of the free source of energy (i.e. solar radiation) with the passive solar design strategies. In the scope of model simulation study, the thermal performance assessment of the building unit is regardless the specific site conditions hence solar gain through the current design of building fenestrations via 4 main orientations is taken account. This section provides a sensibility study to explore the effectiveness of insulation and airtight building on heating performance by developing a simulation scenario with an increased level of thermal insulation and airtightness on the current modular dwelling unit model.

In addition, the concept "build tight, ventilate right" is considered as the basis for good ventilation design (Perera and Parkins, 1992). This requires a good level of airtightness for buildings to minimise uncontrollable ventilation paths so as to provide adequate air exchange rate with fresh air from outside for a healthy environment. In a recent interim report conducted by Zero Carbon Hub's the Task Group, it is observed that that there is a current trend towards mechanical ventilation with heat recovery in new homes and it is likely to become the dominant form of ventilation (ZCH, 2012). It could be to cope with the building compliances resulting in an increasing number of buildings with greater airtightness level. At the same time, there is a rise in scientific awareness of the behaviour of potentially polluting materials and substances in the indoor environment (ZCH, 2012). The mechanical ventilation with the ability to recover heat from the stale, warm indoor air is therefore making an attractive market.

### 6.3.1 Improved building fabric

Building fabric factor in term of heating performance to be discussed in this section includes U-value of building elements, thermal bridging and airtightness. For low energy building, this factor varies in complying with different energy efficient standards. This is illustrated by a selection of design specifications from minimum requirements to cope with the Building Regulations - Approved Document L1A for new dwellings to several well-known energy efficiency standards such as Energy Saving Trust - Best Practice Energy Efficiency (EST BPEE, Energy Saving Trust - Advanced Practice Energy Efficiency (EST APEE) and Passivhaus ((DCLG, 2010b), (ZCH, 2009) and (BRE, 2012)) (See Table 6-5).

The current building fabric meets the requirement for new dwellings in Approved Document part L1A of Building Regulations 2000 "Conservation of fuel and power in new dwelling -2010 editions" (See Table 6-5). However, other energy efficiency standards require U-values of the building elements by nearly half of the current values achieved by the current construction state (except floor construction and door). Via sensitivity study, this section explores the thermal performance of the modular dwelling unit with an improved building fabric factor: low U-values and thermal bridging value as well as very high airtightness level.

Table 6-5: Building factor specifications in some energy efficiency standards

| Fabric factor | | Current construction | Approved Document L1A | EST BPEE (Natural ventilation) | EST APEE (Natural ventilation) | Passivhaus |
|---|---|---|---|---|---|---|
| U- value (W/m$^2$K) | Wall | 0.24 | 0.2 – 0.3 | 0.18 | 0.15 | 0.1 - 0.15 |
| | Floor | 0.16 | 0.2 – 0.25 | 0.18 | 0.15 | 0.1 - 0.15 |
| | Roof | 0.22 | 0.13 - 0.2 | 0.13 | 0.11 | 0.1 |
| | Windows | 1.71 – 1.82 (double glazed) | 1.5 – 2 (double glazed) | 1.4 (double glazed) | 0.8 (triple glazed) | 0.8 – 0.85* (triple glazed) |
| | Doors | 0.92 | 1.5 - 2 | 1.2 | 1 | 0.8 – 0.85* |
| Air permeability ($m^3/hr/m^2$) at 50Pa | | 1.82 | 5 - 10 | 3 | 3 | 0.6 ac/h |
| Thermal bridging (W/mK) | | 0.02– 0.03 | 0.04 – 0.12 | 0.05 | 0.04 | 0.01 |

Note: *U-values for windows and doors (for both the frame and glazing) do not exceed 0.8W/m$^2$K (0.85W/m$^2$.K once installed).

Amongst the three selected energy efficiency standards, the Passivhaus standard introduces the lowest building fabric factors thus it could be most effective in reducing heat loss. This standard is then selected for simulation study.

#### *6.3.1.1* Improved building fabric meeting Passivhaus criteria

The Passivhaus standard (See Chapter 2 Section 2.2.1.5) primarily aims at minimising heating and cooling demand whilst still maintaining excellent indoor comfort levels. It requires that space heating load is equal or less than 15 kWh/m$^2$ annually and consumption of total primary energy demand of 120 kWh/m$^2$ (i.e. total primary energy refers to the consumption from all services including space load, hot water boiler, auxiliary and household appliances) (BRE, 2012).

This section only focuses on the role of building fabric in reducing heating performance thus a change in building construction regarding increased thermal insulation and airtightness level is applied to meet design specifications for Passivhaus. The changes in building construction is the replacement of previous SIP system of 125mm (for external walls and suspended floor) and 150 mm thickness to 250 mm thickness of SIP where an increase in insulation layer from 103 mm to 228 mm for external walls and floor and from 120mm to 220 mm for roof structure. The thicker insulation layers in the new system help the opaque building elements to achieve a low U-value of 0.1 W/m$^2$K. Double pane windows with low e-coating and 93% of argon filled in the cavity is replaced by triple pane windows with double low e-coating glazing and 93% of argon filled in both cavities between 3 panes to achieve U-value (including frame) of windows and French patio doors of 0.776 W/m$^2$K. Regarding the air leakage rate in Passivhaus standard, air exchange rate at 50 Pascal reference pressure $n_{50}$ = 0.6 ac/h whilst knowing the dimensions of the building model, it gives out a conversion result for air permeability of $q_{50}$ = 0.41 m$^3$/hm$^2$, one fifth of the current infiltration rate. A ventilation rate of one twentieth of test results $n_{50}$ is assumed for the building model, thus an air change rate of 0.03 ac/h replaces the initial building infiltration rate of 0.13 ac/h. With regards to Passivhaus criteria, thermal bridging coefficient for the building model is assumed to be 0.01 W/m.K for linear and two dimensional thermal bridges.

#### *6.3.1.2* Simulation results

During heating period, the whole building background ventilation is provided by the infiltration rate and an additional ventilation rate which value is assigned to satisfy the required background ventilation rate. In practice, this additional ventilation rate could be supplied by trickle ventilators and partially opening windows or the use of mechanical ventilation. Space heat loads for 4 different orientations with the improved building fabric factors in comparison with those consumptions of the initial construction are shown in Figure 6-11.

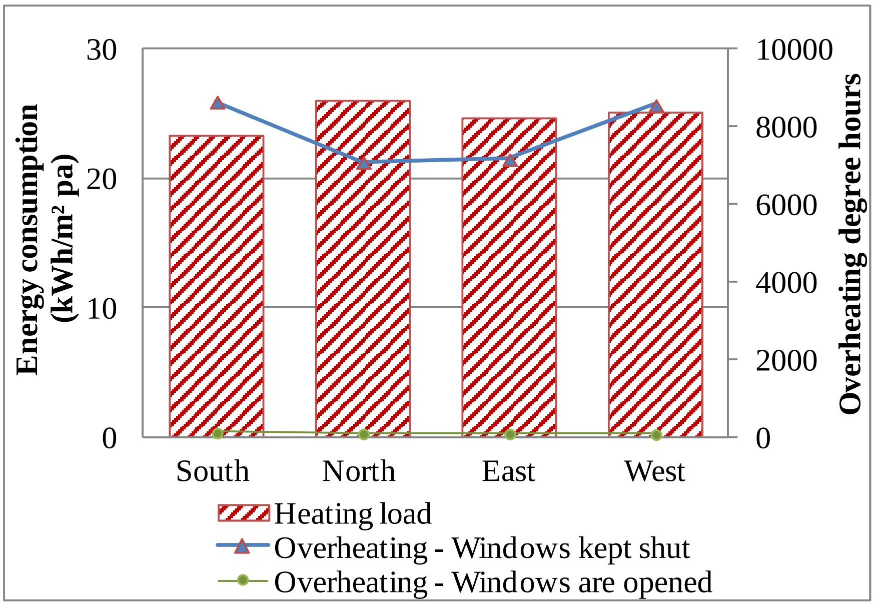


Figure 6-11: Heating loads and overheating degree hours for improved fabric criteria via four main orientations

The difference in total space load (in kWh/m$^2$ per annum) between 4 main orientations is not significant with the lowest consumption for east case of 39.1and the highest consumption is for the west case with 41.1 thus around 5% consuming more. Total space load consumption for the base case (initial construction state) ranges best for south case and worst for north case amongst 4 main orientations with 3.5% consumption difference. It can be concluded that orientation contributes a very little in the thermal performance of highly insulated building envelope. In comparison with the initial construction, the modular dwelling which envelope meets Passivhaus standard criteria is around 36.5 % heating savings (36% for west case to 37% for east case). However, increased thermal insulation slows down the release procedure of the heat built up in the space when windows are kept shut. The overheating degree hours in this case is four times higher than the base case, due to the length of time that the room operative temperature stayed higher than the 28°C benchmark. Figure 6-12 describes the temperature profile in different thermal zones via four main orientations. The simulation outputs included infiltration rate and background ventilation for indoor air quality. However, the peak temperature could be up to 46°C if ventilation is not sought through. It could results in energy savings from heating improvement are insignificant to cooling energy by electricity consumption (mechanical fan or air conditioning system).

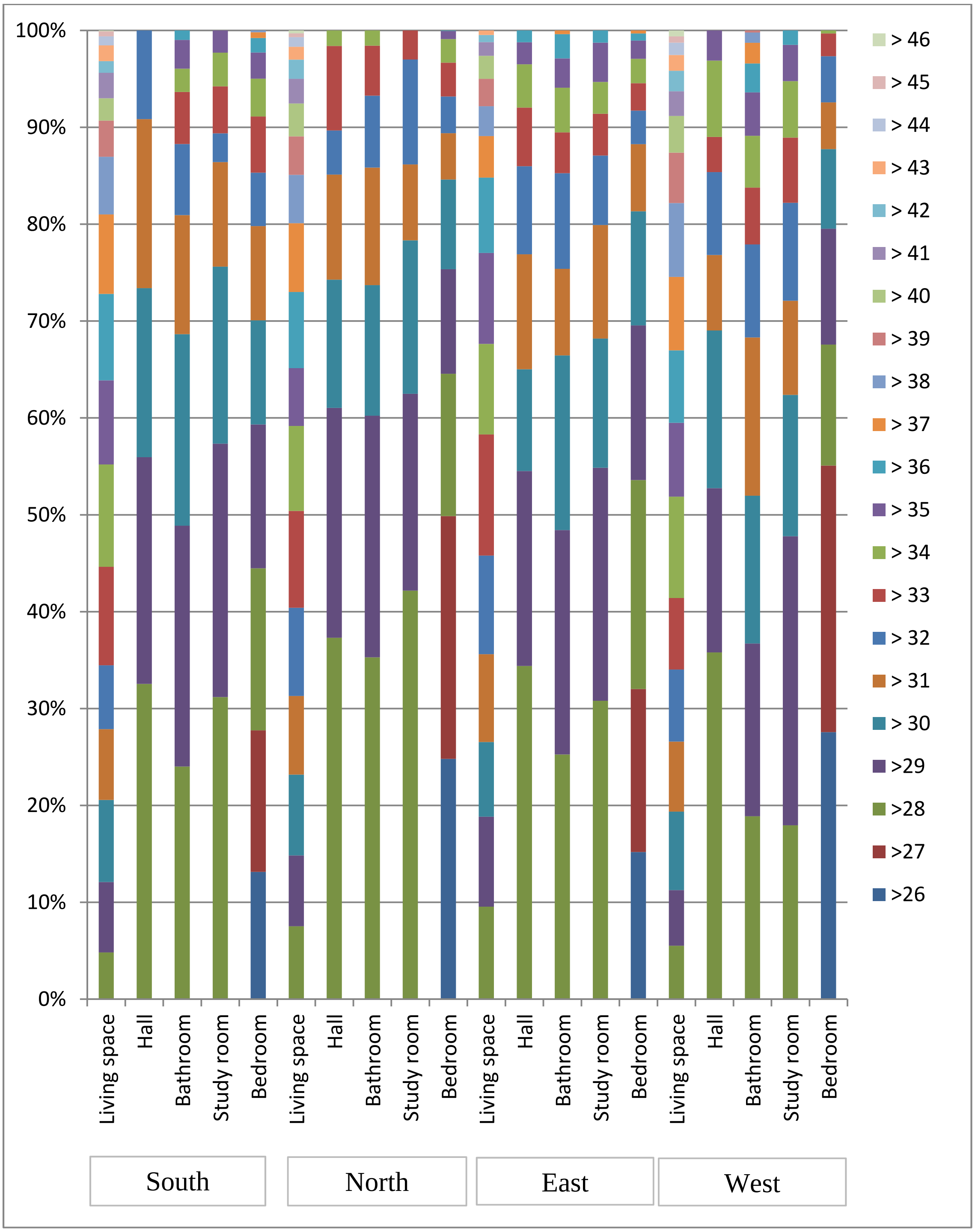


Figure 6-12: Temperature profile in different zones via four orientations

### 6.3.2 Mechanical Ventilation Heat Recovery system

The transition towards airtight buildings where uncontrollable ventilation is minimised means that there is a need for providing controllable ventilation to ensure healthy and comfortable indoor environment. Thus alternatives means to supply adequate air exchange rates through the building envelope are sought. It could be passive ventilation in winter through trickle vents on windows or by passive stack ventilation which mainly rely on stack and wind effects to push air through the dwelling in order to maintain whole building ventilation background. However, simulation results on ventilation performance in Chapter 5 Section 5.3.1 show that trickle vents in the building unit do not meet the criteria thus lower ventilation rate is supplied. Also with respect to the current design of the building unit, there is no room to develop passive stack ventilation so as to fulfil the whole building ventilation rate demand regarding polluted and stale air replaced by outdoor fresh air. By using natural ventilation through opening windows partially in winter (e.g. opening angle of window is 15°), the heat carried with warm air leaving the building escapes that could defeat the purpose of tightening the building envelope. Also, opening windows in winter is undesirable as it involves cold drafts directly affects thermal comfort and increases condensation risk. Moreover, there are some periods of high moisture production (e.g. bath, shower and cooking) that passive ventilation cannot respond thus extract fans are used in wet rooms like bathroom and kitchen.

For these reasons, mechanical ventilation options with the ability to recover heat from the extracted warm air in wet rooms have an obvious attraction. It is recommended to be used in the building unit as the whole building ventilation rate is not met by the use of trickle ventilators during heating season according to results in Chapter 5 Section 5.3.1. A whole-house mechanical ventilation is then recommended for use as it could remove polluted air and adequately ventilate every room rather than individual rooms like bathroom and kitchen where extract fans are installed. This system normally combines supply and extract ventilation in one. Fresh air is supplied to living areas and bedrooms by a supply fan and duct system while stale air and/or with high moisture content is removed from kitchen and bathroom by an extract fan and duct system (Riffat and Gillott, 2002). A heat exchanger can be incorporated into the whole house mechanical ventilation to preheat the incoming air, namely Whole house mechanical ventilation heat recovery (denoted herein as MVHR system). The extracted air which is warm indoor air from wet rooms like kitchen, bathroom via a duct system passes through a heat exchanger before being exhausted. The supplied air which is fresh outdoor air is preheated whilst passing across the heat exchanger and ducted to living areas and bedrooms (CIBSE, 2005a).

#### *6.3.2.1* Design and system selection and simulation information input

For the MVHR to work, the building needs to be well sealed. It is recommended an air leakage index (i.e. air leakage rate at reference pressure of 50Pa: $Q_{50}$ ($m^3/h$) divided by the building envelope S ($m^2$) of 8 $m^3/(h.m^2)$ at 50 Pascal for good practice and 4

$m^3/(h.m^2)$ at 50 Pascal as best practice standard (Table 1 in (CIBSE, 2000)). In fact, the airtightness test result of the building unit conducted in June 2011 obtains the air leakage index of 1.82 $m^3/(h.m^2)$ at the reference pressure of 50Pa which meets the best practice standard thus installation of MVHR is suitable to work in the building unit. Although it will add into the total electricity consumption but potential savings through better control of ventilation as well as means of reducing heat loss through heat recovery from the outgoing air are to be explored. The MVHR chosen for modelling work is an air to air heat recovery system in which heat is extracted from the exhaust air and transferred to the supply air using plate heat exchanger (See Figure 6-13).

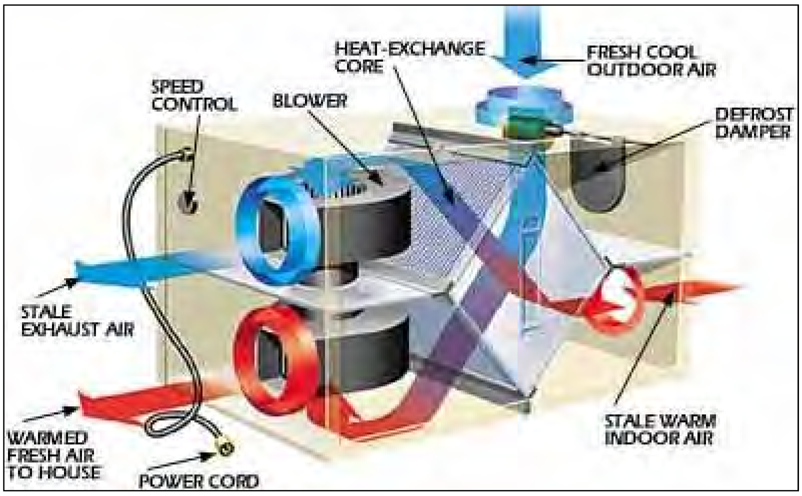


Figure 6-13: An illustration of a heat recovery ventilation unit (REUK, 2012).

The comparative analysis between passive ventilation and MVHR in Passivhaus houses conducted by AECB using Passhivhaus design and SAP packages assumed electrical consumption of MVHR rated about 0.36 $W/h.m^2$ (AECB, 2009). With the gross floor area of the building unit of 46 $m^2$ (e.g. it includes external walls but excludes roof), the power consumption of MVHR is approximately 17 W. The MVHR could operate on continuous mode like 24 hours basis or could be switched off during unoccupied period. From energy efficiency aspect, the study considers the 2nd option so the MVHR system only operates when the building is occupied. It means during weekend and public holidays, the MVHR operates on 24 hours mode and during weekdays, it runs on 15 hours per day mode that excludes 9 hours of work and commuting time (See Chapter 5, Section 5.2.1).

The extract ventilation rates recommended in Approved Document part F – Ventilation indicates a minimum amount of 8 l/s for bathroom and 13 l/s for kitchen on continuous basis whilst intermittent extract requires a minimum extract rate of 15l/s in bathroom and for the kitchen 30 l/s if adjacent to the hob – 60 l/s elsewhere (DCLG, 2010b).

Regarding the established profile of MVHR’s operation time, it is reasonable to assume the extract rate on continuous basis, thus minimum extract rate for the building unit through bathroom and kitchen are 8 l/s +13 l/s = 21 l/s. The supply air rate in liveable spaces of the building unit (excludes wet rooms, here is only bathroom as kitchen area is half of the living space) with regards to Table 5-6 is of 12.3 l/s. It satisfies the requirement of the extract air rate is at least equal to the supply air rate as in Approved Document part F (DCLG, 2010b).

The MVHR system was modelled in IES<VE> using Apache HVAC tool. The energy associated with ventilation includes energy required to heat the space and the fan power required to drive the ventilation. Heating was provided to the room through radiators in the space at the room temperature of 19ºC. And the flow rates were the sum of minimum ventilation rate, plus any boost ventilation if required, that would be translated into fan power of the system to achieve this flow rate.

Regarding the power consumption of the system, the term specific power consumption is introduced which is defined as the ratio of air flow divided by fan power to measure the efficiency of a mechanical ventilation system. In accordance to Energy Saving Trust “best practice” MVHR units have been set certain standards and must have specific power consumption of 1 W/ (l/s) or less and a heat recovery efficiency of 85% or higher (EST, 2008). From the assumptions for the power consumption and the extract rate above, the specific power consumption is then calculated as 17W / 21 (l/s) = 0.8 (W/l/s) which satisfies this requirement. A highly efficiency value of 90% is assumed for heat recovery model with respect to CIBSE guide B statement for heat recovery unit to be able to effectively transfer up to 90% of heat from warm air otherwise will be lost outside (CIBSE, 2005a).

The operation time of MVHR is when the building is occupied (Chapter 5, Section 5.2.1) over a year is calculated below:

During weekend and public holidays, the unit runs on 24 hours mode:

24x [52 weeks x 2 days (weekend) + 8 days (public holidays)] = 24 x 112 = 2688 hours.

During weekdays, it operates during 15 hours then:

15 hours x [365 days - 112 days] = 15 x 253 = 3795 hours.

The total operation time MVHR over a year is 2688 + 3795 = 6483 hours. With the operation time of 6483 hours and building floor area of 46 $m^2$ the MVHR electrical use is calculated as: 0.36 W/h. $m^2$ x 6483 hours x 46 $m^2$ = 107358 Watts or 107 kWh.

#### *6.3.2.2* Simulation results

It is important to clarify that the MVHR developed in this section is for exploring the improvement of heating performance in comparison with the initial design without installation of such system. Besides, its operation time is determined throughout a year to maintain whole building ventilation rate to extract polluted air and supply fresh air for healthy indoor environment during the year. Regarding electricity consumption as well as internal heat gain, the difference between the use of MVHR to provide extracted air continuously for kitchen area and bathroom and the use of mechanical fans to supply intermittent extract rate in these two spaces are not significant. Indeed, the average power consumption of MVHR per day is as:

17 Watts x [(15 hours x5 + 24hours x2)/7] = 298.71W.h = 0.3 kWh, while the daily average consumption of extract fans in use in kitchen and bathroom in Table 5-2 and Table 5-3 is 0.25 + 0.25 = 0.5 kWh. The difference between these consumption figures in proportion with overall household electricity consumption of 2744 kWh could be negligible.

Regarding the cooling performance, passive ventilation is still the main mean of alleviating overheating risk. It is possible that the continuous use of MVHR system could contribute in eliminating the overheating issue. In fact, this followed suggestion in the design guidance of Energy Efficiency Best Practice in Housing that the air flow rate of 5 air changes per hours during the night could help reducing overheating in a very important way, representing most significant effect of any measures (EEBP, 2005: p16).

However opening windows could provide an exchange rate up to 2000 (l/s) (data given from the simulation results in IES<VE> on 20th August with wind speed data at 8.7 m/s) which offers instant effect in removing the heat built up before (e.g. when arriving home from work) thus lessening the period of overheat suffering. The predicted space heating energy requirements for 4 cases of orientations when incorporating with the use of MVHR unit are given in Figure 6-14. This demonstrates an improvement in heating energy savings of approximately 40% in reference with the initial design without installation of MVHR unit in all 4 cases.

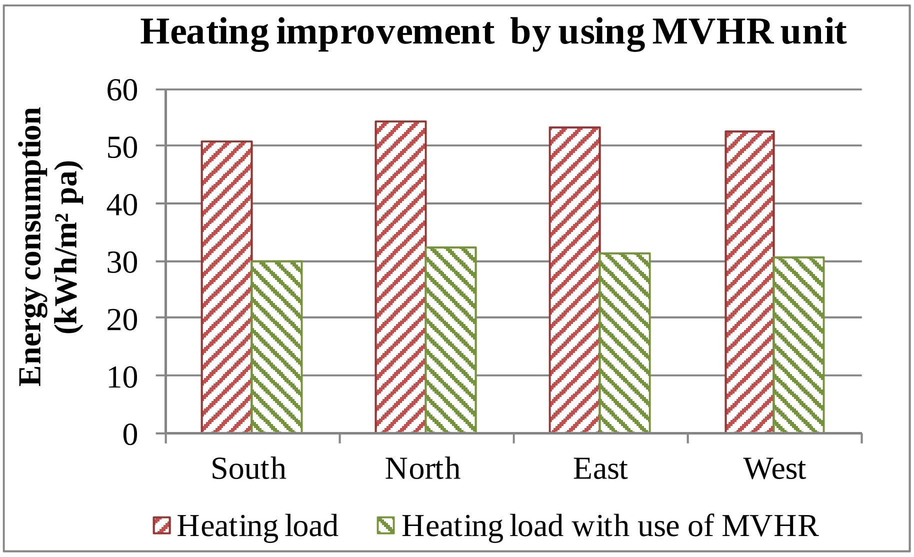


Figure 6-14: Space heat loads without and with installation of MVHR unit via 4 main orientations.

## 6.4 *FURTHER DEVELOPMENT*

As discussed in the sections above, shading design or phase change materials as the cooling intervention was able to solve the cooling demand of the building unit individually. Thus there is no need to consider a combination of these two cooling options for an ultimate performance (denoted as $Z_I Z_{II}$ ). For warmer climatic conditions elsewhere or under future climate change, the use of PCM with effective passive ventilation strategy together with suitable shading design option could lower overheating risk in such modular lightweight dwellings.

In term of heating interventions, increased thermal insulation offers significant improvement in heating energy savings that further investigations in improving building thermal performance could be beneficial. This section will discuss about combining two intervention options where increased thermal insulation interoperates with MVHR for heating improvement, with either selected shading design or PCM for cooling performance or if necessary combining both cooling interventions.

This case was $Y_I Y_{II}$ as illustrated in Figure 6-1.

### 6.4.1 Design meeting Passivhaus' criteria

The core of Passivhaus design guideline is the combination of fabric factor regarding super insulated and highly airtightness level of building envelope together with the use of MVHR system. As shown in Figure 6-15, the use of MVHR system helps to reduce more than half of heating demand that the highest consumption is predicted for the north case to be at 12.1 kWh/m$^2$ per annum which meets the Passivhaus standard of 15 kWh/m$^2$ pa.

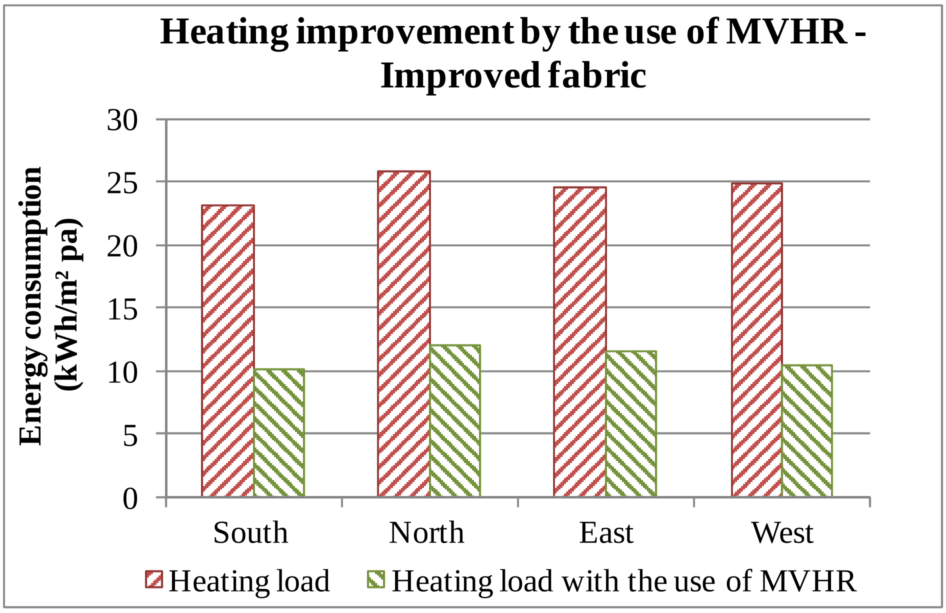


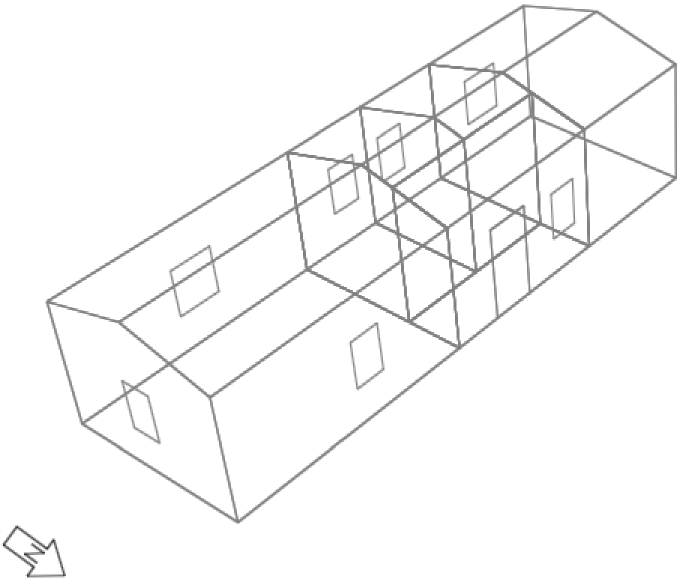
Figure 6-15: Comparison of heating demand for the building fabric meeting Passivhaus' criteria design with and without the use of MVHR

### 6.4.2 Fenestration design meeting minimum daylight factor

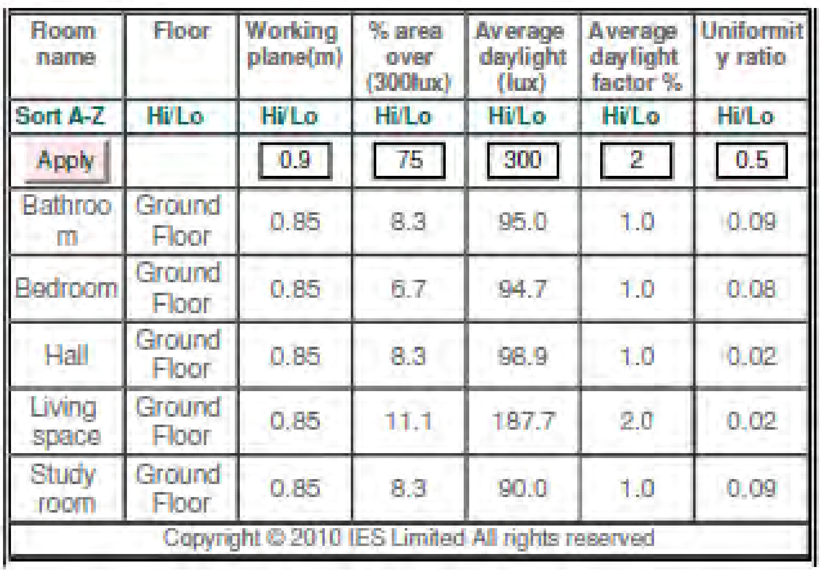
Controlling solar access can also be achieved by reducing the glazing to wall ratio. Daylight is always welcome though simulation outputs presented in Chapter 5 Section 5.3.3 and 5.3.4, suggested that the current fenestration offers significant daylight and over glazing especially from French patio doors receiving heat gains that caused peak temperature and becoming source of excessive heat loss. The model was rebuilt with resized windows as shown in Figure 6-16 (a).

This section presents a simulation scenario, where the building model was modified to the reduced glazed area, used the minimum daylight factor of 1% for bedrooms and 2% for living areas, as shown in Figure 6-16(b)

The simulation results showed that the length of overheating reduced by half, in comparison with the current building fenestration. For instance, for the south-facing case when windows were kept shut, the frequency of overheating reduced from 17.1% to 8.6% at the living space, and from 9% to 1.5% in the bedroom. The severity of overheating in the bedroom (expressed in overheating degree hours) was improved significantly, with 84 hours against 508 hours of the base case and peak operative temperature reduced from 34ºC to 31ºC. This was due to the over-sizing of the glazed area in bedroom and the French patio door of 1.66 m² net glazing area facing west. The reduced glazed to wall area of the building fenestration system leads to the reduction of useful solar heat gain during heating months. However, simulation results showed that heating demand for this case was lower than the base case. For the south case, the energy load was predicted to be 46 kWh/m² per year, compared to 50.6 kWh/m² per year. This is because the rate of heat loss through the building fenestration system out-performs the solar radiation



(a) Model view of the resized building fenestrations



| Room name | Floor | Working plane(m) | % area over (300lux) | Average daylight (lux) | Average daylight factor % | Uniformity ratio |
|---|---|---|---|---|---|---|
| Sort A-Z | Hi/Lo | Hi/Lo | Hi/Lo | Hi/Lo | Hi/Lo | Hi/Lo |
| Apply | | 0.9 | 75 | 300 | 2 | 0.5 |
| Bathroom | Ground Floor | 0.85 | 8.3 | 95.0 | 1.0 | 0.09 |
| Bedroom | Ground Floor | 0.85 | 6.7 | 94.7 | 1.0 | 0.08 |
| Hall | Ground Floor | 0.85 | 8.3 | 98.9 | 1.0 | 0.02 |
| Living space | Ground Floor | 0.85 | 11.1 | 187.7 | 2.0 | 0.02 |
| Study room | Ground Floor | 0.85 | 8.3 | 90.0 | 1.0 | 0.09 |

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(b) IES<VE> outputs of daylighting performance

Figure 6-16: Resizing glazing area to meet the minimum daylight factor

# Chapter 7: **ECONOMIC EVALUATION**

In order to assess the cost efficiency of energy performance requirements for different design options, life cycle costs for buildings or building elements over a building's lifetime, need to be calculated. The calculation operates on the basis of different packages of measures applied to the reference building (the base case) in relation to both energy use and $CO_2$ emissions. The calculation scheme of BS EN 15459:2007 was employed to assess the impact of different options for energy efficiency on a building over its service life (BSI, 2007b). The costs considered include: the correspondent investments; replacement needed as a result of different life expectancies of building components; running costs, which include maintenance, repairs and added cost for insurance or inspection; energy costs coupled with energy systems; and disposal costs, if relevant (ECEEE, 2011). This chapter is devoted to the evaluation of cost efficiency between EH building as base case and UK conventional home of similar size, and between different solar design strategies for performance improvement.

## *7.1 COST STUDY FOR TWO DWELLING TYPES*

This section includes all data used for comparative study between the standard home (denoted herein as SH) and the ErgoHome dwelling unit (EH). SH refers to a masonry dwelling built using traditional construction methods, in which materials were selected from typical construction in Environmental Design - CIBSE Guide A (CIBSE, 2006) and other thermal properties (i.e. thermal bridging and airtightness level) were based on 2010 Building Regulations for a new built dwelling (DCLG, 2010a). It is also acknowledged that thermal bridging and air leakage rate in masonry dwellings are higher than the criteria set in the 2010 Building Regulations and more work and investment cost is required to meet the criteria according to the 2007 English Housing Condition Survey (EHCS, 2009) and Appendix D: Cost Analysis for Energy Efficiency Building Fabric (ZCH, 2009). EH is the test dwelling unit as part of the research project, which used SIPs as the main construction and employed modern method of construction.

### 7.1.1 Methodology

The methodology takes into account the investment costs that are directly related to energy efficiency measures (or energy supply rate of a building) (BSI, 2007b). This means the cost calculations exclude costs related to load-bearing structures and finishing layers (e.g. carpets, interior doors, roof-tiles), neither of which have a substantial impact on building energy performance.

The investment costs for building construction include investments in insulation, windows, energy supply systems, etc. An example of typical building construction was taken from a range of selective construction data given in (CIBSE, 2006a).

The approach of global cost calculation is directly linked to the duration of the calculation period. The calculation considers the initial investment, the annual cost for every year and the final value, all of which refer to the starting year. The global cost is calculated by the formula given in BS EN 15459:2007 (BSI, 2007b):

$$C_G(\tau) = C_i + \sum_j \left[ \sum_{i=1}^{t} C_{a,i}(j) \times R_d(i) - V_{f,t}(j) \right] \tag{7-1}$$

Where: $C_G(\tau)$ is the global cost (referred to the starting year $t_o$). The global cost is directly linked to the calculation period t.

$C_i$ is the initial investment costs.

$C_{a,i}$ (j) annual cost year i for component j (including running costs and periodic or replacement costs).

$R_d$ (i) discount rate for year i.

$V_{f,t}$ (j) final value of component j at the end of the calculation period (referred to the starting year $t_o$).

The discount rate $R_d$ depends on the real interest rate $R_R$ and on the timing of the costs (p), with the real interest rate accounting for adjustment of the market interest rate ( R) and inflation rate and p is number of years after the starting year. The real interest rate is given as below:

$$R_R = \frac{R - R_i}{1 + R_i/100} \tag{7-2}$$

And the discount rate is calculated by the formula:

$$R_d = \left( \frac{1}{1 + R_R/100} \right)^p \tag{7-3}$$

The final value of component j is determined by straight line depreciation of the initial investment, until the end of the calculation period and related to the beginning of the calculation period. The BS EN 15459:2007 does not fix a specific calculation period for the global cost method (BSI, 2007b). The cost optimal report (ECEEE, 2011) recommended the calculation period could be set at 30 years because this timeframe covers the lifetime of most of the measures subjected to the cost and it is also a time span of fixed interest rates offered by banks.

For any annual costs (e.g. energy cost or maintenance/insurance cost) and any annual incomes being referred to the starting year, the present value factor was introduced. It takes into account the real interest rate ($R_R$) and the number of years (n) considered for the annual costs as shown in Equation 7-4 below:

$$f_{pv}(n) = \frac{1-(1+R_R/100)^{-n}}{R_R/100} \tag{7-4}$$

In order to take into account annual variations of the discount rate, as well as annual variations of the rate of development of prices related to the any cost included in the annual costs (e.g. energy cost, operation/maintenance cost, periodic/replacement cost and added cost), dynamic calculations are required. The running cost for dynamic calculations is then determined by:

$$C_r = \left(C_e \times \beta_e + C_o \times \beta_o + C_m \times \beta_m + C_{ad} \times \beta_{ad}\right) \tag{7-5}$$

Where:

The index x: e = energy costs, o = operational costs, m = maintenance costs, ad = added costs.

$C_r$ - running costs throughout the calculation period.

$C_x$ - particular running costs.

$\tau$_building is the design payback period of the building.

And $\beta_x$ is the price dynamic factor, which is a function of the inflation rate $R_i$, the market interest rate R and the rate of development of the price considered $R_x$. It is calculated below:

$$\beta_x = \frac{1-\left(\dfrac{1+R_x/100}{1+R/100}\right)^{\tau\_building}}{1-\left(\dfrac{1+R_i/100}{1+R/100}\right)^{\tau\_building}} \times \frac{\left(R-R_i\right)/\left(1+R_i/100\right)}{\left(R-R_x\right)/\left(1+R_x/100\right)} \tag{7-6}$$

In the basic case of cost calculation as seen in Appendix E of the BS EN 15459:2007, the t rate of development of prices $R_x = R_i$, then $\beta_x=1$. And the running cost which covers annual costs (energy, operational, maintenance and added cost of installation and building component) for non dynamic calculation is then given by:

$$C_r = \left(C_e + C_o + C_m + C_{ad}\right) \tag{7-7}$$

### 7.1.2 Cost study

An economic analysis for the base design of SIP dwelling developed from Chapter 5 was compared with a new built masonry construction, of a similar size, representing the traditional construction method dominant in the house building sector. In fact, the housing stock profile derived from EHCS in 2007 showed 15.5 million dwellings with cavity walls (equating to 70% of the housing stock), half of which are insulated (EHCS, 2009).

By selecting a brick/block work with insulation filled cavity, as the new built dwelling meeting the requirements of the Building Regulations (2010 part L1A), the comparison could demonstrate the differences between buildings using a traditional construction method, with heavy weight, and the modern construction method, with lightweight SIPs. For a timber framed dwelling, performance, and cost can lie in between this range as being reasonably cheap and popular, as it is constructed by traditional methods, emits less carbon dioxide compared to masonry dwellings and thermally performs worse than a SIPs building. Masonry constructional information was selected from Table 3.49 – 3.51 in CIBSE guide A (CIBSE, 2006a), which meet the current criteria for new built dwellings as set out in 2010 part L1A.

Due to a lack of information about building onsite, between SIPs used in the project and estimation for a masonry dwelling of the same size, the cost calculation in the study excludes the substructure, only covering material cost, heating and DHW system, replacement cost for building elements and operational cost. Most of the material cost for masonry construction, windows were derived using the Spon's Architects' and Builders' Price Book (Langdon, 2010). The cost of SIPs and VELFAC windows were sourced from the suppliers. The information on heating and DHW, system cost and replacement as well as the lifespan are given in the BS EN 15459:2007.

It was observed that a central heating system (a system with boiler and radiators that distributes heat throughout the dwelling) was the predominant form, representing 87%

of the total English housing stock, which equates to 19.3 million dwellings in 2007 (Nowak, 2009). 84% of housing stock uses a central heating system fuelled by gas, as it is generally considered to be a fuel which combines low cost and low $CO_2$ emissions most effectively. In the scope of cost comparison, heating and DHW system were chosen to be fuelled by mains gas, as the masonry dwelling will fail performance requirements for an electric heating/DHW installation. Indeed, heating by electricity has a higher fuel cost and greater emissions than any other alternative fuel even where installation and maintenance costs are lower. In some limited circumstances such as small and well-insulated properties, best practice recommendations would allow electricity heating (EST, 2003b). Whilst if electricity is an obligatory  source in several restricted locations for mobile homes, then SIPs construction becomes an obvious choice as it conforms with all high standard performance required for installing electric heating as set out in Good Practice Guide 345: Domestic Heating by Electricity (EST, 2003b). In the case of improved performance in which a masonry dwelling could cope with an electric heating installation, the benefits of energy savings based on the predicted heating demand gap between the two construction methods, a significantly higher cost saving would be predicted compared to the result presented below, because electricity price is much higher than mains gas, approximately three times more expensive.

To enhance comparison between different building geometries and sizes, it is proposed to express the results in Pounds Sterling per square metre of conditioned floor area. The global costs calculation of two different packages of measures: SIPs dwelling denoted as EH and masonry dwelling as SH were conducted. For results sensitivity analysis, different price scenarios were looked at and different interest rates for three levels, for both packages: high, medium, and low. Interest rates were derived from market interest rates, adjusted for inflation (i.e. interest rates offered minus inflation rate). The rates are subject to changing market conditions and differ depending on whether being viewed from the private or societal sector: all kind of taxes (VAT, etc) need to be included in private sectors whilst from societal perspective, these taxes are excluded (ECEEE, 2011).

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Table 7-1: Building constructional data

| **Housing type** | **Building component** | **Identification of constructional information** | **U-value, W/m$^2$K** | **Area, m$^2$** | **Reference** |
|---|---|---|---|---|---|
| **SH** (new built masonry dwelling meets ADL1A (DCLG, 2010a) | Wall with filled cavity insulation | 105 mm brick, 100 mm PU foam, 100 mm dense concrete block, 13 mm dense plaster | 0.3 | 75.4 | Selected constructional data from Table 3.49, 3.50, 3.51, 3.54 in (CIBSE, 2006). |
| | Insulated to raft level pitched roof | 12.5 mm plasterboard, 150 mm mineral wool between rafters and 50 mm over rafters, ventilated airspace, roofing felt, 25 mm ventilated airspace, clay tiles | 0.2 | 43.1 | |
| | Concrete cast suspended floor | Vinyl floor covering, 50 mm screed, 150 mm cast concrete and 100mm EPS | 0.25 | 45.95 | |
| | Insulation filled cavity with effective sealing | 13 mm lightweight plaster, 100 mm lightweight concrete block, 25mm air cavity with batten filled with mineral wool, 13 mm lightweight plaster | 0.5 | 37.01 | |
| | Double glazed windows | Low emissivity coating layer on the outside surface of inside pane to reduce heat loss | 2.0 | 9.94 | |
| | Entrance door | Composite door: aluminium and mineral fibreglass | 1.54 | 1.84 | (DCLG, 2010a) |
| | Air permeability | Test at pressure difference at 50 Pa | 10 m$^3$/m$^2$h | - | |
| **EH** | External walls | Cedar timber, cavity, SIPs 125, gypsum paper faced board | 0.24 | 75.4 | Refer to Appendix B.2. and Chapter 4 Section 4.4.1 |
| | Pitched roof | Corrugated aluminium, SIPs 150 mm, plasterboard | 0.22 | 43.1 | |
| | Suspended floor | SIPs 150 mm, polystyrene, oak | 0.16 | 45.95 | |
| | Partition wall | Timber studs with rock wool insulation | 0.50 | 37.01 | |
| | Double glazed windows | Low e-coating and argon filled to 93% in the air cavity | 1.82 | 9.94 | |
| | Entrance door | Composite door, extreme low U (Door style SFS 405) | 0.9 | 1.84 | |
| | Air permeability | Tested and certified by BSRIA at 50Pa pressure difference | 1.82 m$^3$/m$^2$h | - | |

*The thermal transmittance of a conventional hardwood of 65 – 75 mm thickness entrance door with U-value = 2.5 – 3 W/m$^2$K thus in order to meet the compliance for new built dwelling with U-value less than 1.8 W/m$^2$K, a composite door with was selected.

#### 7.1.2.1 Initial investment costs

##### *7.1.2.1.1 Investment costs for building construction*

Table 7-2: Cost of VELFAC windows

| **VELFAC 200** used in the case study | **Dimension** | **Quantities** | **Area, m$^2$** | **Cost** in pounds sterling per square meter (small project) | **Reference** |
|---|---|---|---|---|---|
| Large window | 0.886 x 1.023 | 2 | 0.906 | 262.37 | (Chadwick, 2011) |
| Small windows | 0.623 x 1.023 | 5 | 0.637 | 250.25 | |
| French patio door | 1.173 x 1.983 | 2 | 0.288 | 719.72 | |
| Fixed windows | 0.373 x 0.773 | 1 | 0.288 | 126.31 | |
| Sum | | | 9.937 | 3341.74 | |
| Material cost, £/m$^2$ | | | | 336.29 | |
| Guided price for installation, £/m$^2$ | | | | 62.10 | L 10, p634 in (Langdon, 2010) |
| Cost per square meter, £/m$^2$ | | | | 398.40 | |

The windows, supplied by VELFAC Ltd as the fenestration system of the EH dwelling, were priced by each window unit, with specific dimensions. Table 2.A-2 established the cost per unit in order to convert into the cost per square metre of the fenestration system to agree with the calculation costs for other building elements and systems as seen in Table 2.A-3.

Cost difference between large scale project (more than 4 units) and small project (less than 4 units) (in Table 2.A.4) is calculated to be 11% for SH (See Table above). It is claimed by the SIPs manufacture, that for the SIPs unit, the saving would be up to 20% as a result of employing modern methods of construction (SIPCO, 2009).

Table 7-3: Price of building materials

| **Housing types** | **Building component** | **Area, m$^2$** | **Costs per square meter £/m$^2$**, (large scale) | **Reference**s in (Langdon, 2010) | **Costs per square meter £/m$^2$**, (small project) | **References** in (Langdon, 2010) |
|---|---|---|---|---|---|---|
| **SH** (new built masonry dwelling meets 2010 Building Regulations (DCLG, 2010a) | Solid wall with fully filled cavity insulation | 75.25 | 53.82+ 4.61 | F10, p219 and P11, p 405 | 58.32+ 5.13 | F10, p540 and P11, p702 |
| | Insulated to raft level pitched roof | 47.5 | 28.98+7.38 | H60, p281and P10, p 402 | 35.41+9.95 | H60, p586 and P10, p700 |
| | Concrete cast suspended floor with insulation | 45.87 | 44.82 + 10.70 + 9.21 +13.27 | E60, p214; M10, p656; M50, p376 and P11, p403 | 41.83 + 13.29 + 11.25 + 15.1 | E60, p214; M10, p656; M50 p 672 and P11, p701 |
| | Insulation filled cavity with effective sealing party wall | 42.02 | 23.33 + 7.21 + 4.50 | F10, p232; K10, p313 and P10, p 402 | 27.27 + 7.99 + 5.98 | F10, p55; K10, p614 and P10, p700) |
| | Double glazing, low e coating | 9.47 | 264.94 | L40, p357 | 316.63 | H10, p582 |
| | Entrance door* | 1.84 | 567.5 | | 567.5 per unit | 2F, p141 |
| **EH** | External wall - SIPs 125 | 75.25 | | | 50+16.3 | (SIPCO, 2009) |
| | Pitched roof SIPs 150 | 47.5 | | | 50+16.3 | |
| | Suspended floor SIPs 150 | 45.87 | | | 70+16.3 | |
| | Timber stud and fiberglass party walls | 42.02 | | | 55+16.3 | (2G, p142, P10, p700) |
| | Double glazed, argon filled, low e coating | 9.47 | 14.5 + 4.5 | (2G, p142; P10, p402) | 18.5+ 5.98 | See Table 7-1 |
| | Door (SFS 405) | 1.84 | | | 398.4 | (Chadwick, 2011) |

Table 7-4: Investment cost of building construction

| **Housing types** | **Building component** | **Total cost, (large scale), inc. VAT** | **Total cost, (small project), inc. VAT** | **Life span** |
|---|---|---|---|---|
| SH (new built masonry dwelling meets 2010 Building Regulations (DCLG, 2010a) | Solid wall | 4050.1 | 4388.6 | Building |
| | Insulation filled in wall cavity | 346.8 | 386 | 25 |
| | Pitched roof | 1376.55 | 1681.98 | Building |
| | Insulation to raft level | 350.55 | 472.63 | 25 |
| | Concrete cast suspended floor | 2969.17 | 3044.39 | Building |
| | Insulation of suspended floor | 608.69 | 692.64 | 25 |
| | Timber stud and plasterboards of masonry party wall | 1283.29 | 1481.63 | 30 |
| | Insulation within timber stud cavity | 189.1 | 251.28 | 25 |
| | Double glazing, low e coating | 2508.98 | 2998.49 | 30 |
| | Composite entrance door | 567.5 per unit | 567.5 per unit | 25 |
| | Total cost | 14,250.68 | **15,965.13** | |
| EH | External wall - SIPs 125 | | 4989.08 | 50 |
| | Pitched roof SIPs 150 | | 4099.25 | 50 |
| | Suspended floor SIPs 150 | | 3270.53 | 50 |
| | Timber stud and fiberglass of party walls | | 951.33 | 30 |
| | Double glazed, argon filled, low e coating | | 3772.85 | 30 |
| | Low U door (SFS405) | | 1000 per unit | Building |
| | Total cost(20% reduced) | 14,466 | **£18,083.04** | |

#### *7.1.2.1.2 Initial investment cost for building energy system*

Based on statistical data in English Housing Condition Survey, natural gas is still the main fuel resource for heating in buildings. The building heating system was assumed as gas condensing combination boiler with flue for both construction units.

The ventilation strategy applied here is natural ventilation: intermittent extract fan for extract ventilation in moisture producing areas (e.g. kitchen and bathroom), trickle ventilators for whole dwelling ventilation and window openings for reducing overheating (See Chapter 5 Section 5.3.3). Ventilation provision employs mechanical system in kitchen and bathroom, with fan and flexible ducts. Intermittent operation is used only when the need for removing pollutants or water vapour arises. Regarding the occupant usage pattern established in Chapter 5, Section 5.2.1, the number of hours that the extractor fans operates in total is 365 hours. The electricity consumption for extracting fans could be calculated from specific fan power value, expressed in Watts per litre second. Mechanical extraction ventilation is needed in moisture producing areas (e.g. kitchen and bathroom).

The cost in Euro is converted into British Pound, using the exchange rate conversion at the considered time according to HM Revenue & Customs (HMRC): Average for year 2007 the period of cost, is stated within the reference as €1 = £0.684755.

(See http://www.hmrc.gov.uk/exrate/european-union.htm).

Initial investment cost for building energy system is shown in Table 7-5 in the next page

### *7.1.2.2* Periodic costs for replacement

In this step, information regarding lifespan and costs for replacement of building components and systems are gathered for calculations. At the replacement time, the average replacement costs of systems should include inflation effects where cost levels are foreseen to increase or decrease (BSI, 2007b).

The lifespan of a masonry dwelling is more than 50 years, which is the lifespan of the SIP structure. Traditional construction, with concrete and poured block footings and foundations, could last a lifetime (i.e. 100+) with the assumption that they are properly built

Periodic costs for building construction are shown in Table 7-6

Table 7-5: Description of building system used in the comparative study (Table E.1, BSI, 2007b)

| **Building system** | **Identification** | **Life span** | **Total cost inc. VAT, €** | **Total cost inc. VAT, £** |
|---|---|---|---|---|
| **Heating system** | | | | |
| Emission | Steel radiators including hydraulic valve control, thermostatic valve and room control system | 20 | 3792 | 2597 |
| Distribution | Steel pipe | 30 | 474 | 325 |
| Generation | Gas condensing combination boiler with flue<br>Power: 23 kW | 15 | 1494 | 1023 |
| Connection to energy | Gas<br>Electricity | 25 | 457<br>762 | 313<br>522 |
| **Domestic hot water** | | | | |
| Emission | Thermostatic valve (kitchen and bathroom) | 20 | 153 | 105 |
| Distribution | Copping piping | 30 | 237 | 162 |
| Generation | See heating system | | | |
| **Ventilation** | | | | |
| Emission | Air input<br>Mechanical ventilation in kitchen and bathroom | 25 | 303 | 207 |
| Generation | Fan and flexible ducts | 20 | 273 | 187 |
| Connection to electric board | | 25 | 69 | 47 |
| Total energy system | | | **8014** | **5488** |

Table 7-6: Periodic costs for replacements of building components

| **Type of dwelling** | **Building element** | **Investment cost, £** | **Lifespan** | | | |
|---|---|---|---|---|---|---|
| | | | **25** | **30** | **50** | **Building** |
| **SH** | External walls | 4388.6 | | | | 4388.6 |
| | Roof | 1681.98 | | | | 1681.98 |
| | Floor | 3044.39 | | | | 3044.39 |
| | Insulation materials | 1802.55 | 1802.55 | | 1802.55 | - |
| | Plasterboards for party wall | 1481.63 | | 1481.63 | | - |
| | Insulating windows | 2998.49 | | 2998.49 | | - |
| | External door | 567.5 | 567.5 | | | - |
| | Total | **15965.13** | **2370.05** | **4480.12** | **1802.55** | **9114.97** |
| **EH** | External walls | 4989.08 | | | 4989.08 | |
| | Roof | 4099.25 | | | 4099.25 | |
| | Floor | 3270.53 | | | 3270.53 | |
| | Insulating windows | 3772.85 | | 3772.85 | | - |
| | Timber stud and fibreglass | 951.33 | | 951.33 | | |
| | Entrance door | 1000 | | | 1000 | |
| | Total | **18083.04** | | **4724.18** | **13358.86** | - |

Table 7-7: Periodic costs for components of the energy system for both dwelling types

| **Building system** | **Identification** | **Investment cost, £** | **Life span** | | | |
|---|---|---|---|---|---|---|
| | | | **15** | **20** | **25** | **30** |
| **Heating system** | | | | | | |
| Emission | 8 steel radiators | 2597 | | 2597 | | |
| Distribution | Steel pipe | 325 | | | | 325 |
| Generation | Gas condensing combination boiler with flue<br>Power: 23 kW | 1023 | 1023 | | | |
| Connection to energy | Gas connection | 313 | | | 313 | |
| | Electricity connection | 522 | | | 522 | |
| **Domestic hot water** | | | | | | |
| Emission | Thermostatic valve (kitchen and bathroom) | 105 | | 105 | | |
| Distribution | Copping piping | 162 | | | | 162 |
| **Ventilation** | | | | | | |
| Emission | Inlet air | 33 | | | 33 | |
| | Mechanical extraction (kitchen and bathroom) | 175 | | | 175 | |
| Generation | Fan and flexible ducts | 187 | | 187 | | |
| Connection to electric board | | 47 | | | 47 | |
| Total in £ | | **5488** | **1023** | **2889** | **1090** | **487** |
| Reference | Table E.3 in (BSI, 2007) | | | | | |

### *7.1.2.3* Running costs except energy costs

Running costs include the costs for building energy consumption, costs for periodic inspection of energy systems for heating system (e.g. boiler) or annual contracts for cleaning, maintenance of building components and systems, and added costs known as insurance and taxes related to energy systems.

The maintenance costs were assumed to equate to 2.75% of the investment costs, related to emissions and generation for heating and distribution according to Annex E in BS EN 15459: 2007 (BSI, 2007b). The maintenance cost for the heating system (see Table 7-7) is calculated below:

2.75% x (2597 + 1023 + 105) = 102 (Pound Sterling)

### *7.1.2.4* Energy costs

There are two parts of energy costs: one is directly related to energy consumption, which varies in accordance with fuel consumption of the building systems and household appliances is a fixed value according to the quantity of energy subscribed with energy utilities (e.g. gas tank, electricity transformation) (BSI, 2007b).

Energy requirements for heating and domestic hot water (DHW) for SH and EH were calculated using IES<VE> software. The simulation weather file in use was CIBSE TRY for Birmingham location and the same profile of occupancy pattern as discussed in Chapter 5 Section 5.2. Input building constructions for SH were established based on information given in Table 7-1. Because the same building energy system was used for both types of dwelling (i.e. condensing gas fired combination boiler for space heating and DHW, mechanical extracting ventilation for kitchen and bathroom usage), only the energy costs from annual consumption differ in these two cases. Energy consumption for lighting and household appliances are excluded as this comparative study focuses on thermal performance and energy saving aspects of the building envelopes.

The minimum ventilation rate required for intermittent usage is 30 l/s in the kitchen and 15l/s in the bathroom, according to Approved Document part F – Ventilation (DCLG, 2010b). Without selecting a specific fan product, electricity consumption of the extractor fan is based on data in SAP 2009 calculation. The specific fan power value which accounts for the in use factor is determined by: 0.8x 2.5 = 2 W/ (l/s). The electricity consumption (in kWh per year) for extracting a flow rate of 30 l/s for one hour daily usage, the electricity consumption in kWh per year for extractor fans is calculated below:

2 (W/ (l/s)) x 30 (l/s) x 365 (hours) = 21900 (Wh) = 21.9 (kWh).

Table 7-8: Energy costs for SH and EH

| | **Energy system** | **Annual energy access** | **Price per unit (inc. VAT), £/kWh** | **Energy requirement, kWh** | **Total price, £** |
|---|---|---|---|---|---|
| **SH** | Space heating: gas fired boiler | Standing charge: gas | 106 | | 106 |
| | | Annual consumption | 0.031 | 4054.1 | 125.68 |
| | | Auxiliary electricity | 57 | | 57 |
| | DHW | Annual gas consumption | 0.031 | 1132.2 | 35.1 |
| | Mechanical extraction | Annual electricity consumption | 0.1146 | 21.9 | 2.51 |
| | | Total | | | **326.29** |
| **EH** | Space heating | Standing charge: gas | 106 | | 106 |
| | | Annual gas consumption | 0.031 | 2321.2 | 71.96 |
| | | Auxiliary electricity annual access | 57 | | 57 |
| | DHW | Annual gas consumption | 0.031 | 1132.2 | 35.1 |
| | Mechanical extraction | Annual electricity consumption | 0.1146 | 21.9 | 2.51 |
| | | Total | | | **272.57** |
| Fuel prices including VAT refer to Table 12 (SAP2009, 2010) and energy consumptions were calculated using IES<VE> program | | | | | |

### *7.1.2.5* Global cost calculation

As previously discussed in Section 7.1.2.1, the calculation period and the design payback period of the building were set to be at 30 and 50 years respectively. Taking the inflation rate $R_i$ = 2%, market interest rate R = 4.5% as the example for calculation following the value suggested in Appendix E of BS EN 15459:2007 (BSI, 2007b).

### *7.1.2.5.1 Calculation of replacement cost and final value*

Table 7-9 determined the value of building components and energy systems at the end of the calculation period of 30 years

Table 7-9: Final value of building components and energy system

| | **Replacement costs/final value** | **Life span** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **15** | **20** | **25** | **30** | **50** | **Building** | |
| **SH** | Replacement costs (building components) | | | 2370.05 | 4480.12 | 1802.55 | 9114.97 | |
| | Replacement costs (energy systems) | 1023 | 2889 | 1090 | 487 | | | |
| | Total | 1023 | 2889 | 3460.05 | 4967.12 | 1802.55 | 9114.97 | |
| | Final value at the end of calculation period | 100% | 50% | 80% | 100% | 40% | 40% | |
| | Final value at $\tau_n$ | 1023 | 1444.5 | 2768.04 | 4967.12 | 721.02 | 3645.99 | **14569.67** |
| **EH** | Replacement costs (building components) | | | | 4721.18 | 13358.86 | | |
| | Replacement costs (energy systems) | 1023 | 2889 | 1090 | 487 | | | |
| | Total | 1023 | 2889 | 1090 | 5211.18 | 13358.86 | - | - |
| | Final value at the end of calculation period | 100% | 50% | 80% | 100% | 40% | | |
| | Final value at $\tau_n$ | 1023 | 1444.5 | 1707.2 | 5211.18 | 5343.54 | | **14729.42** |

Final values referred to the starting year, as shown in Tables 7-10 and 7-11 were obtained by applying the appropriate discount rate coefficient, depending on inflation rate and market interest rate (BSI, 2007b: p47).

In the basic case, as illustrated in Appendix E of BS EN 15459:2007, the rate of development of prices is considered equal to the inflation rate; thus operation cost = 2%, gas price = 2%, electricity= 2% (BSI, 2007b). The discount rates in Table 7-10 and 7-11 were calculated by using Equation 7-3 for different timing of the considered cost. For example with a life span of 15 years, the real interest rate is calculated as 2.45%

(obtained from market interest rate R=4.5% and inflation rate $R_i$=2%) and the discount rate is calculated as 0.6954.

For a component with a lifespan of 15 years, for the calculation period of 30 years, the replacement costs would occur twice as seen in Tables 7-10 and 7-11.The discount rate, corresponding with of second replacement after a further 15 years' lifespan, will be for 30 years.

Table 7-10: Total global cost for the standard home (SH)

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Present value factor** | **Total due for owner** | **Total due for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Building component | 15,965.13 | 1.0 | 15965.13 | |
| | Energy system | 5488 | 1.0 | 5488 | |
| | | | Discount rate | | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.6954 | 711.4 | |
| | Lifespan of 20 years | 2889 | 0.6161 | 1779.9 | |
| | Lifespan of 25 years | 3460.05 | 0.5459 | 1888.8 | |
| | Lifespan of 15 years | 1023 | 0.4836 | 494.7 | |
| | Lifespan of 30 years | 4967.12 | 0.4836 | 2402.1 | |
| | Final value at the end of calculation period | 14569.67 (Table 7-9) | 0.4836 | 7045.89 | |
| | | | Present value factor | | |
| **Running costs (maintenance)** | | 102 | 21.07 | | 2149.14 |
| **Energy costs** | Gas | 266.78 | 21.07 | | 5621.05 |
| | Electricity (including auxiliary) | 59.51 | 21.07 | | 1253.88 |
| | Total | | | 21684.14 | 9024.07 |
| **Total Global cost** | | | | **30708.21** | |

Table 7-11: Total global cost for the case study (EH)

| Type of cost | Details of each type | Cost inc. VAT, £ | Present value factor | Total due for owner | Total due for occupant |
|---|---|---|---|---|---|
| **Investment costs** | Building component | 18083.04 | 1.0 | 18083.04 | |
| | Energy system | 5488 | 1.0 | 5488 | |
| | | | Discount rate | | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.6954 | 711.4 | |
| | Lifespan of 20 years | 2889 | 0.6161 | 1779.9 | |
| | Lifespan of 25 years | 1090 | 0.5459 | 595 | |
| | Lifespan of 15 years | 1023 | 0.4836 | 494.7 | |
| | Lifespan of 30 years | 5211.18 | 0.4836 | 2520.1 | |
| | Final value at the end of calculation period | 14729.42 (Table 7-9) | 0.4836 | 7123.15 | |
| | | | Present value factor | | |
| **Running costs (maintenance)** | | 102 | 21.07 | | 2149.14 |
| **Energy costs** | Gas | 213.06 | 21.07 | | 4489.17 |
| | Electricity (including auxiliary) | 59.51 | 21.07 | | 1253.88 |
| | Total | | | 22548.99 | 7892.19 |
| **Total Global cost** | | | | **30441.18** | |

### 7.1.3 Sensitivity analysis

Regarding cost development, two financial measures were included: fuel price and interest rate.

#### *7.1.3.1* Price scenarios

It is recommended to use three different price scenarios: high, medium and low to assess the sensitivity of results. The reference (or average) price scenario refers to the current use of energy price data in SAP2009 calculation. This is suggested in the report of cost optimal for sensitivity analysis for high and low price is ±30% (ECEEE, 2011).

The rate of development of the price within the reference base case in the section above was of the same inflation rate $R_x = R_i$ (= 2%) which implies the price dynamic factor equates to 1 (BSI, 2007b). On the high and low price scenarios, the rates of development of the price are 2.6% and 1.4% respectively. By using the formula above, the price dynamic factor $\beta_x$ and the operation costs related to running costs (maintenance, insurance) and energy costs for two types of dwellings (SH and EH) are calculated in the table below:

Table 7-12: Influence of energy price on operational costs

| **Type of dwellings** | **Price scenarios** | **The rate of development of the price, $R_x$** | **Price dynamic factor $\beta_x$** | **Operation cost in £/$m^2$ floor** |
|---|---|---|---|---|
| **SH** | Reference | 2% | 1 | 149.88 |
| | Low | 1.4% | 0.9235 | 138.41 |
| | High | 2.6% | 1.085 | 162.62 |
| **EH** | Reference | 2% | 1 | 125.31 |
| | Low | 1.4% | 0.9235 | 115.73 |
| | High | 2.6% | 1.085 | 135.96 |

### *7.1.3.2* Interest rate

According to BS EN 15459 (BSI, 2007b), the interest rate is derived from the market interest rate adjusted for inflation rate, which depends on the change of market conditions and differs one to another in terms of private or societal perspectives. In order to assess the influence of different interest rates on the relative costs in the two dwelling cases, three scenarios of interest rates were used: reference (4.5%) as being used in all calculations above, low rate (2.5%) and high rate (6.5%), as suggested in an example in the cost optimal report (ECEEE, 2011).

#### *7.1.3.2.1 Low interest rate*

With the market interest rate R= 2.5% and the inflation rate still at 2%, the real interest rate is then recalculated using the equation 7-1 to be at 0.49%. The discount rates determined by Equation 7-2 for 15 years, 20 years, 25 years and 30 years calculation period are given in Table 7-13 and 7-14. The final value factor of the total package, by the end of calculation period (30 years), is obtained by using Equation 7-3, as seen in the two tables below.

Table 7-13: Total global cost for the standard home (SH) at low interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Present value factor** | **Total due for owner** | **Total due for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Building component | 15,965.13 | 1.0 | 15965.13 | |
| | Energy system | 5488 | 1.0 | 5488 | |
| | | | Discount rate | | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.929 | 950.37 | |
| | Lifespan of 20 years | 2889 | 0.905 | 2641.55 | |
| | Lifespan of 25 years | 3460.05 | 0.882 | 3051.76 | |
| | Lifespan of 15 years | 1023 | 0.86 | 879.78 | |
| | Lifespan of 30 years | 4967.12 | 0.86 | 4271.72 | |
| | Final value | 14569.67 (Table 7-9) | 0.86 | 12529.92 | |
| | | | Present value factor | | |
| **Running costs (maintenance)** | | 102 | 27.84 | | 2839.68 |
| **Energy costs** | Gas | 266.78 | 27.84 | | 7427.16 |
| | Electricity (including auxiliary) | 59.51 | 27.84 | | 1656.76 |
| | Total | | | 20718.39 | 11923.6 |
| **Total Global Cost** | | | | **32641.99** | |

Table 7-14: Total global cost for the case study (EH) at low interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Present value factor** | **Total due for owner** | **Total due for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Building component | 18083.04 | 1.0 | 18083.04 | |
| | Energy system | 5488 | 1.0 | 5488 | |
| | | | Discount rate | | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.929 | 950.37 | |
| | Lifespan of 20 years | 2889 | 0.905 | 2614.55 | |
| | Lifespan of 25 years | 1090 | 0.882 | 961.38 | |
| | Lifespan of 15 years | 1023 | 0.86 | 879.78 | |
| | Lifespan of 30 years | 5211.18 | 0.86 | 4481.61 | |
| | Final value at the end of calculation period | 14729.42 (Table 7-9) | 0.86 | 12667.3 | |
| | | | Present value factor | | |
| **Running costs (maintenance)** | | 102 | 27.84 | | 2839.68 |
| **Energy costs** | Gas | 213.06 | 27.84 | | 5931.59 |
| | Electricity (including auxiliary) | 59.51 | 27.84 | | 1656.76 |
| | Total | | | 20791.43 | 10428.03 |
| **Total Global cost** | | | | **31232.61** | |

To enhance comparison between different building geometries and sizes, it is proposed to express the results in Pound Sterling per square metre of conditioned floor area. From results calculated, as shown in Table 7 -13 and 7-14, the global costs in £/m$^2$ are 711.62 for SH and 680.61 for EH.

#### *7.1.3.2.2 High interest rate*

Market interest rate is at 6.5%, the real interest rate is then calculated as 4.41%. A similar calculation process for discount rates and present value factor was applied as seen in Table 7-15 and 7-16.

Table 7-15: Total global cost for the standard home (SH) at high interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Present value factor** | **Total due for owner** | **Total due for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Building component | 15,965.13 | 1.0 | 15965.13 | |
| | Energy system | 5488 | 1.0 | 5488 | |
| | | | Discount rate | | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.523 | 535.03 | |
| | Lifespan of 20 years | 2889 | 0.422 | 1219.16 | |
| | Lifespan of 25 years | 3460.05 | 0.340 | 1176.42 | |
| | Lifespan of 15 years | 1023 | 0.274 | 280.3 | |
| | Lifespan of 30 years | 4967.12 | 0.274 | 1360.99 | |
| | Final value at the end of calculation period | 14569.67 (See Table 2.A-9) | 0.274 | 3992.09 | |
| | | | Present value factor | | |
| **Running costs (maintenance)** | | 102 | 16.46 | | 1678.92 |
| **Energy costs** | Gas | 266.78 | 16.46 | | 4391.20 |
| | Electricity (including auxiliary) | 59.51 | 16.46 | | 979.53 |
| | Total | | | 22032.94 | 7049.65 |
| **Total Global cost** | | | | **29082.59** | |

To enhance comparison between different building geometries and sizes, it is proposed to express the results in Pound Sterling per square metre of conditioned floor area. From results calculated, as shown in Table 7-15 and 7-16, the global costs in £/m$^2$ at high interest rate scenario are 634.02for SH and 643.85for EH.

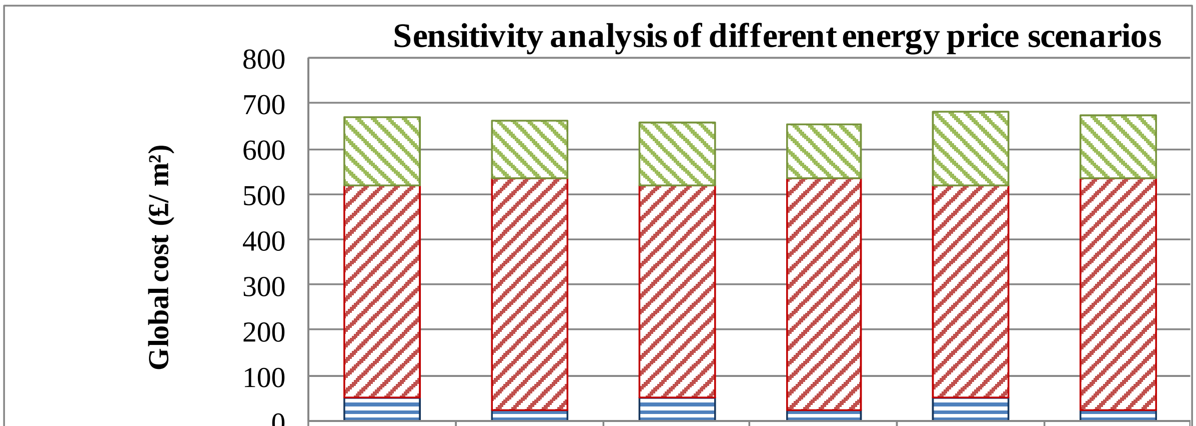
Table 7-16: Total global cost for the case study (EH) at high interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Present value factor** | **Total due for owner** | **Total due for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Building component | 18083.04 | 1.0 | 18083.04 | |
| | Energy system | 5488 | 1.0 | 5488 | |
| | | | Discount rate | | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.523 | 535.03 | |
| | Lifespan of 20 years | 2889 | 0.422 | 1219.16 | |
| | Lifespan of 25 years | 1090 | 0.340 | 370.6 | |
| | Lifespan of 15 years | 1023 | 0.274 | 280.3 | |
| | Lifespan of 30 years | 5211.18 | 0.274 | 1427.86 | |
| | Final value at the end of calculation period | 14729.42 (See Table 2.A-9) | 0.274 | 4035.86 | |
| | | | Present value factor | | |
| **Running costs (maintenance)** | | 102 | 16.46 | | 1678.92 |
| **Energy costs** | Gas | 213.06 | 16.46 | | 3506.97 |
| | Electricity (including auxiliary) | 59.51 | 16.46 | | 979.53 |
| | Total | | | 23368.13 | 6165.42 |
| **Total Global cost** | | | | **29533.55** | |

### 7.1.4 Discussion

Different price scenarios (e.g. high, medium, low) related to energy price and interest rate were used to assess the sensitivity of results. The following graphs show examples of the global costs of two different packages of measures, taking into account different energy prices (See Figure 7-1) and different interest rates (See Figure 7-2).

Higher energy price will leads to adopting energy efficiency measures as illustrated in Figure 7-1, in which EH outperforms SH in term of global costs, in high energy price scenario in comparison with the lower energy price.

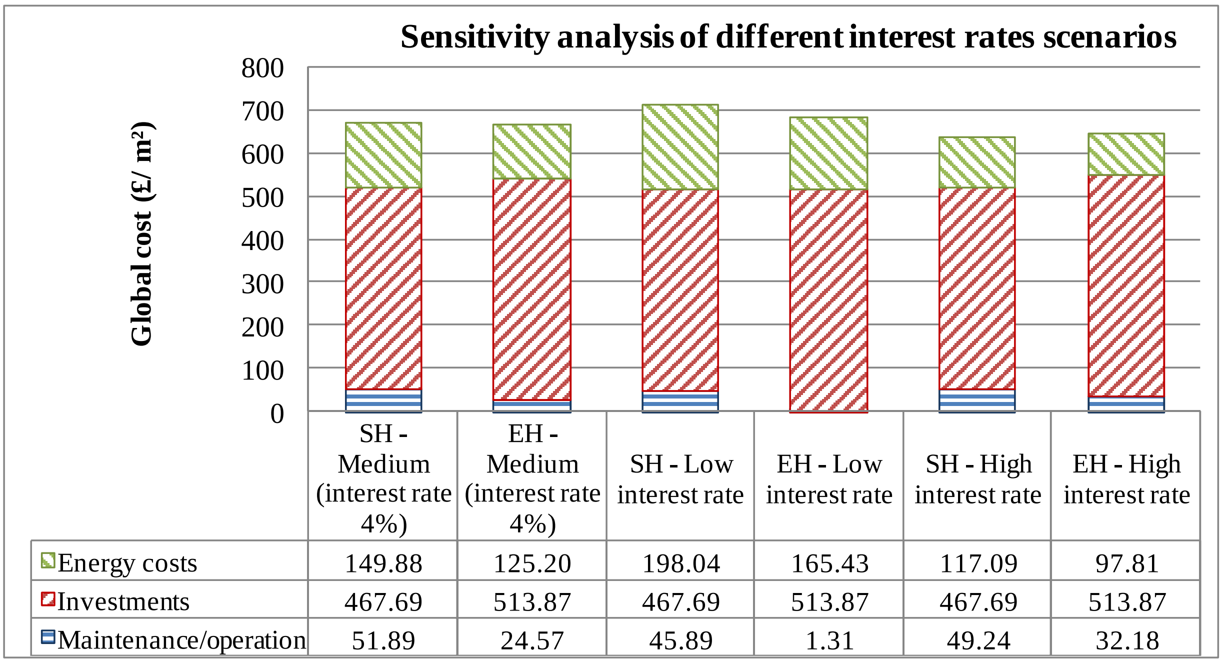


| | SH-Average price | EH-Average price | SH - Low price | EH - Low price | SH - High price | EH - High price |
|---|---|---|---|---|---|---|
| 🟩Energy costs | 149.88 | 125.20 | 138.41 | 115.73 | 162.62 | 135.96 |
| 🟥Investments | 467.69 | 513.87 | 467.69 | 513.87 | 467.69 | 513.87 |
| 🟦Maintenance/operation | 51.89 | 24.57 | 51.89 | 24.57 | 51.89 | 24.57 |

Figure 7-1: Comparison of two different packages for new built (energy prices scenario)

Changes in energy prices would clearly influence what energy efficiency measures individual to adopt. Higher energy price would encourage more investments in energy efficient technologies and stakeholders would collaborate and think of creative ways for economising inputs or find alternatives. For instance, the construction industry has not experienced much change that traditional construction method with cavity wall of brick/block work dominating. A slight change was then adopted in building new homes since the first energy crisis of 1973 with an addition of insulating materials in between the layers (Hens et al., 2007).

Figure 7-2 shows EH outrages SH in the lower interest rates scenario. The global cost calculation of each package compares the Net Present Value of the annual costs and benefits over the building’s lifetime. The calculation of NPV requires assumption for discount rate obtained from the market interest rate, which differs depending on the stakeholder perspectives, taking account of the inflation rate. Lower interest rates favour investments in energy saving or energy efficiency measures (in this case is EH), that whereas higher interest rates hamper such activities. Because energy efficiency measures require upfront investments whereas energy savings and maintenance/operation cost accrue months and years later. Thus a significant driver of overall cost-effectiveness for energy efficiency measures is the discount rate which needs more attention towards more cost effectiveness of energy efficiency development.



| | SH - Medium (interest rate 4%) | EH - Medium (interest rate 4%) | SH - Low interest rate | EH - Low interest rate | SH - High interest rate | EH - High interest rate |
|---|---|---|---|---|---|---|
| ▨ Energy costs | 149.88 | 125.20 | 198.04 | 165.43 | 117.09 | 97.81 |
| ▨ Investments | 467.69 | 513.87 | 467.69 | 513.87 | 467.69 | 513.87 |
| ▤ Maintenance/operation | 51.89 | 24.57 | 45.89 | 1.31 | 49.24 | 32.18 |

Figure 7-2: Comparison of two different packages for new built single family buildings – analysis of average, low, and high interest rates scenarios.

The global cost is higher when lower interest rates applied, as shown in Figure 7-2, is as a result of financial calculation where the effect that futures costs are discounted with a lower rates leading to a higher present value of the global cost at the year zero (ECEEE, 2011).

## *7.2 ANNUITY CALCULATION OF INTERVENTIONS*

In order to provide cost benefit analysis of alternative design strategy for improved building performance, an annuity cost calculation method was employed. A design payback period, which covers the lifetime of long lasting equipment within the assessed package is suggested to be 50 years to avoid distortion between systems of different life expectancy (ECEEE, 2011). This section presents examples of cost calculation for different design strategies, to evaluate the cost efficiency of each solution. This method was used to place values on the cost and benefits of the interventions developed in Chapter 6.

This includes comparison between the reference case of the EH dwelling and the improved building envelope (e.g. increased insulation level and air tightness) that meets Passivhaus fabric criteria, the installation of an MVHR system and the combined packages of better fabric and MVHR, which are key features of Passivhaus design. These are solutions for reducing heating load and the analysis could answer whether savings from energy consumption could pay back the investment cost or bring about any other benefits. The study did not evaluate the economic aspect for cooling design strategies, because the dwelling was subjected to natural ventilation, thus the performance improvement was reflected by the overheating risk assessment.

For air conditioned space or a building with a mechanical ventilation system, where cooling improvement could be measured by reduction in electricity consumption, the economic evaluation can be performed to compare the cost efficiency of shading devices or thermal mass usage in the building. This section neglected the cost benefits from cooling improvement interventions because the dwelling is naturally ventilated; thus no cooling energy spent could offset the investment for shadings and use of PCM. Interventions for cooling improvement enhance comfort indoors by reducing overheating risk occurrences indoors and the need for the frequent opening of windows for natural ventilation.

### 7.2.1 Annuity cost calculation

In order to provide cost effectiveness analysis of alternative design strategy for improved building performance, an annuity cost calculation method was employed. Heating improvement solutions applied to the base case (EH) include installing a heat recovery system, increased insulation of the  building envelope and the combination of both, which meets the Passivhaus criteria. By choosing a “design payback period” that covered the long lasting equipment of systems or components (e.g. 50 years), this time span was then determined as the projection year for energy costs and interest rates.

Assumptions, used for the calculation are listed below, as suggested in BS EN 15459:2007:

- Design payback period of building is 50 years
- Inflation rate: 2%, market interest rate 4.5%
- Operation cost and rate of development: 2%. Rate of development for energy, human operation, products, maintenance and added costs.

The real interest rate is calculated as above: $R_R = 2.45\%$. The present value factor which depends on the real interest rate ($R_R$) and number of years considered for annual cost (50 years) is calculated from the formula presented above, thus obtaining: $f_{pv} = 28.648$. The annuity factor is the inverse value of the present value factor: $a = 1/ f_{pv} = 0.0349$.

#### *7.2.1.1* Annuity cost calculation for EH

The same process to calculate the present value factor, then the annuity factor, for different life spans regarding replacement time can be seen in Table 7-17.

Based on material cost and life span of building components of ErgoHome building given in Tables 7-2 and 7-4

Table 7-17: Material cost and lifespan of ErgoHome building component

| Type of cost | Details of each type | Cost inc. VAT, £ | Annuity factor | Annualised cost for owner | Annualised cost for occupant |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged during design payback period | 13358.86 | 0.0349 | 466.22 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.0805 | 82.35 | |
| | Lifespan of 20 years | 2889 | 0.0639 | 184.6 | |
| | Lifespan of 25 years | 1090 | 0.0540 | 58.86 | |
| | Lifespan of 30 years | 5211.18 | 0.0475 | 247.53 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 213.06 | 1 | | 213.06 |
| | Electricity (including auxiliary) | 59.51 | 1 | | 59.51 |
| **Annualised costs depending on actors** | | | | 1039.56 | 374.57 |
| **Total annualised cost** | | | | **1414.13** | |

#### *7.2.1.2* Annuity cost calculation for improved fabric

Information about improved building fabric that meets Passivhaus' fabric criteria can be found in Chapter 6, Section 6.3.1. The material costs of SIP with the thicker insulation layer that meets Passivhaus criteria and the insulating of windows were consulted by the current supplier for ErgoHome building unit: SIPCO Ltd. The cost included VAT and installation/assembly onsite for a small scale project or individual case (e.g. building from one to three units) as indicated in the Architects' and Builder's price book (Langdon, 2010).

Table 7-18: Material cost and lifespan of Passivhaus' fabric

| **Building component** | **Area, $m^2$** | **Cost inc. VAT and installation, £/$m^2$** | **Total cost, incl. VAT, £** | **Life span** | **References** |
|---|---|---|---|---|---|
| External wall - SIPs 250 | 75.25 | 91.3 | 6870.33 | 50 | SIPCO Ltd |
| Pitched roof - SIPs 250 | 47.5 | 91.3 | 4336.75 | 50 | |
| Suspended floor – SIPs 250 | 45.87 | 91.3 | 4187.93 | 50 | |
| Party walls: timber stud and increased thickness of fiberglass insulation | 42.02 | 18.5+ 9.95=28.45 | 1195.47 | 30 | (2G, p142 and P10, p700) in (Langdon, 2010) |
| Triple glazed, argon filled, low e coating | 9.47 | 473.4 | 4483.1 | 30 | See note |
| Door (SFS 405) | 1.84 | £1000 per unit | 1000 | 50 | (Chadwick, 2011) |
| | | | **22073.58** | | |

(*Note: Additional cost for change from double glazed to triple glazed windows is around £75/$m^2$ (See L40 - p357 in (Langdon, 2010).

See Table 7-5 and 7-7 for initial investment costs and periodic costs of the building energy system). For annuity calculation, the payback period is calculated for 50 years.

Table 7-19: Periodic cost for building component and energy system

| **Type of cost** | **Life span** | | | | |
|---|---|---|---|---|---|
| | **15** | **20** | **25** | **30** | **50** |
| Component unchanged during design payback period (50 years) | | | | | 16395.01 |
| Replacement costs (building components) | | | | 5678.57 | |
| Replacement costs (energy systems) | 1023 | 2889 | 1090 | 487 | |
| Total | 1023 | 2889 | 1090 | 6165.57 | 16395.01 |

Fuel prices (including VAT) can be referred to Table 12 (SAP2009, 2010) and energy consumptions were calculated using IES<VE> program. Table 7-20 shows the calculated energy cost for improved fabric which meets Passivhaus’ fabric criteria.

Table 7-20: Energy cost for Passivhaus' fabric

| **Energy system** | **Annual energy access** | **Price per unit (inc.VAT), £/kWh** | **Energy requirement, kWh** | **Total price, £** |
|---|---|---|---|---|
| Space heating: gas fired boiler | Standing charge: gas | 106 | | 106 |
| | Annual consumption | 0.031 | 1061 | 32.89 |
| | Auxiliary electricity | 57 | | 57 |
| DHW | Annual gas consumption | 0.031 | 1132.2 | 35.1 |
| Mechanical extraction | Annual electricity consumption | 0.1146 | 21.9 | 2.51 |
| | Total | | | **233.5** |

From the results in the tables above, the annuity cost is calculated as seen in Table 7-21

Table 7-21: Annuity calculation for Passivhaus' fabric

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged during design payback period | 16395.01 | 0.0349 | 572.19 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.0805 | 82.35 | |
| | Lifespan of 20 years | 2889 | 0.0639 | 184.6 | |
| | Lifespan of 25 years | 1090 | 0.0540 | 58.86 | |
| | Lifespan of 30 years | 6165.57 | 0.0475 | 292.86 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 173.99 | 1 | | 173.99 |
| | Electricity | 59.51 | 1 | | 59.51 |
| **Annualised costs depending on actors** | | | | 1190.86 | 335.5 |
| **Total annualised cost** | | | | **1526.36** | |

#### *7.2.1.3* Annuity cost calculation for option of installing MVHR system

The use of a whole house mechanical ventilation heat recovery system will only change the investment cost and periodic costs for the ventilation system, as its lifespan is 20 years according to "Data for lifespan of building system" in Table A.1 (BSI, 2007). The description of the MVHR system followed the guideline set in Table B.8 in (BSI, 2007) as below:

The simulation results of MVHR usage can be found in Chapter 6 Section 6.3.2. With specific fan power of 0.36 W/h.m$^3$ running on a continuous basis when the building is occupied (i.e. 6483 hours with the current occupancy profile), the electricity consumption equates to 107.358 kWh per year.

Table 7-22: Description of ventilation system

| **MVHR** | **Component** | **Lifespan** | **Investment cost, £** |
|---|---|---|---|
| Emission | Extract air grills | 20 | £1634 for all package including 2 wet rooms (kitchen and bathroom) exclude VAT* (See note). Cost included VAT (20%) is **£1960.80** |
| Distribution | Flexible ducts | 20 | |
| Generation | Fan and heat recovery unit | 20 | |
| Connection to energy board | Electricity board | 20 | |

(Price quoted from http://www.thegreenbuildingsite.co.uk/subcategory/mvhr-heat-recovery). This price package includes designing, flexible ducts for small size property and installation.

Table 7-23: Periodic cost for building component and energy system

| **Type of cost** | **Life span** | | | | |
|---|---|---|---|---|---|
| | **15** | **20** | **25** | **30** | **50** |
| Component unchanged during design payback period (50 years) | | | | | 13358.86 |
| Replacement costs (building components) | | | | 4721.18 | |
| Replacement costs (energy systems) | 1023 | 4662.8 | 835 | 487 | |
| Total | 1023 | 4662.8 | 835 | 5208.18 | 13358.86 |

Table 7-24: Energy cost for option of installing MVHR

| **Energy system** | **Annual energy access** | **Price per unit (inc. VAT), £/kWh** | **Energy requirement, kWh** | **Total price, £** |
|---|---|---|---|---|
| Space heating: gas fired boiler | Standing charge: gas | 106 | | 106 |
| | Annual consumption | 0.031 | 1367.8 | 42.4 |
| | Auxiliary electricity | 57 | | 57 |
| DHW | Annual gas consumption | 0.031 | 1132.2 | 35.1 |
| Mechanical extraction | Annual electricity consumption | 0.1146 | 107.358 | 12.3 |
| | Total | | | **252.8** |

Table 7-25: Annuity calculation for option of installing MVHR system

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged during design payback period | 13358.86 | 0.0349 | 466.22 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.0805 | 82.35 | |
| | Lifespan of 20 years | 4662.8 | 0.0639 | 297.95 | |
| | Lifespan of 25 years | 835 | 0.0540 | 45.09 | |
| | Lifespan of 30 years | 5208.18 | 0.0475 | 247.39 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 183.5 | 1 | | 183.5 |
| | Electricity | 59.51 | 1 | | 69.3 |
| **Annualised costs depending on actors** | | | | 1139 | 354.8 |
| **Total annualised cost** | | | | **1493.8** | |

### *7.2.1.4* Annuity cost calculation for option of Passivhaus design

The key feature of Passivhaus building is the combination of increased insulation level of the building envelope and the use of an MVHR system. The initial investment and periodic costs include calculation data from Section 7.2.1.2 to 7.2.1.3.

Table 7-26: Periodic cost for building component and system of the Passivhaus building

| **Type of cost** | **Life span** | | | | |
|---|---|---|---|---|---|
| | **15** | **20** | **25** | **30** | **50** |
| Component unchanged during design payback period (50 years) | | | | | 16395.01 |
| Replacement costs (building components) | | | | 5678.57 | |
| Replacement costs (energy systems) | 1023 | 4662.8 | 835 | 487 | |
| Total | 1023 | 4662.8 | 835 | 6165.57 | 16395.01 |

Energy consumption data can be referred to Chapter 6, Section 6.3.1

Table 7-27: Energy cost for the Passivhaus building

| **Energy system** | **Annual energy access** | **Price per unit (inc. VAT), £/kWh** | **Energy requirement, kWh** | **Total price, £** |
|---|---|---|---|---|
| Space heating: gas fired boiler | Standing charge: gas | 106 | | 106 |
| | Annual consumption | 0.031 | 461.4 | 14.3 |
| | Auxiliary electricity | 57 | | 57 |
| DHW | Annual gas consumption | 0.031 | 1132.2 | 35.1 |
| Mechanical extraction | Annual electricity consumption | 0.1146 | 107.358 | 12.3 |
| | Total | | | **224.7** |

Table 7-28: Annuity calculation for Passivhaus design

| **Type of cost** | **Details of each type** | **Cost (inc. VAT), £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged during design payback period | 16395.01 | 0.0349 | 572.19 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.0805 | 82.35 | |
| | Lifespan of 20 years | 4662.8 | 0.0639 | 297.95 | |
| | Lifespan of 25 years | 835 | 0.0540 | 45.09 | |
| | Lifespan of 30 years | 6165.57 | 0.0475 | 292.86 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 155.4 | 1 | | 155.4 |
| | Electricity | 69.3 | 1 | | 69.3 |
| **Annualised costs depending on actors** | | | | 1290.44 | 326.7 |
| **Total annualised cost** | | | | **1617.14** | |

### 7.2.2 Sensitivity analysis

#### *7.2.2.1* Different price scenarios

The fuel price scenarios can be found in Section 7.1.3.1. Annuity cost calculation for 4 different development cases can be found in Section 7.2.1.1 to 7.2.1.4. For comparison purposes, the annuity cost will be derived in Pound Sterling per square metre conditioned floor area as seen in Table 7--29.

Table 7-29: Influence of change in energy price on annuity cost calculation

| **Type of dwellings** | **Price scenarios** | **The rate of development of the price, $R_x$** | **Price dynamic factor $\beta_x$** | **Annuity cost, £/m$^2$** |
|---|---|---|---|---|
| **EH (base case)** | Reference | 2% | 1 | 30.83 |
| | Low | 1.4% | 0.9235 | 30.37 |
| | High | 2.6% | 1.085 | 31.33 |
| **Improved fabric** | Reference | 2% | 1 | 33.28 |
| | Low | 1.4% | 0.9235 | 32.89 |
| | High | 2.6% | 1.085 | 33.71 |
| **MVHR system** | Reference | 2% | 1 | 32.57 |
| | Low | 1.4% | 0.9235 | 32.14 |
| | High | 2.6% | 1.085 | 33.03 |
| **Passivhaus design (Improved fabric + MVHR system)** | Reference | 2% | 1 | 35.25 |
| | Low | 1.4% | 0.9235 | 34.88 |
| | High | 2.6% | 1.085 | 35.67 |

#### *7.2.2.2* Interest rate

A similar assumption to market interest rate is used for sensitivity analysis of cost, in which the low interest rate is at 2.5% and high interest rate is at 6.5% (See 7.1.3.2), with the reference market interest rate of 4.5% for previous annuity calculation, from Section 7.2.1.1 to 7.2.1.4.

##### *7.2.2.2.1 Low interest rate*

With the market interest rate R= 2.5% and the inflation rate still at 2%, the real interest rate is then recalculated using the equation 7-1 to be at 0.49%. The discount rates determined by Equation 7-2 for 15 years, 20 years, 25 years and 30 years calculation period are given in Table 7-30 and 7-33. The final value factor of the total package, by the end of calculation period (30 years), is obtained by using Equation 7-3, as seen in the two tables below.

Table 7-30: Annuity calculation for EH at low interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged during design payback period | 13358.86 | 0.023 | 307.25 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.069 | 70.59 | |
| | Lifespan of 20 years | 2889 | 0.053 | 153.12 | |
| | Lifespan of 25 years | 1090 | 0.043 | 46.87 | |
| | Lifespan of 30 years | 5211.18 | 0.036 | 187.60 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 213.06 | 1 | | 213.06 |
| | Electricity | 59.51 | 1 | | 59.51 |
| **Annualised costs** | | | | 765.43 | 374.57 |
| **Total annualised cost** | | | | **1140** | |

Table 7-31: Annuity calculation for option of Passivhaus' fabric at low interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged during design payback period | 16395.01 | 0.023 | 377.09 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.069 | 70.59 | |
| | Lifespan of 20 years | 2889 | 0.053 | 153.12 | |
| | Lifespan of 25 years | 1090 | 0.043 | 46.87 | |
| | Lifespan of 30 years | 6165.57 | 0.036 | 221.96 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 173.99 | 1 | | 173.99 |
| | Electricity | 59.51 | 1 | | 59.51 |
| **Annualised costs** | | | | 869.63 | 335.5 |
| **Total annualised cost** | | | | **1205.13** | |

Table 7-32: Annuity calculation for installation of MVHR system at low interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged during design payback period | 13358.86 | 0.023 | 307.25 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.069 | 70.59 | |
| | Lifespan of 20 years | 4662.8 | 0.053 | 247.13 | |
| | Lifespan of 25 years | 835 | 0.043 | 35.91 | |
| | Lifespan of 30 years | 5208.18 | 0.036 | 187.49 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 183.5 | 1 | | 183.5 |
| | Electricity | 69.3 | 1 | | 69.3 |
| **Annualised costs** | | | | 848.37 | 354.8 |
| **Total annualised cost** | | | | **1203.17** | |

Table 7-33: Annuity calculation for Passivhaus design at low interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged during design payback period | 16395.01 | 0.023 | 377.09 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.069 | 70.59 | |
| | Lifespan of 20 years | 4662.8 | 0.053 | 247.13 | |
| | Lifespan of 25 years | 835 | 0.043 | 35.91 | |
| | Lifespan of 30 years | 6165.57 | 0.036 | 221.96 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 155.4 | 1 | | 155.4 |
| | Electricity | 69.3 | 1 | | 69.3 |
| **Annualised costs** | | | | 952.68 | 326.7 |
| **Total annualised cost** | | | | **1279.38** | |

#### *7.2.2.2.2 High interest rate*

- Design payback period of building is 50 years
- Inflation rate: 2%, market interest rate 6.5%
- Operation cost and rate of development: 2%. Rate of development for energy, human operation, products, maintenance and added costs.

The real interest rate is calculated by Equation 7-1 as above: $R_R$ = 4.41%. The present value factor, which depends on the real interest rate ($R_R$) and number of years considered for annual cost (50 years), is calculated from the formula presented above, giving: $f_{pv}$ = 20.055. The annuity factor, the inverse value of the present value factor is: a = 1/ $f_{pv}$ = 0.05. The same process to calculate the present value factor then the annuity factor for different lifespan regarding replacement time is shown in Table 7-34 to Table 7-37.

Table 7-34: Annuity calculation for EH at high interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged (50 years) | 13358.86 | 0.05 | 667.94 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.093 | 95.14 | |
| | Lifespan of 20 years | 2889 | 0.076 | 219.56 | |
| | Lifespan of 25 years | 1090 | 0.067 | 73.03 | |
| | Lifespan of 30 years | 5211.18 | 0.061 | 317.88 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 213.06 | 1 | | 213.06 |
| | Electricity (including auxiliary) | 59.51 | 1 | | 59.51 |
| **Annualised costs** | | | | 1373.56 | 374.57 |
| **Total annualised cost** | | | | **1748.13** | |

Table 7-35: Annuity calculation for option of Passivhaus' fabric at high interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged (50 years) | 16395.01 | 0.05 | 819.75 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.093 | 95.14 | |
| | Lifespan of 20 years | 2889 | 0.076 | 219.56 | |
| | Lifespan of 25 years | 1090 | 0.067 | 73.03 | |
| | Lifespan of 30 years | 6165.57 | 0.061 | 376.1 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 173.99 | 1 | | 173.99 |
| | Electricity | 59.51 | 1 | | 59.51 |
| **Annualised costs** | | | | 1583.58 | 335.5 |
| **Total annualised cost** | | | | **1919.08** | |

Table 7-36: Annuity calculation for option of installing MVHR at high interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged during design payback period | 13358.86 | 0.05 | 667.94 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.093 | 95.14 | |
| | Lifespan of 20 years | 4662.8 | 0.076 | 354.37 | |
| | Lifespan of 25 years | 835 | 0.067 | 55.95 | |
| | Lifespan of 30 years | 5208.18 | 0.061 | 317.70 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 183.5 | 1 | | 183.5 |
| | Electricity | 69.3 | 1 | | 69.3 |
| **Annualised costs** | | | | 1491.1 | 354.8 |
| **Total annualised cost** | | | | **1845.9** | |

Table 7-37: Annuity calculation for the Passivhaus building at high interest rate

| **Type of cost** | **Details of each type** | **Cost inc. VAT, £** | **Annuity factor** | **Annualised cost for owner** | **Annualised cost for occupant** |
|---|---|---|---|---|---|
| **Investment costs** | Component unchanged during design payback period | 16395.01 | 0.05 | 819.75 | |
| **Replacement costs** | Lifespan of 15 years | 1023 | 0.093 | 95.14 | |
| | Lifespan of 20 years | 4662.8 | 0.076 | 354.37 | |
| | Lifespan of 25 years | 835 | 0.067 | 55.95 | |
| | Lifespan of 30 years | 6165.57 | 0.061 | 376.1 | |
| **Running costs (maintenance)** | | 102 | 1 | | 102 |
| **Energy costs** | Gas | 155.4 | 1 | | 155.4 |
| | Electricity | 69.3 | 1 | | 69.3 |
| **Annualised costs depending on actors** | | | | 1701.31 | 326.7 |
| **Total annualised cost** | | | | **2028.01** | |

### 7.2.3 Discussion on cost effectiveness

These are solutions for reducing heating load and the analysis could answer whether savings from energy consumption could pay back the investment cost, or bring about any other benefits. The study did not evaluate the economic aspects of cooling design strategies, because the dwelling is cooled by natural ventilation. Thus interventions reducing overheating risk will enhance thermal comfort and health in the space, but could not be offset by cost savings or $CO_2$ reduction.

In other cases, where air conditioning or mechanical ventilation systems are installed in office, school or public spaces, shading and thermal mass design solutions to enhance cooling performance in the space could be offset by electricity savings.

The cost effectiveness of three interventions in comparison with the base case is illustrated in Figure 7-3. The base case is the most cost effective solution in delivering energy efficient measures. Installing a heat recovery system helps reduce heating demand by half though, because the heating system is fuelled by mains gas, whereas the mechanical ventilation runs on electricity and this option is more expensive than the initial design. In fact, at the average interest rate scenario, the difference is £80 per square metre more expensive. If the heating system is using electricity then installing MVHR will bring real benefits. At the low interest scenario, the use of a super-insulated building envelope presents a slightly more expensive route than using MVHR, of £2 per square metre more. Thus, a lower interest rate market is favourable for energy efficiency measures.

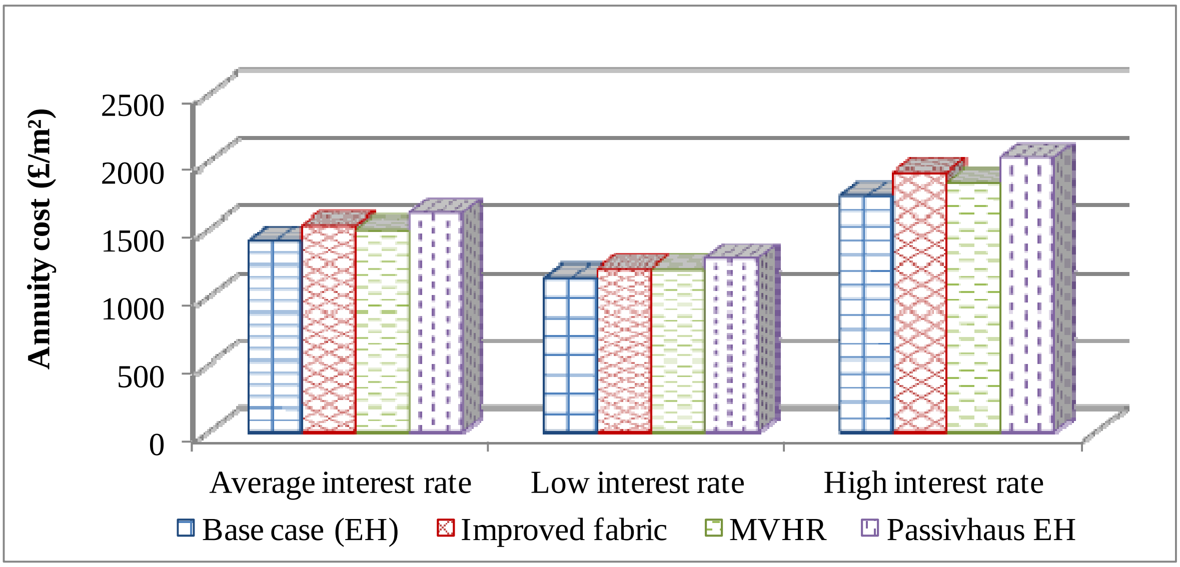


Figure 7-3: Annuity cost calculation for interventions of heating improvement

# Chapter 8: **DISCUSSION AND IMPLICATION**

The UK Government focus on reducing carbon emissions associated with energy consumption in buildings is driving the market for energy efficient, highly insulated buildings that incorporate sustainable technologies. One area of significant development is through highly insulated and airtight building envelopes. These produce energy efficient designs, whilst maintaining stable thermal conditions through low levels of heat loss/gain and air leakage rates. One of the MMC solutions is through the use of SIP, a ready-insulated and prefabricated product that offers positive benefits in energy efficiency.

The work presented herein shows that this is the first time a systematic post construction evaluation of a SIPs-based dwelling has been undertaken in the UK. This work involved using thermo-dynamic simulation software for simulation model, validation and development thus providing evidence base from which the gap between design and as-built performance can be achieved.

## *8.1 DISCUSSION*

An iterative research approach was applied through monitoring - simulation - validation - development. A brief insight of analytical calculations, derived from the given building construction information to determine thermal parameters, predict heating/cooling loads, was included as part of simulation validation work. The numerical work allows several key thermal parameters of the building components to be calculated. These included actual thermal transmittance of the building element accounting for timber fraction at connections; thermal bridges occurring at the bottom and top plates of the building elements at the junctions; thermal transmittance of glazed elements; and the admittance procedure calculation for building components for non-steady state parameters (See Appendix A.3). The detail calculation provided more accurate values of thermal parameters for a typical SIP construction, regardless of building shape or size, and a transparent evaluation of the whole evaluation procedure.

In the monitoring work, the most recent weather conditions were recorded and the building performance was measured over several periods of time covering the extreme conditions, e.g. outdoor air temperature fell below -12°C and a late summer period when outdoor temperatures rose to +25°C. The monitoring period covered from March 2010 to February 2012. The recorded data showed that the overheating occurred even when the weather was not as particularly warm and further showed how the integration of shading instead of clear windows, effectively reduced this effect (e.g. solar control films for glazing in the bedroom and internal blinds for the rest which were also used for privacy purposes). The field data were then used to calibrate against the computer model to enable a validated reliable model to be used to test several passive design solutions. The test building was evaluated without occupancy, in which the internal environmental conditions perform in accordance with the external environment through the building envelope by dynamic heat transfer processes. This allowed the minimising of unnecessary errors caused by interactions of the occupant that could affect readings. A key contribution provided by this work is to generate post construction performance data which are used to validate and verify models developed in thermo-dynamic simulation software. The anticipated occupant behaviour was established at the later stage of simulation development and monitored for the post occupancy evaluation. Through understanding the interaction between building design and occupants, it helped identify ways to improve building design, and performance.

Having established the validated building model (See Chapter 4), several heating and cooling interventions were integrated to this simulation model in order to investigate their improved performance (See Chapter 6) and they were compared to the base case (established in Chapter 5). With the designated occupancy profile, the interventions were based on selected passive design solutions, looking at increasing insulation levels or/and installing a MVHR system for heating improvement, or to consider different shading options and/or integration of PCM for reducing overheating risk indoors, combining with effective natural ventilation.

By increasing the insulation thickness, SIP 125 to SIP 250, plus replacing double glazed low emissivity coated glazing with triple glazed low emissivity coated glazing for building fenestrations that meet Passivhaus efficiency requirements, the heating demand reduced by half. However, the overheating risk doubled with closed windows when only background ventilation was provided by either trickle ventilators or by mechanical ventilation. Using the CIBSE benchmark for overheating criteria at 28ºC in living areas and 26ºC for bedrooms, simulation results showed the frequency 37 % for improved insulation against 17 % of base case.

In addition, the peak temperature in initial state (or EH) was 39ºC while with increased insulation (Passivhaus fabric) it was found to be 46ºC. To express the severity of overheating by using overheating degree hours, the simulation outputs showed degree hours overheating increased from 1962 (EH) to 8639 hours (Passivhaus fabric). With the current design of building fenestrations, whilst opening all windows, overheating risk reduced significantly, with hours overheating reduce to 105 from 1962 (EH), and reduce to 123 hours from 8639 hours (Passivhaus fabric).

This suggested that with the same amount of heat input from solar and internal gain, the super insulated building envelope worsen overheating indoors by trapping heat inside. Overheating is however resolved by a throughout ventilation sought through in combination with shading and mass. Thus a carefully considered cooling strategy is essential if SIPs are to be used.

Operation of a MVHR system with efficiency of 90% helped to reduce heating demand by 40%.For example, the heating load for EH is 50.6 and was reduced to 29.8 kWh/m$^2$ per year when integrated with the operation of the MVHR system in EH. It was acknowledged that the use of mechanical ventilation on providing continuously a certain amount of air exchange rates during night time could alleviate overheating to provide a favourable condition. In cool days, the use of MVHR to provide background ventilation can be beneficial in term of controlling indoor conditions, but might not be cost efficient compared to free ventilation from partially opening windows. In warm days, the effect of the MVHR system in providing the constant air change rates would be insignificant, because the amount of heat entering the space caused overheating building fast. Thus when the occupant return home after work, it might be more effective to open windows thus purge out the amount of heat entering the space on hot days, depending on outdoor air temperature.

Amongst shading design options, fixed overhang design varies according to orientation. For the main facade facing due south with all windows shut, the overheating severity reduced significantly, measured in degree hours overheating from 1962 to 331 hours. However, the fixed overhang blocks out solar gain during the heating period leading to an increase in heating demand from 50.6 kWh/m$^2$ per year (EH) to 53.5 kWh/m$^2$ per year. The best option was found to integrate a fixed overhang on the south facade windows and shutters on the east and west-facing French patio doors, for which degree hours overheating was 389 hours, before cooling down by opening windows; thus the heating demand slightly increased to 51.9 kWh/m$^2$ per year.

External and internal shadings were simulated to be half covering the height of the window to reflect the option of allowing day lighting for indoor activities, to avoid using electric lighting, respecting the desire to save energy and the preference for daylight over artificial light. The external shading devices appear more effective in reducing overheating risk than the internal devices. This is because the external shading devices absorb a large part of the solar radiation, which is returned to the outdoor ambient air through re-radiation and convection, whereas the building fenestration allows solar radiation into the internal space between the glazed system and the internal shading device, making it less effective in reducing heat accumulation. Indeed, the overheating severity for external shading was 604 hours and for internal shading was 725 hours. By letting the daylight into the space, the use of internal light translucent shading offered a covering for the whole window to reduce solar heat gain, with degree hours overheating at 522 hours, a significant improvement compared to external shading.

Another option to reduce solar radiation is to employ solar control glass as discussed in Chapter 6 Section 6.2.1.4. The simulation output suggested that the frequency of overheating for the south-facing facade, when windows were kept shut, was 2.9% for the living space and 1.1% for bedrooms, against a 1% overheating benchmark of CIBSE criteria. It is suggested that the use of solar control glass is beneficial in terms of saving cooling energy consumption for spaces with high loads (high level of occupancy and internal loads, such as offices or computer rooms). The solar control glass option is not suitable for the current EH design where overheating risk can be resolved by a good natural ventilation strategy. The fixed re-radiated option of the building fenestration system leads to significant loss of solar heat gain in cold periods, thus heating demand increased by 28% (highest in the south-facing case with 31% where annual heating energy in kWh/m² was 66.3 to 50.6 of the base case).

Controlling solar access can also be achieved by altering the building fenestration. An attempt was made to resize the glazing area that meets the minimum criteria of visual comfort. By using the minimum daylight factor to calculate the glazing area and running this simulation scenario (i.e. same thermal performance, different glazing to wall ratio), the outputs showed a significant reduction in overheating. The percentage of annual occupied hours when the room exceeds 28 ºC reduced by more than half in comparison with the original building fenestration, such as 17.1% to 8.6% in living space, 9% to 1.5% in the bedroom in the south case (See Section 6.4.2). Significant improvement in the bedroom was observed as a result of over-sizing of glazing area in the bedroom where a net area of 1.66 $m^2$ faces due west in the original design. If using overheating degree hours to express the severity of warm spaces, the simulation results were 84 against 508 degree hours. The decision of original design was made with preference of French patio doors to allow walking out to the balconies attached to two short sides of the building. This is the compromise between design for user and energy efficient consideration. Although the large glazing area permitted significant heat gain, natural ventilation achieved through opening the door was effective to remove all heat gain through cross ventilation (opening the door and window on two side external walls) and great amount of air exchange through large opening area. Besides, other solutions as discussed in Chapter 6 Section 6.2 deemed to resolve the overheating issue of the original design.

Regarding heating performance, the simulation results showed that the heating load is lower in this case compared to the original design (e.g. 46 kWh/m$^2$ against 50.6 kWh/m$^2$ in the south case). This illustrates the rate of heat loss through the building fenestration exceeded the solar gain through this system.

With SIPs construction as part of a MMC lightweight dwelling, there are limited solutions at the moment to increase its thermal mass. It is possible to integrate concrete onto SIP floors or walls. However, as warm air rises, integrating thermal mass into the roof structure exposed to internal air would be most effective as heat from indoor air would be absorbed by PCMs hence reducing room temperature the most effectively. PCMs as alternative materials out-perform conventional building materials (concrete, bricks or blocks) as they offer the highest heat storage capacity. The exemplary use of DuPont™ Energain® product integrated into the SIP based-dwelling showed that the length of overheating occurrence was significantly reduced. A large number of occurrences of high temperatures were shifted to lower temperatures as a result of PCM capacity to store heat at its melting point. Additionally, the benefit of PCM boards can be appreciated as their surface temperature stays in the comfort zone (i.e. at the temperature of PCM’s melting or solidifying). This can add to improving local thermal comfort regarding radiant asymmetry exchange between the occupant and internal surface of the building envelope (See Appendix A.4.3.4). The simulation results (See Figure 6-10) suggested that thermal mass alone offered limited performance and the amount of storage capacity and location of mass should be carefully designed, in combination with solar radiation, for the most effective performance.

## *8.2 IMPLICATION*

Other simulation work has focused on either simulating the building performance or suggesting optimum solutions (Abaza, 2002). As previously discussed in Chapter 3 Section 3.2.1.1, work involved in building energy simulation often developed based on utilities bills in which there are number of interference factors including occupant factors like number of households, occupancy period and usage pattern, as well as energy efficiency levels of building systems and appliances. These factors vary significantly from one building to others, thus it occurs some levels of uncertainties and to some extent, conclusion drawn from one studies might not be applicable to others.

In other term, as found in Chapter 3 Section 3.2.2, there have been several studies conducting testing and monitoring of existing building such as Scottish traditional building (Baker, 2008); side by side thermal test of modular offices (Judkoff et al., 2000); Hathaway “Solar Patriot House” (Norton et al., 2005), etc. to gather evidences of in-situ building performance.

This is the first time that this kind of systematic post construction evaluation of a SIP based dwelling has been undertaken in the UK. An iterative approach includes monitoring – simulation – validation to simulation development taking into account of balancing between energy efficiency measures and cost effectiveness. This evaluation model provides a holistic approach to the integration of and interaction between the main building components through comprehensive analysis and graphical data presentation.

### 8.2.1 Implication for integrating passive solar design strategies

This section reviews the integration and interaction between thermal mass, thermal insulation, solar radiation and natural ventilation as key elements of passive solar design.

#### *8.2.1.1* Thermal insulation

Through this research, it can be concluded that thermal insulation is the most determinant factor in building energy performance. However, determining the appropriate amount of thermal insulation, for any given building design, is complex because of its interaction with other factors such as mass, solar radiation, ventilation, internal heat loads and occupancy patterns.

The SIP based dwelling helps to maintain a stable indoor condition because the insulation foam boards were rigid and fixed within the structure. The field readings from different air temperatures and relative humidity sensors located at three or four different height levels above the floor in the living space and the bedroom showed a closely match data of air temperatures and relative humidity. The continuity of the polyurethane layer of rigid insulation, forming the solid core of insulation throughout the structure, reduces thermal bridging and ensures that the building is heated evenly, which improves thermal comfort and reduces heating load.

A super-insulated dwelling, in this case obtained by SIP250 and triple glazed, low e coating windows that meet the fabric requirements of Passivhaus criteria, offers 47% of heating savings. As the insulation level increased, the heat built up from solar radiation and internal gain (metabolic heat and household appliances) was trapped, thus worsening the overheating state. However, natural ventilation was sufficient in reducing the overheating risk, and the overheating risk is eliminated if integrating with excessive ventilation by opening French patio doors, using shading options or mass.

#### *8.2.1.2* Solar radiation

Building orientations, aperture size and location are factors in solar access control strategies, as developed and demonstrated in passive design literature review (Bell and Burt, 1995).

The current building fenestration was redesigned to meet the minimum daylight factor, using the same type of insulating windows (i.e. low e coating and argon filled in cavity between glass panels). The simulation results suggested that the conduction heat loss through glazing elements outperform the solar gains received from current fenestration systems. Besides, the overheating did not occur in this scenario. It illustrates the importance of controlling solar access in offering solar heat gain during heating months but preventing it during cooling months.

This research showed that shading design has significant impact on solar gain, from both direct and diffuse solar radiation. For south facing glazing, fixed overhang with a depth that is not too large (e.g. up to 1.67 metres in form of awning to the balcony) is very effective for sun protection in summer without increasing annual heating demand too much. It allows diffuse solar radiation to enhance daylight within the space whilst blocking solar heat causing overheating. Shading devices has significant impact on controlling direct solar radiation (both direct and diffuse sunlight).

### *8.2.1.3* Thermal mass

The research revealed that the effectiveness of thermal mass, in this case PCM, depends on effective ventilation and solar radiation. The use of PCM in enhancing latent heat storage helps to reduce cooling demand and improve thermal comfort.

The first case considered when PCM board was installed on the inner side of the pitched roof, behind the plasterboard. When windows were kept shut and a fixed air exchange rate was simulated to be continuously supplied to maintain the background ventilation, the overheating risk, as well as the peak temperatures occurring indoors, was reduced significantly. The simulation was developed based on effective night ventilation during a warm period to achieve complete PCM cycles. When considering PCM boards on walls, the improvement was not significant despite the area of PCM board in this case being higher in comparison with the PCM in the roof. It was probably due to PCM board when on walls were affected directly and indirectly by solar radiation causing them to reach their melting points and become less effective in reducing indoor air temperature. Also, heat would rise towards the PCM board in the pitched roof and be absorbed, thus maintaining a cooler indoor air temperature.

### *8.2.1.4* Natural ventilation

A supply of fresh air, in the form of background ventilation required for spaces, is needed in living areas to provide a healthy indoor environment. Simulation results suggested that inadequate background ventilation was supplied through the 40 cm$^2$ of trickle ventilator per each window installed in the openings. Additional simulations, in which the trickle ventilators were resized to meet the Building Regulations - 2010 part F showed that only during several occasions (e.g. higher wind speed) did air flow introduced into dwelling meet the supply rate, as indicated for background ventilation in this guide.

Natural ventilation was effective in reducing overheating risk. Integrated design solutions such as orientation, shading devices and thermal mass were developed to provide favourable conditions. The incorporation of thermal mass helps to stabilise internal temperatures and shift peak temperatures to a lower range thanks to its heat storage capacity. Night time ventilation purged heat from the PCM so it could act as a heat sink for the following day; thus ineffective ventilation could result in partly discharging the heat sink. Night time ventilation can be driven by natural forces, both stack and wind effects, or by the use of an auxiliary fan to enhance flow, when needed.

However, night time ventilation by opening windows may reduce security, particularly for ground floor dwellings. It is suggested from the study of Abaza (2002) that night time ventilation could be applied as early as 7pm in the evening. At 11pm, depending on outside and inside environmental conditions, heat maybe purged from the PCM. Another solution is to provide external louvers for inward-opening windows, if applicable, or use a fan to provide the required air flow.

The main drawback of natural ventilation is lack of control, either excessive ventilation leading to heating energy waste, or inadequate ventilation resulting in an uncomfortable and unhealthy environment. MVHR is an alternative ventilation strategy for background ventilation which recovers heat so that energy savings can offset its consumption during operation. The use of MVHR offers controlled supply of background ventilation, thus maintaining thermal comfort and reducing waste from ventilation heat loss. The simulation results showed that the annual heat load reduced from 50.6 to 29.82 kWh /$m^2$.

During occupancy, the use of MVHR, which continuously supplies a constant amount of fresh cool air from outside, alleviates overheating risk when windows are kept shut. For energy saving purposes, the MVHR system was switched off when a window was open for passive cooling. Moisture in air is often considered as the dominant pollutant in dwellings when air is sourced from wet zones within the building. Other pollutant sources might arise from cooking and smoking. Mechanical ventilation was required to extract air directly at source.

### 8.2.2 Cost efficiency

In the context of low carbon transition, implementation of energy efficiency measures is critical, however there are still number of barriers in UK housing sector, particularly the need for cost effective and energy efficient solutions whose building performance under current condition and uncertainties of climate changes, fuel resources and market fluctuations.

Estimating the cost of a building construction project is not always taken serious at early design stages. The characteristics of design variables could vary from location to location depending on the local environmental conditions and other circumstances that dictate the building designs. A combination of several energy efficiency measures can lead to better building performance, energy and cost savings. However, these only can be achieved whilst using a holistic approach based on integrated design solutions than simplified application of different measures.

Life cycle cost study is required in order to compare different energy efficient packages to evaluate the economical aspect of different building design: construction methods, building materials and other energy efficiency measures. The packages used in cost analysis study should be defined and calculated separately, differentiate between new building and retrofitting, between building types (apartment block, detached/semi-detached dwelling...) and locations if affecting environment conditions and market.

In the current context, energy efficient measures still require higher investment which discourages customers, but they could add substantially to lower operation and maintenance cost thus an overall cost study over a building life time will provide a broader view of financial evaluation.  In this sense, assessing different packages show the impact on costs and overall energy performance of marginally varying the thermal performance of the building envelope provides a broad spectrum of results (ECEEE, 2011). Also with the mechanism for market demand of energy efficiency measures, their price could be lower. For a specific project, the prices used for cost analysis should be driven from the supply manufacture than from the Spon's Architects' and Builders' Price Book. Beyond the financial assessment, energy efficiency measures are beneficial in term of decreasing the dependency of the building owner and society on fuel purchase, In addition, the use of renewable energies do not only influence the environmental and financial performance of a building but also decrease the dependency of the building owner and society of fossil fuel.

# Chapter 9: **CONCLUSIONS**

## *9.1 Achievements*

A key driver that directly impacts the built environment is the UK Government commitment to low carbon construction through the setting of ambitious targets for the reduction of carbon dioxide emissions associated with energy use in building. A key target contained within this is that all new homes to be zero carbon rated by 2016. As a result, the requirement set in part L Building Regulations for driving the reduction of carbon emissions in new homes has been tightened up. In addition, the house building sector is under pressure to supply 240,000 new homes per year to meet the demand at the affordable rate (DCLG, 2007c).

Some success has been achieved by the use of structural insulated panels (SIPs), ready insulated and prefabricated panels offering several key benefits for energy efficient buildings. Being an offsite manufactured and ready insulated product, SIP offers considerably lower thermal transmittance and advantageous in term of erection as well as construction time and cost compared to traditional building materials. SIPs are structural element thus there is no need of studs or wall ties like in traditional building materials. Thermal bridges are therefore minimised in this type of construction. Besides, as SIP building structure are assembled from components to manufacturing tolerance and connections are ensured by both tightly fitting with overlapping plasterboard linings and sealing techniques, a high level of air tightness can be achieved thus resulting in a positive effect in energy efficiency.

English Housing Condition Survey showed recently that there were around 22.2 million homes in 2007, mostly built by traditional construction method, with an average emission per household at 5.46 tonnes (DCLG, 2007b, EHCS, 2009). This illustrated that any attempt to build zero carbon homes should cover increasing controllability over the construction process and building in operation. Therefore, the Government is committed to promote modern methods of constructions because they can deliver better quality house faster in scoping with current housing shortage and reducing waste/defects by offsite fabrication. However, there is reluctance to innovate due to lack of knowledge, skills and experience of construction labour and standard house sets existing within the development of each house building company for cost and defects reduction.

Despite SIPs possesses potential key benefits for building materials in reducing building environmental impact, there is limited usage of SIPs in house building in the UK. The gap in SIPs knowledge can be identified as lack of evidence in performance of SIPs construction built in the UK, and the need of an overall view of SIPs construction in reference with traditional building materials (e.g. masonry construction and timber framed dwelling). Post occupancy evaluation based on collecting data of utilities bills used in simulation for validation experience inaccuracy and cannot provide an insight into contribution of building fabric in improving indoor environment. Simulation results drawn from heating degree days and/or cooling degree days do not provide a holistic understanding of thermal parameters and their level of contribution to indoor environment. In addition, previous studies have suggested that overheating is likely to occur in lightweight construction using MMC, SIPs included. A building envelope with high level of airtightness and insulation provides improved heating performance in cold period but may cause heat stress and discomfort during warm period.

Thus the aims of this research were to provide a framework for holistic evaluation model of a SIPs- based dwelling covering design – build – monitoring, simulation – development – feedback to design for improvement. Through the framework, it enables designer and developers an understanding of the process for further work in developing evidence based case studies for any alternative building material and system in shifting to low carbon construction. Thus close the gap in the understanding between design and post construction performance.

To achieve this, an investigation of a SIP unit performance was undertaken. This generated post construction performance data, which were used to validate and verify models developed in thermo-dynamic simulation software to help address one the most pressing challenges in the required evidence base. Consideration of a SIP unit was particularly important as it offered the opportunity to solve a number of challenges faced by the UK housing sector, particularly the need for cost effective and energy efficient solutions whose performance under a range of changing conditions or orientations can be predicted

A key finding from this work related to field performance over a selected period of time, which showed that SIPs construction provides a steady indoor environment as a result of good level of air tightness and insulation. These data demonstrated for example that over-glazing in the bedroom would require effective shading to maintain appropriate comfort levels. Further illustration of the impact of this work on assessment of thermal performance was through solar controlled blinds that were installed in the bedroom space. These were effective in reducing heat gain thus demonstrating that there is likely overheating risk experiencing in SIPs construction, and how effective natural ventilation can help to eliminate such a risk. Further aspects demonstrated a clear correlation and full agreement between the simulation and measurement, providing evidences filling the gap between design and performance of SIP construction unit.

Another key finding relates to the validation component of the work undertaken. In this study, an analytical verification of heating and cooling performance through steady state calculation was initially undertaken. It was then refined for the performance of the SIP unit following on with comparative testing of the program itself via sensitivity analysis. Empirical comparison was independently established with actual measured performance against the building model simulated at as-built state. The surrounding conditions were simulated to reflect information from site survey along with assumption made in thermodynamic modelling. The IES<VE> weather simulation file was edited to enable manual input of ongoing climate data. The output for comparison includes temperature and operative temperature as they are key thermal parameters for heating/cooling design and thermal comfort. If the project budget had been more generous, measurement of indoor air velocity, heat flux and surface temperature would have taken place allowing further check on the building simulation. Though the research work showed that this was sufficient for assessing the building performance whilst considering the purpose of comparison between different energy efficient design solutions and cost effectiveness measures using validated simulation model.

This work has shown by both computer simulations and field data that overheating can be an issue in SIPs dwelling. Though it can be resolved by a good passive thermal control achieved by natural ventilation integrated with increased mass level of the building envelope (e.g. integrated PCM onto the building envelope) or through the incorporation of effective shading design options. Whilst taking account of occupancy factor, an occupant profile and its usage pattern were also established from the validated building model to further illustrate the potential of the approach developed in this thesis. Simulation results showed that trickle ventilator, for example under-performed with respect to the required air exchange rate maintained for background ventilation. Thus was further demonstrated for later developments through resizing trickle ventilator to meet equivalent ventilation area set in 2010 Part F. However, an earlier field study combining detailed CFD simulation, laboratory test and real monitoring of trickle ventilator conducted by BRE suggested that the purpose designed trickle ventilators, sized according to these criteria, can provide the required background ventilation during the heating season without compromising thermal comfort.

Interventions developed from building simulation to investigate heating improvement illustrated that MVHR outperforms super insulated building envelope (e.g. SIPs construction meeting Passivhaus fabric requirements in addition to higher airtightness level and triple glazed low-e coating glass with double argon filled) in term of energy savings and cost effectiveness. By combining super insulated building envelope and MVHR use, as the core factor of Passivhaus criteria, energy saving was up to 80% compared to the initial design.  However, in term of costing, the current design was more affordable due to higher investment to meet Passivhaus criteria. This suggested in other scenarios where electric heating was used in the premise and/or in colder climate that Passsivhaus would be more beneficial than in the UK climate.

Thus overall this is the first time that this kind of systematic post construction evaluation of a SIP based dwelling has been undertaken in the UK. Thus the results make a significant contribution to the development of the evidence based so desperately needed to help make the transition to a low carbon construction sector in the UK. The focus on generating post construction performance data which are used to validate and verify models developed in thermo-dynamic simulation software helps to address one the most pressing challenges in the required evidence base; namely the need to understand how to close the gap between design and post construction performance. Consideration of a SIP based product is particularly important as it offers the opportunity to solve a number of challenges faced by the UK housing sector, particularly the need for cost effective and energy efficient solutions whose performance under a range of changing conditions or orientations can be predicted.

## *9.2 Further work*

There is a potential need to take the research forward involving extensive monitoring for detailed performance of SIPs test unit to confirm the findings of the work presented herein. This includes: using thermal camera to identify any thermal anomalies, conducting co-heating test to evaluate whole house building heat loss, tracer gas decay method for assessing the ventilation performance of either trickle ventilator and ventilation system installed in the test unit, and omni-directional air flow meter to measure indoor air velocity for thermal comfort purpose. The use of infrared thermal camera could be used during the air pressurisation test to detect the leakage paths within the building envelope.

The next stage would be to conduct post occupancy evaluation and system controls developed in conjunction with integrated low and zero carbon technologies. This will provide feedback on interaction of occupants on building control and thermal comfort as well as assess actual interaction with various passive control measures, allowing the gap between design and actual performance to be closed.

A key aspect that requires further investigation is the overheating risk both under current and any future climate scenario. With potential climate changes leading to more extreme events there is a greater potential risk of overheating occurs inside the well-insulated and airtight lightweight construction using MMC. As the UK dwellings are mainly relied on natural ventilation to avoid summer overheating, the paradox lies with respect to installing air conditioning to maintain comfort and the heating savings from the super insulated and airtight envelope.

Figure 9-1: Extraction of EH unit from the construction site at the University of Birmingham, UK.

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# APPENDICES

## Appendix A BUILDING PHYSICS

A building is an enclosed construction where human activities take place, such as living, working, manufacturing, entertaining and so on. Depending on usage purpose, microclimate, landscape, budget and other factors, building vary from one to another. The task of building design prioritises requirements including aesthetic, economy, environmental comfort and energy conservation. In order to reduce building's reliance on high grade energy yet still provide human comfort for occupants, 4 main design issues listed as heating, cooling, ventilation and lighting are to be considered. These elements are interdependent, so that the strategy that improves one can worsen another. Therefore, it is important to understand the background of building thermal behaviour then determine key elements so as to develop good building design strategies

This appendix provides an insight into heat mechanism in buildings, the interactions between the building and the external climate, and the physical indoor environment factors affecting human. From the background of building physic, it discusses the building thermal behaviour by introducing several main fabric parameters and also addresses thermal comfort issues in building design and the method to be used for predicting the comfort level in a room.

### *Appendix A.1 HEAT MECHANISM*

The difference between outdoor and indoor climate generates mass and energy flows across the building envelope. As being subject to the fluctuation in weather conditions such that temperature, solar radiation, wind and rain penetration, the building envelope is the key factor affecting the building thermal performance. In a cold weather, energy is consumed to keep the internal space warmth during its occupancy. Depending on the building elements that some require more energy to maintain the warmth than other. Building design aims at delivering strategies that not only prevent too much energy consumption to heat up the space leading to waste but also if possible to take use of free solar gain for heat and light use. In hot weather, if too much heat can enter the building, the internal space will be overheated and energy might be required to vent or air condition the space.

The following is a brief theoretical description of the heat mechanism within a space, see Figure A-1. It illustrates the four heat transfer process of conduction, convection, radiation and evaporation/condensation. Conduction transfers heat through direct contact between solid objects, liquid or gases in order of its importance. Convection transfers heat between solids and fluids or within fluids. Radiation transfers thermal energy directly through a space without requiring matter in transmission. For instance, heat from the body of occupants in a cold room radiates to the ambient air and makes occupants feel cold (Thomas, 2006). Evaporation relates to a change of phase from liquid state to vapour state. This process requires energy to add in the matter from a lower to a higher energy phase. The process is reversed for condensation process. The phase changes occur at specific temperatures known as the boiling point (Thomas, 2006).

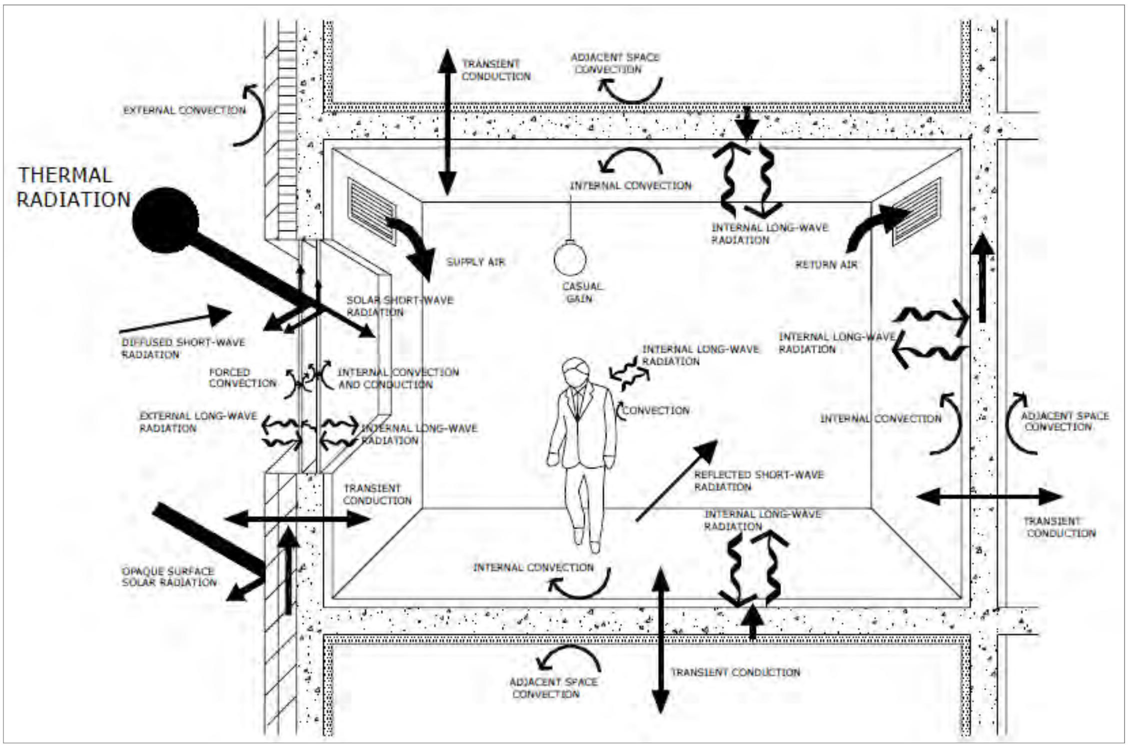


Figure A- 1: Heat Mechanism within the space (Abaza, 2002)

As described in Figure A-1, conductive heat transfer occurs through the building envelope components (i.e. walls, roofs, floors, windows and doors), through internal partition walls and internal windows/doors. Primary paths of heat loss or gain in a dwelling are windows, external walls and roofs. As the ground temperature is fairly stable and the difference between ground and indoor temperature is not as high compared to other parts, conductive heat transfer through ground floor is less considerable. Heat also flows through junctions between building components such as walls in contact with floors and ceiling or roofs and through connections between frames of windows and doors with external walls, namely thermal bridges (See Section A.3.1).

Convective heat transfer resulting from air movement and variety of density with temperature takes place through opening the windows for ventilation (i.e. wind driven and stack effect ventilation, See Section A.3.2). If windows are kept close, it occurs when there are differences in temperature or air flow between the external building surfaces and outdoor air as well as internal building surfaces with indoor air and between glazing surfaces and the air gap between glazed panels. A significant part of convection occurs via porous construction of building envelope, cracks around building components within the building envelope (e.g. windows, doors), services entries and joist connections between building structures. It is known as air infiltration and is quantified as leakage rate or airtightness level (CIBSE, 2000).

In radiant heat transfer, the rate of heat flow depends on the temperature of the radiating and receiving surfaces as well as the surface qualities through 2 parameters (i.e. absorbance and emittance). The radiation heat transfer is important between the external surface of building envelope and the sky that includes solar radiation in daytime (radiation gain) and black sky in night time (radiation loss). This also occurs between external surface and the surroundings (e.g. the ground, nearby buildings, vegetations). If curtains or blinds are used to cover the window, an insulation layer is installed in walls and roofs, “sight connections” are broken and there is no longer radiation transfer (Thomas, 2006).

A building receives solar radiation gain directly and indirectly. The former related to transparent surface of building envelope where some parts of solar radiation is transmitted, some of it is reflected and some absorbed, heating the glass itself. Then the heated glass will re-emit the absorbed heat to the internal space (Szokolay, 1980). The later refers to solar heat gain which is absorbed by opaque component of building envelope and transferred to building inside through conduction, convection or radiation (Thomas, 2006).

In evaporation process, heat is removed from the liquid and transferred to the vapour, thus produces local cooling on the wet surfaces in buildings. The energy added to turn a liquid into a gas is the latent heat of evaporation. In the reverse process, warm moist air meeting cold surfaces at thermal bridging locations or unheated space causes condensation on building surfaces. This can result in dampness, mould growth and deterioration of building fabric. In order to avoid condensation, vapour barrier or vapour control layer is employed that helps reducing the volume of gaseous which leaks from the interior to exterior of building envelop (CIBSE, 2006a).

In summary, the energy flows across the building envelope is the combination of the three elements of heat transfer procedure: conduction through building envelope, convection to indoor and outdoor air, and radiation from building surfaces to surroundings. Mass flows occur in form of both air flow and vapour flow which are naturally induced or artificially forced into the building.

## *Appendix A.2 EXTERNAL ENVIRONMENT AND BUILDING*

The impact of external environment on a building varies in different kinds: thermally, acoustically, hygienically, and so on. In term of its impact on building thermal performance and human comfort, the set of externally environmental factors is known as meteorological factors or outdoor climate. There is only a few typical weather parameters used in thermal design of buildings like air temperature and humidity. However, for the building thermal behaviour to be simulated, a large number of meteorological factors should be included. These factors should be monitored especially for experimental assessment of the building performance. A list of the meteorological factors is given below according to (Fracastoro and Lyberg, 1983) and later update in CIBSE (2002):

- Air temperature
- Wind (direction and speed)
- Air humidity
- Atmospheric pressure
- Atmospheric radiation
- Solar radiation
- Cloudiness and precipitation

These factors depend on the interaction between the Sun and the Earth thus they depend on geographic (i.e. latitude of the location), the time of the day and of the year (i.e. the Sun declination and hour angle), physical characteristics of the atmosphere (e.g. optical thickness, thermal capacity), and the ground characteristics (e.g. reflectivity, thermal capacity) (Fracastoro and Lyberg, 1983).

Air temperature is the most important meteorological factor affecting the building thermal performance. It is the parameter describing a seasonal as well as daily variation as a result of the convective heat transfer from the ground, and heated in its turn by solar radiation. Whilst comparing the seasonal and daily trends of air temperature and global radiation, there is a certain delay as a result of the thermal capacity of the atmosphere (Fracastoro and Lyberg, 1983). Air temperature plays key role in driving heat transmission and enthalpy flow across the building envelope as discussed further in Section A.3.1 to A.3.2.

Air humidity is defined as the water vapour content of the ambient air, often measured by the ratio of actual water vapour content to the saturate state of water vapour content at its actual temperature and pressure, known as relative humidity. It does not have direct impact on the heating demand of a building, but rather be considered in air conditioning problems (Fracastoro and Lyberg, 1983). Wind refers to air motion on the horizon described by its direction and velocity, caused by large scale pressure gradients by uneven heating of land and sea driving energy comes from the sun (Fracastoro and Lyberg, 1983). The effects of wind on the building envelope includes forced convective heat transfer occurs at external building surfaces and air infiltration rate across the building envelope driven by pressure difference between the inside and outside conditions separated by the building envelope (See Section A.3.2)

Atmospheric pressure refers to the weight of air contained in an infinitely high vertical cylinder with its base on the ground. Its effect is indirectly and it is included in meteorological data as it is used to determined humidity from atmospheric pressure and wet- and dry-bulb temperatures. The Earth surface emits an amount of radiation which is proportional to the fourth power of its absolute temperature and emissivity. The long wavelength radiation is reflected, or absorbed and re-emitted by the air in all directions. The part of radiation reflected or re-emitted downwards is called atmospheric radiation, which is contained in the spectrum region ranging between 4 and 100 μm. The atmospheric radiation is responsible for radiant heat losses from building energy perspective.

Solar radiation constitutes the infrared wavelengths of the electromagnetic spectrum as radiation exchanges between the Sun and the Earth. The sun emits radiation with wavelengths between 0.29 and 3.0μm, termed as short wavelength radiation, which includes the visible spectrum (0.38 and 0.78μm) (Thomas, 2006). The shortwave solar radiation falls into a surface is divided into three components: direct solar radiation from the Sun disk (namely beam radiation), diffuse radiation from the sky vault after scattering and inter-reflection within the atmosphere and reflected diffuse radiation coming from inter-reflection of these two above, from the ground and the surroundings

(CIBSE, 2002). The solar radiation gives a major contribution to the building thermal performance as it is transmitted across the transparent elements of building envelope as well as absorbed by opaque elements (See Section A.3.3.1 and A.3.3.2).

Cloudiness refers to the fraction of the sky covered by the clouds and its influence on building is only indirect. The precipitation is defined as liquid (rain or drizzle) or solid (snow or hail) water falling onto the ground and its impact on energy demand of building is indirect (Fracastoro and Lyberg, 1983). Driving rain and snow cause moisture penetration into building elements thus increasing mould growth and condensation risk as well as U-value of the elements themselves.

## *Appendix A.3 BUILDING ENVELOPE*

The building envelope itself is a fabric factor that influences the internal environment hence energy consumption in the building. The energy demand is due to responding requirements of thermal, visual comfort and indoor air quality related to ventilation within the indoor environment. Since the building envelope regulates heating, cooling loads and daylight when available, it plays an important role in energy savings. The previous section provides an insight about external environmental impact on building thermal performance and heat flow mechanism as result of these impacts. In order to quantify heat transfer in buildings, steady state and dynamic heat transfer calculation are briefly discussed in this section.

The heat transfer through the building envelope can be studied by subdividing the structure into wall types for which heat transfer can be determined separately. The temperature difference between indoor and outdoor conditions separated by walls driving heat transmission and enthalpy flow across the building envelope (Fracastoro and Lyberg, 1983). Section A.3.1 discusses heat transfer through walls in steady-state and dynamic modes, Section A.3.2 is concerned with air infiltration then radiant heat transfer is reviewed in Section A.3.3.

### A.3.1 Building fabric heat loss/ gain

This section will explain heat conduction through buildings, defining the difference between steady-state and dynamic calculation procedure. Table 2 in (ASHRAE, 2009, p 4.3) indicates the shape factor in one dimensional conduction which is concerned in steady state heat transfer. It is designated that the walls (i.e. obtained by subdividing the building envelope) are slabs of constant cross sectional areas which differentiate to the hollow cylinder and hollow spherical shapes.

### *A.3.1.1 Steady state heat transfer or thermal transmittance*

The law of heat conduction, also known as Fourier's law, states that the heat flow rate through a material is proportional to the area of the section at right angles to the direction of heat flow, and to the temperature gradient (ASHRAE, 2009: p3.1), as given below:

$$\vec{q} = -\lambda \overrightarrow{\nabla T} \tag{A-1}$$

Where:

$\vec{q}$ is the heat flux (W/m$^2$)

$\overrightarrow{\nabla T}$ is the temperature gradient (°C/m or K/m)

$\lambda$ is the thermal conductivity (W/m°C or W/mK)

The negative is chosen so that thermal conductivity is always of positive value and heat always flows from a high temperature to a low temperature.

Steady-state conditions assume that the temperatures on both sides of the wall remained unchanged over a substantial period of time thus allow the heat flux to reach to a constant value. The Fourier's Law applied for one dimensional heat transfer through homogeneous and isotropic materials (i.e. this assures heat flows through the element is in the normal direction with no significant heat transfers taking place in the other 2 directions). The Equation A-1 can be written in steady state conditions, with d is the thickness of the wall (m), the heat flux (unit in W/m$^2$) in the normal direction of the wall cross sectional surface, is determined below:

$$q = -\lambda \frac{T_1 - T_2}{d} \tag{A-2}$$

The thermal resistance is concerned with the material resistance and its thickness, was introduced in (BSI, 2007b) to combine individual resistances thus obtain the total thermal resistance of component, is calculated by Equation A-3:

$$R = r \text{ x } d = d/\lambda \tag{A-3}$$

Thermal conductance or transmittance U-value is defined in (CIBSE, 2006a); (BSI, 2007a) as:

$$U=\lambda/d = 1/R \ (\mathrm{W/\ m^2\ K\ or\ W/\ m^2\ °C}), \tag{A-4}$$

Thus applying in Equation A-2 to obtain:

$$q = U\Delta T \quad \text{or} \quad q = \frac{\Delta T}{R} \tag{A-5}$$

The calculation of heat transfer through building envelope is generally performed in one dimension (Fracastoro and Lyberg, 1983). The Fourier equation is still complex to solve for multilayer walls thus a rigorous analytical approach leads to a simple solution only for steady-state conditions (BSI, 2007a). While in practice, each constructional layer is non planar and composite, for instance, masonry layer that surface of brick cannot be absolutely plane and have some sand or mortar stick on its surface. For simplification as in steady-state conditions, the heat flux through multilayer wall composed of uniform and parallel planar layers which are homogeneous and isotropic materials can be written as:

$$q = \frac{\Delta T}{\sum_i R_i} \tag{A-6}$$

Thermal transmittance or U-value itself depends on the conductance of the element and on the surface heat transfer coefficients. These in their turn depend on air temperature, surrounding surfaces, air velocity and direction of the external and internal environments (CIBSE, 2006a).

Practically, within one constructional layer there are two or more materials, for instance, mortar joints within brick/ block work in wall structure, or timber frame in wall frame structure that bridges the insulation. The thickness and thermal conductivity of component layers become dissimilar forming repeated thermal bridges (i.e. where a thermal bridge occurs at regular intervals within the construction). These occur when heat does not flow in a straight line of normal direction but is directed via a path least resistant to heat through the element. Commonly, the least resistant path is the one which material possesses a much higher conductivity than the surrounding materials. The presence of a thermal bridge and its effects to U-value calculation requires a two and three dimensional heat flow analysis. However, a simpler calculation process presented as “combined method” gives satisfactory results where the component contained bridging parts needs to be divided into thermally homogeneous parts with sections and layer thicknesses (BSI, 2007b). Calculation method and examples of calculation can be found in Appendices B.1 and B.2

Non-repeated thermal bridges relate to three dimensional or two dimensional heat flows, which occur at the junction between two or more building elements (e.g. window installed on a wall) or due to changing in structural composition of building element (e.g. a column in a wall). Figure A-2 indicates possible locations of thermal bridges in a dwelling. As a consequence, an increase of 10-15% of the total heat loss if thermal bridges are not eliminated (CIBSE, 2006a). They also result in changing temperature at internal surfaces that leads to thermal discomfort and moisture risk. The dominant and most commonly non-repeated thermal bridges are in form of two-dimensional heat transfer, known as linear thermal transmittance (CIBSE, 2006a).

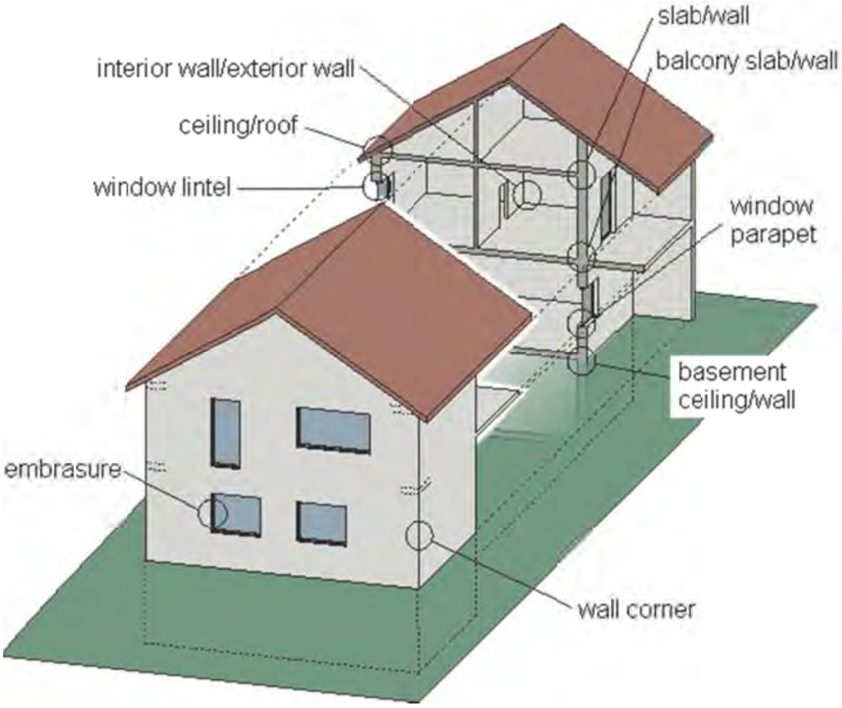


Figure A- 2: Location of thermal bridges within the building envelope (Division of Building physics and solar energy- Universität Siegen, 2004)

Three dimensional or two dimensional heat flows can be determined using numerical calculation methods given in BS EN ISO 10211 (BSI, 2003), with part 2 focuses on calculation of linear thermal transmittance or Ψ –value (BSI, 2001). In this context, the thermal bridges are bounded by two different thermal environments. The calculation is valid only when the following conditions are satisfied (BSI, 2001):

Steady-state conditions apply when:

- All physical properties are independent of temperature
- There are no heat sources within the building element
- Only one internal thermal environment applies
- One or two external thermal environments apply.

#### *A.3.1.2 Dynamic heat transfers*

In practice, steady-state conditions never truly exist because the thermal environment is complicated and involves many dynamic interactions. As the building is subjected to the weather fluctuations, the building responses differently depending on thermal resistance and capacitance of the materials forming building envelope as can be seen in Figure A-3. With the diurnal of the external temperature, thermal response is categorised into heavy and light weight building structure that means the building with high or low level of thermal mass, as explained later in this section.

Previously we considered heat conduction under steady conditions, for which the temperature of a body at any point does not change with time. This certainly simplified the analysis, especially when the temperature varied in one direction only, and we were able to obtain analytical solutions. In this section, we consider the variation of temperature with time as well as position in one- and multidimensional systems.

The temperature of a body, in general, varies with time as well as position. In rectangular coordinates, this variation is expressed as T(x, y, z, t), where (x, y, z) indicate variation in the x-, y-, and z-directions, and t indicates variation with time. The Equation A-1 in rectangular coordinates is expressed by:

$$q_x = \frac{\partial T}{\partial x}; \quad q_y = \frac{\partial T}{\partial y}; \quad q_z = \frac{\partial T}{\partial z} \tag{A-7}$$

Whist combining Equation A-1 with energy conservation law, assuming thermal conductivity is constant in all directions and no internal energy generation, the three-dimensional heat conduction equation can be written in (Fracastoro and Lyberg, 1983):

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \left( \rho c \middle/ \lambda \right) \frac{\partial T}{\partial t} \tag{A-8}$$

With $\rho$ and c are the density and specific heat capacity of the material.

$(\rho c / \lambda) = \alpha$ is called the thermal diffusivity of the material.

The diffusivity is an indication of the speed of the heat diffuse through the material, thus it is the key value determining the capacity of heat storage of the building envelope, known as thermal mass. Thermal mass refers to the capacity of the building envelope in storing heat. At room temperature, a high thermal mass envelope will absorb a significant quantity of heat for a period of time then the room is warm.

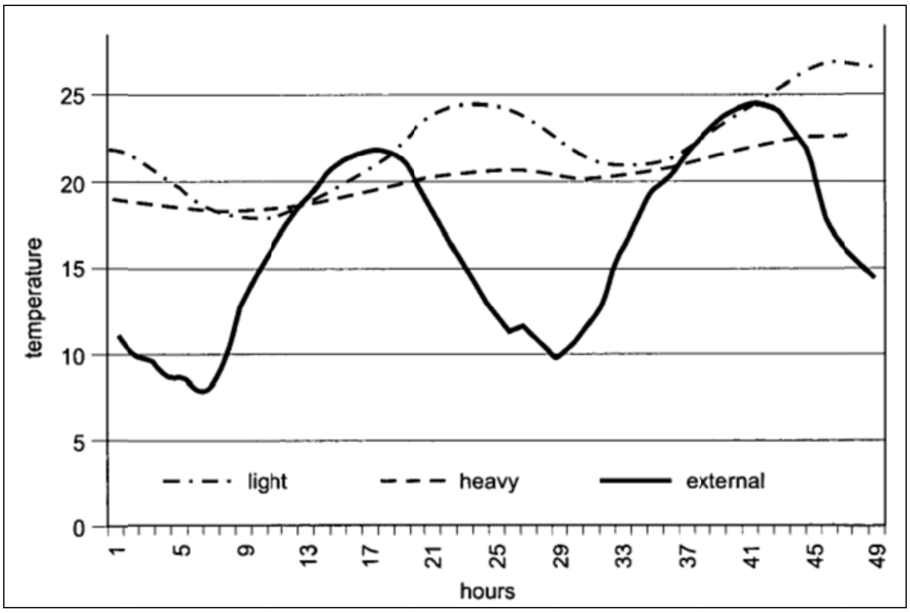


Figure A- 3: Thermal response of heavy weight and light weight buildings over 2 day period (Littlefield, 2000)

There are several methods to assess the non-steady state of a structure. One of the simplest one is the admittance procedure which is employed in thermal modelling software and this also is presented and applied in CIBSE guides of calculation. The method of calculation of dynamic thermal characteristics is given in BS EN ISO 13786:2007 (BSI, 2007d).

The thermal admittance (Y-value) indicates the rate of heat flow between the internal surface and external environment for each degree temperature difference in accordance with a time lead (w). Admittance is also measured by W/m$^2$K, where temperature is the difference between the mean daily value and actual value within the space ((CIBSE, 2006a) and (BSI, 2007d)). Admittance describes the ability of a material to exchange heat with the environment during a cycle variation in temperature which is 24 hours for buildings. The decrement factor relates the magnitude of the cyclic temperature of the internal surface to the cyclic temperature of the external surface. The time delay due to the thermal mass is known as a time lag. The thicker and more resistive the material, the longer it will take for heat waves to pass through (CIBSE, 2006a).

The above procedure applies to building components consisting of plane homogeneous layers. Thermal bridges usually present in such building components do not affect significantly the dynamic thermal characteristics, and can hence be neglected (BSI, 2007d).The physical properties of the construction building fabric which are used in calculation of thermal heat transfer, computer programmes and building guidance are listed in the table below

Table A- 1: Physical properties of building materials in calculation

| **Thermal parameters** | **Symbol** | **Unit** | **Definition** |
|---|---|---|---|
| Thermal conductivity | $\lambda$ | [W/mK] | The amount of heat transfer from one side to another of a unit thickness at a unit temperature difference. |
| Density | $\rho$ | [kg/m$^3$] | Measure of mass per unit of volume. |
| Specific heat capacity | c | [J/kgK] | The amount of heat that a material is able to store per unit of mass and per unit of temperature change. |
| Thermal resistance | R | [m$^2$K/W] | Measure of a material's ability to resist heat flow. |
| Thermal transmittance | U | [W/m$^2$K] | Rate of heat flow in watts through a building element for each degree temperature difference between the ambient airs on each side. |
| Linear thermal transmittance | $\psi$ | [W/mK] | Heat flow rate in the steady state divided by length and by the temperature difference between the environments on either side of a thermal bridge. |
| Thermal diffusivity | $\alpha$ | [m$^2$/s] | Ratio of thermal conductivity to volumetric heat capacity. |
| Penetration depth | $\delta$ | [m] | Depth at which the amplitude of the temperature variations are reduced by the factor e in a homogeneous material of infinite thickness subjected to sinusoidal temperature variations on its surface. |
| Thermal Admittance | Y | [W/m$^2$K] | Ability to exchange heat with the environment when subjected to cyclic variations in temperature. |
| Surface heat capacity | M | [kg/m$^2$] | Mass of building construction that store actively energy. |
| Decrement factor | f | - | Ratio of the modulus of the periodic thermal transmittance to the steady state thermal transmittance U. |
| Time lag | $\phi$ | [s] | Period of time between the maximum amplitude of a cause and the maximum amplitude of its effect. |

### A.3.2 Ventilation

The driving force of air flow is due to wind pressure or temperature differences resulting in a difference of air density (also known as stack effect) and combination of these 2 mechanisms. Unfortunately, the pattern of pressure distribution arising from wind and stack effect is extremely complex and considerable simplification is necessary in any mathematical representation.

The stack effect is explained as when warm air which occurs indoors is less dense than colder air from outside or in other words, the difference in air temperature causes difference in air density which leads to an imbalance in pressures across the building envelope. These pressures drive colder air at the lower inlet into the building and warm air escapes at higher outlet. The air movement through any openings of the building envelope, due to wind pressure and/or stack effect is called natural ventilation. It is to distinguish with mechanical ventilation where air is supplied to or extracted from a space using a fan or more complex systems possibly providing supply and extraction of air, conditioning of the air and heat recovery from the extracted air. The magnitude of air flow through openings is a function of the applied pressure difference across the openings and its length, cross sectional area and internal geometry (CIBSE, 2006a: p.4-6).

The empirical relations have been expressed depending on types of openings: small openings (infiltration or trickle ventilators); orifice type openings (open windows); and long regular pipes/ducts. It is given in BS 5925 (1991), the flow rate expressed in terms of the power of pressure differences for these openings as below:

For small opening or crack:

$$q_{vc} = l \times k \times \left(\Delta p\right)^{n} \qquad \text{(A-9)}$$

Where:

$q_{vc}$ - Volumetric flow rate through the crack ($m^3/s$)
$\Delta p$ - Pressure difference across the opening (Pa)
l - Total length of crack (m)
k - Flow coefficient per unit length of opening (l/ (s. m. $Pa^n$))
n- Flow exponent

The flow exponent characterizes the flow regime, varying between 0.5 for fully turbulent flow to 1.0 for laminar flow. Air flow through small sized openings like cracks and gaps tend to be more laminar nature, that n is ranged between 0.6 and 0.7.

For orifice-type openings such as open windows:

$$q_v = C_d \times A \times \left(2\Delta p/\rho\right)^{0.5} \tag{A-10}$$

Where:

$q_v$ - Volumetric flow rate through large opening ($m^3/s$)
$C_d$ - Discharge coefficient,
A - Area of the opening ($m^2$),
$\rho$ - Density of air ($kg/m^3$)

The purpose of ventilation is to create air circulation, which introduces outside air into the building to dilute pollutants, revitalize and refresh air, sufficiently for healthy and comfortable conditions to the building occupants (CIBSE, 2006a: p.4-2). Air infiltration refers to the uncontrolled air exchange through a building envelope resulted from cracks around windows/panels, services entries, porous materials, gaps or joint connections. Air leakage plays a part in providing air change but the problem is that it is uncontrollable and needs to be minimised. In fact, it is claimed to be responsible for up to 30% of the total heat loss (Jaggs and Scivyers, 2006). Besides, the higher the air exchange rate is, the more discomfort to occupants with draughts. And condensation can take place at cold parts of the structure due to the transportation of moist air from inside through leakage path. A good ventilation strategy is a fundamental requirement for building design to guarantee a healthy and comfortable for building users. It principles built from the concept of “build tight-ventilate right” that a good design primarily based on airtight building envelope and supplied natural ventilation design (Perera and Parkins, 1992).

### *A.3.2.1 Infiltration rate*

Airtightness should be considered at an early stage in the design procedure by identifying the line through the building that forms the air barrier. The barrier or the line of airtightness should provide a continuous line around or through all elements in the building that separate heated and unheated spaces as illustrated in Figure 2.5 (Jaggs and Scivyers, 2006). In a simple understanding, airtightness is the strategy to avoid joints and gaps as well as seal joints if gaps and junctions are unavoidable.

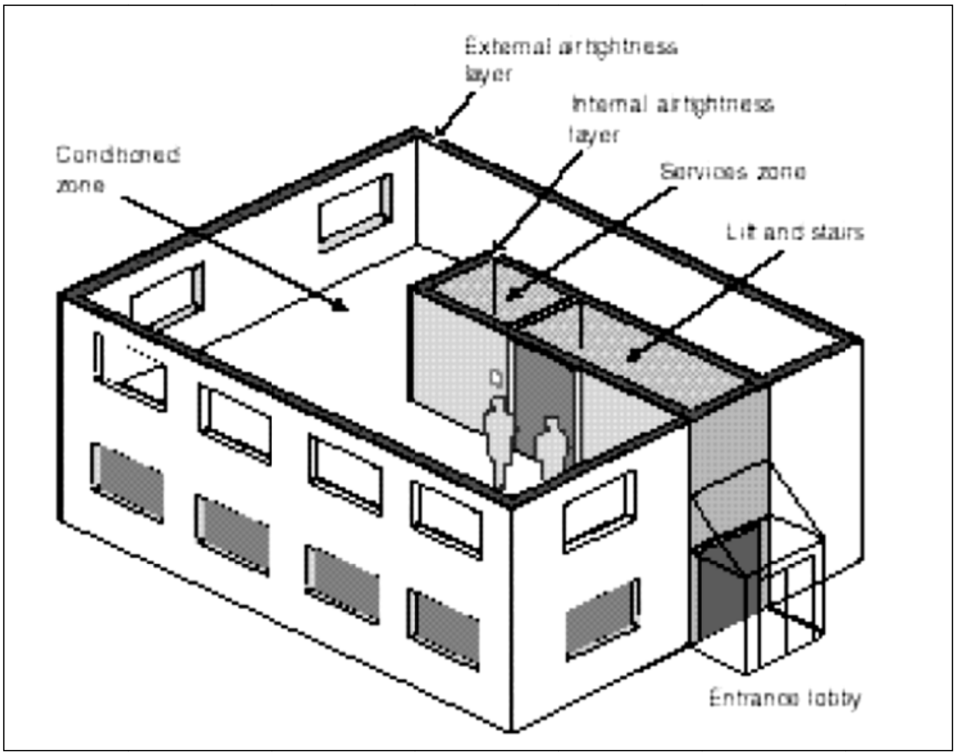


Figure A- 4: Illustration of external and internal airtightness layers (Jaggs and Scivyers, 2006)

Even for perfect air impermeable structures, the air leakage rate will not be nil. The leakage rate depends on many different impacts such as how the building is used as well as temperature difference and wind which varies significantly with the time of day and year. Hence, when referring to an airtight building, rough estimates are generally used and accepted to evaluate how leaky the structure is. Empirical data can be used to estimate possible infiltration rates that may be expected in buildings of typical construction in normal use in winter and under average annual conditions. Air permeable data provided by either pressurisation or depressurisation method though is representative data, it enables the comparison of leakiness from one building to others. In addition, the test data will be used to derive a relationship between the tested pressure difference and natural infiltration (Kronvall, 1978 and 1980). It is then useful in making a number of simplifications in the computer modelling of building performance to allow prediction of infiltration rate at normal conditions.

#### *A.3.2.2 Ventilation*

Pollutants built up in indoor air result from daily activities, for instance, unavoidable sources ($CO_2$) from metabolism of occupants or the use of equipments and household appliances. There are 3 types of ventilation as classified in Building Regulation 2000 (DCLG, 2010b) in term of ventilation rate: extract ventilation, whole building ventilation and purge ventilation. Extract ventilation is needed to remove water vapour and/or pollutants in some specific rooms (i.e. bathroom or kitchen). Whole building ventilation refers to continuous procedure of air exchange through which fresh air is provided throughout the whole building. Purge ventilation is intermittently provided throughout habitable rooms so as to remove water vapour and/or dilute pollutant concentration from occasional activities. Besides, purge ventilation provision may help to enhance thermal comfort, and/or avoiding overheating.

In dwellings, ventilation rates are required not be less than the value given in Table A-2 for extract ventilation and in Table 3-3 for whole building ventilation. Purge ventilation is required for each habitable room with extracting capability of at least 4 ac/h per room directly to outside.

Table A- 2: Recommended extract ventilation rates for dwellings (Table 1.1a in DCLG, 2010b)

| **Room** | **Minimum intermittent extract rate** | **Continuous extract** | |
|---|---|---|---|
| | | Minimum high rate | Minimum low rate |
| **Kitchen** | 30 l/s (adjacent the hob) or 60 l/s else where | 13 l/s | Total extract rate must be at least the whole building ventilation rate in Table A-3 |
| **Utility room** | 30 l/s | 8 l/s | |
| **Bathroom** | 15 l/s | 8 l/s | |
| **Sanitary accommodation** | 6 l/s | | |

Table A- 3: Recommended whole building ventilation rates for dwellings (Table 1.1b in DCLG, 2010b)

| | Number of bedrooms in dwelling (*) | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Whole building ventilation rate (l/s) | 13 | 17 | 21 | 25 | 29 |
| Notes:<br>- In addition, the minimum ventilation rate should not be less than 0.3l/s per $m^2$ internal floor area (i.e. for a two-storey dwelling, both ground floor and first floor should be taken into account in the surface determination)<br>- (*) The given value is based on the criteria that two occupants in the main bedroom and single occupants in other bedrooms (so called default value). | | | | | |

### A.3.3 Direct and indirect solar radiation

The sun emits its heat energy as short-wave radiation (wavelength below 3.0µm, that includes visible wavelength or daylight) whilst lower temperature surfaces (e.g. building surface) emits long wave radiation (wavelength above 3.0μm) (Thomas, 2006). Glass is perceived as transparent to shortwave radiation and opaque to long wavelength, its presence in building envelope is designated as the building fenestration system. Fenestration is the term used by ASHRAE to designate any light-transmitting opening in a building wall or roof (ASHRAE, 2001). Direct solar radiation passes through fenestration and warm up the internal surfaces which in turn emit long wavelength radiation. Indirect solar radiation is the amount of heat gain due to solar radiation that is absorbed by the building envelope and transferred to internal space by conduction, convection and long wavelength radiation (Stein and Reynolds, 1991).

#### *A.3.3.1 Fenestration*

When solar radiation is incident on building fenestration, it will be partly reflected, transmitted and some of it absorbed which heats the glass itself (Stein and Reynolds, 1991). The heated glass will re-emit the absorbed heat, inwards and outwards. By altering the component of fenestration, it provides mean to control solar access and solar radiation intensity. This can be done by number of solution: using additional glazing layers (from single to double or triple glazing system); applying coating on glazing panel, filling in or evacuating air or various gases (e.g. argon, krypton, xenon) within the gap between the glazing panels; employing exterior and interior shading. For instance, applying low emissivity coating on the glazing panel helps reflecting long wavelength radiation back into the space, thus reducing energy loss. Or applying solar control coating on external glass panel in order to reflect solar radiation from its surface outwards requires balancing between reducing solar heat gain and allowing light transmittance. Solar factor (g-value) is a measure of proportion of solar transmittance through building fenestration by all means (ASHRAE, 2001).

#### *A.3.3.2 Opaque element*

The wall element absorbed solar radiation, heats up the external walling surface then conductive heat transfer occurs, result in rising surface temperature of internal walling surface. The internal surface reradiates long wavelength radiation, which amount depends on the its surface emissivity and temperature (Stein and Reynolds, 1991).

With continued radiation input, the external surface of wall element will increase. If the incident radiant flux density (G) is known, the absorptance ($\alpha$) is the amount of radiation absorbed by a surface compared to that absorbed by a black body, the heat absorbed by the surface ($Q_r$ ) on the element area A given in (Stein and Reynolds, 1991):

$$Q_r = A \times G \times \alpha \tag{A-12}$$

When the temperature surface of the wall increases, the heat loss from the surface consequently increases until equilibrium is reached when the rate of this heat loss equals the radiant heat input, following the Conservation Law. Heat loss to air takes account of both radiant ($h_r$) and convective ($h_c$) components of the surface:

$$Q_{loss} = A \times (t_s - t_o) \times (h_r + h_c) \tag{A-13}$$

If the environmental temperature $t_o$ known, the surface temperature $t_s$ is determined:

$$t_s = t_o + \frac{G \times \alpha}{(h_r + h_c)} \tag{A-14}$$

Since this equation neglects any heat flow through the surface, $t_s$ will not be a true surface temperature, and it is referred to as the sol-air temperature. Sol-air temperature is defined as the temperature of the outdoor air which, in the absence of all radiation exchanges, would give the same rate of heat entry into the surface as would exist with the actual combination of incident solar radiation, and radiant energy exchange with the outdoor air (ASHRAE, 2001). Sol-air temperature takes into account the effect of incident solar being partially absorbed by a building element exposed to solar radiation, and used in the conduction heat flow expression.

$$Q_c = A \times U \times \Delta t \tag{A-15}$$

Where $\Delta t = t_s - t_i$, with $t_s$ is the sol-air temperature,

$t_i$ is the indoor air temperature

## *Appendix A.4 INTERNAL ENVIRONMENT AND OCCUPANT*

The indoor environment should be kept at a comfortable temperature for the occupants to maintain their daily activities, taking account of activities and clothing insulation. The heating of the dwellings and activities performed by the occupants will result in adding of pollutants to indoor air. Building fabric could dissipate gaseous constituents into indoor air which will look at heat balance and metabolism of the human body. This section will look at the interaction of occupant in modifying internal environment and the impact of surrounding environment on human in terms of thermally sensation.

### A.4.1 Human presence within the space

Heat flow is from a hot body to cold one. An individual can lose or gain heat depending on the relative temperature of the body and the surroundings. Sensible heat flow from the skin occurs as a complex mixture of conduction, convection and radiation from a clothed body. However, it is equal to the sum of convection and radiation heat transfer at the outer clothing surface and exposed skin (ASHRAE, 2004). Latent heat exchange occurs through evaporation process of sweat and moisture diffused through the skin. Respiration exchanges heat in both sensible and latent form, one through convection and the later is through evaporation of moisture during respiration.

The heat loss from the body to its surrounding environment is the joint effects of different heat exchange routes that the proportions of each route vary with the thermal conditions. For example, in well insulated buildings where air and radiant temperature are similar values, the ratio of each heat loss route could be around 24% for evaporation, 38% radiation and 38% convection (CIBSE, 2006b). While in a moderate thermal environment, these rotas could typically be 25% evaporation, 45% radiation and 30% convection (CIBSE, 2006b).

The human body generates heat all the time through the metabolic heat production. The amount of heat generation depends on the activity level, the more active the body is the more heat is produced, varying from about 100W for sedentary person to around 1000W for a very active person (ASHRAE, 2004). An amount of 115W, for example, is given off by a seated or very light work in office, hotel or apartment taking account of mixture of males/females, 70W of which is sensible heat and the remaining is latent heat (CIBSE, 2006a). Daily activity consists of a mixture of specific activities and/or a combination of work and rest periods. For design purpose, it requires the use of weighted-average metabolic rate, taking account the mixture of sex, age and generalised activities. A unit used to express the metabolic rate per unit DuBois area is the met which is defined as the metabolic rate of a sedentary person (i.e. seated and at rest) that 1 met equates to 58.1 W/ $m^2$ (ASHRAE, 2004). A maximum rate for trained athletes or long distance runners could be up to 20 met while a normal and healthy 20 years old male has a maximum rate of about 12 met which drops to 7 met at the age 70. Maximum rates for women are about 30% lower (ASHRAE, 2004).

Clothing is one of the dominant factors affecting heat dissipation from the body to its surrounding environment. Clothes worn vary within seasons, outdoor and indoor conditions and between individuals (e.g. sex and age). Regarding thermal comfort studies, the insulating cover of clothing garments is represented by a clo unit. This corresponds to an insulating cover over the whole body with 1 clo is equivalent to a resistance of 0.155 $m^2K/W$ (ASHRAE, 2004).

### A.4.2 Human thermal sensation

The thermal sensation of a human body is affected by 4 environmental factors listed as: air temperature, mean radiant temperature, relative humidity and air velocity (CIBSE, 2006a). Indeed, these are key environmental factors driving the aforementioned heat exchange processes at the body surface. Air temperature and air velocity affect evaporative and convective heat exchange, mean radiant temperature affects radiant heat transfer and relative humidity affects evaporation heat loss only.

Air temperature is the most important factor to help determining thermal comfort experiencing in a room but it is not the only one. The comfort or discomfort sensation depends on the joint effect of all the 4 environmental factors. Mean radiant temperature provides an average measure for the relative effect of all the radiant heat transfers from surfaces of the room components (e.g. walls, floor, ceiling, and windows) and any other radiant sources in the room (e.g. heaters, lights and equipments). It is suggested that the room air temperature and mean radiant temperature are combined into a single value - the operative temperature to express their joint effect, which is used in both International Standards and ANSI/ASHRAE (CIBSE, 2006a).

Humidity has little effect on thermal sensation near the comfortable temperature. As long as the environment is not too dry or too humid, the changes in the humidity levels are relatively imperceptible. Low humidity can lead to shocks due to static electricity, drying of the skin and mucous surfaces. With a relative humidity below 25%, it raises comfort complaints about dry nose, throat, eyes and skin (CIBSE, 2006a). At high humidity level, typically when relative humidity above 80%, it can result in condensation and mould growth on surfaces as well as discomfort feeling of sticky (CIBSE, 2006a).

Air movement in a room affects human comfort because it enhances convection and evaporation which produces cooling effect. Though uncontrollable and high air speed known as draughts causes uncomfortable feeling whereas too low air speed can reduce room air quality that can give rise to complaints of stale and stuffy air. In hot conditions and for natural ventilated buildings, it is accepted for cooling purpose with air movement of high air speed (e.g. air velocity ranges within 1 – 1.5 m/s) and of varying directions.

In order to improve thermal sensation for comfort, individuals adapt to the environmental conditions both passively and actively. In the passive way, body physics itself responds to the environmental change so as to maintain its core temperature close to 37°C at which human can function best (Thomas, 2006). When room air temperature rises, the body reacts by directing more bloods to the surface that leads to increasing in skin temperature and heat loss as well as by sweating to lose heat via evaporation. In reverse, when room air temperature drops, heat loss is reduced by limiting bloods directed to surface hence skin temperature is reduced as well as stopping sweating (Thomas, 2006).

Regarding active means, it refers to two human factors: metabolic heat rate and clothing are included in heat exchange processes thus having significant effect on human thermal sensation. When it is cold, individuals could be more active to increase metabolic heat and/or changing to warmer clothes. Reversely, individuals could rest in hot conditions and change to lighter clothing. They also include being active in modifying the internal environment such as opening windows for natural ventilation, using curtain to shade the Sun or switching on the heater to improve thermal sensation for comfort. These will be discussed in the thermal comfort section as part of adaptive methods that human could make change to improve their comfort in a space.

All the heat transfer processes described in section above contribute to the body thermal balance. For an individual to feel comfortable with the environment, a balance between heat production and heat loss from body to the environment needs to be maintained without much effort, neither shiver to generate heat nor sweat to lose it (CIBSE, 2006b). Therefore, the comfort levels fall between these limits of shivering and sweating.

Besides, an individual could be comfortable as a whole but still feel uncomfortable if having one or more parts of the body too cold or too warm, which is known as local discomfort issues. This could be as a result asymmetric thermal radiation, draughts, wide variation in vertical air temperature and warm or cold floors (CIBSE, 2006b). The most common reasons for discomfort due to asymmetric thermal radiation are large windows in winters or heat producing equipments. While a part of the body is exposed to cold surfaces, a significant amount of radiant heat emits from the body causes cold sensation. Research shows that for 1°C drop in air temperature on average equates to an incident radiant flux of 7W (Szokolay, 1980). As the temperature increases with the height above the floor level, if the gradient temperature is significantly large (e.g. more than 3degrees), local discomforts of warm head and cold feet are experienced even the body as a whole is thermally neutral (CIBSE, 2006a). Due to the direct contact of the feet and the floor, too high or low temperatures of the floor often cause local discomfort of the feet.

The undesired local cooling discomfort caused by higher air movement at low temperature known as draughts. There are 2 parts of the body: ankles and the back of the neck which are susceptible to draughts (CIBSE, 2006b). Thus it requires careful design of room air diffusion system further to minimising the air leakage paths on the building envelope. Additionally, it is recommended that the difference between radiant temperature and air temperature are not too wide and ideally with the radiant temperature is slightly above the air temperature. In fact, a heating system which is more convective like warm air heating, the air temperature is higher than radiant temperature thus it tends to feel stuffy. Whilst using heating system such as radiator systems or radiant panels, the radiant temperature at a space is higher than the air temperature and it tends to give a feeling of freshness (CIBSE, 2006b).

### A.4.3 Human thermal comfort

Building design aims to provide comfortable conditions for greatest possible number of people and minimise discomfort. Practically thermal comfort is defined as “a subjective response, or state of mind, where a person expresses satisfaction with the thermal environment” (ASHRAE, 2004). It is necessary to specify the measurable limits or ranges of each of environmental factors regarding comfort criteria. This section briefly presents the criteria for thermal comfort set out for natural ventilated residential buildings with regards to the scope of the project.

#### *A.4.3.1 Thermal comfort design criteria*

Comfort design criteria needs to be discussed and set out at the briefing stages and in term of acceptable range or values for key comfort criteria. These for thermal environment are listed as operative temperature and humidity together with fresh air supply rate. An example of typical initial design conditions might therefore be given as: operative temperature at around 21°C ± 1°C and relative humidity of 50% RH ±10% with 10 litres per person of fresh air required (CIBSE, 2006b). However, comfort requirements and priorities vary between purposes of space usage, building types, winter and summer conditions, air conditioned and free running mode and occupancy factors. Table A-4 presents the guidance for comfort criteria in designing dwellings.

Table A- 4: Recommended comfort criteria for dwelling (CIBSE, 2006a)

| Dwellings/ Room types | Winter operative temperature range, °C | Indoor summer comfort temperature for free running buildings, °C** | Air supply rate litre/second per person |
|---|---|---|---|
| Living rooms | 22-23 | 25 °C operative temperature | 0.4 – 1 ac/h* |
| Kitchen | 17-19 | | 60 litre/s |
| Bathrooms | 20–22 | | 15 litre/s |
| Halls, stairs | 19-24 | | - |
| Bedrooms | 17-19 | 23 °C operative temperature | 0.4 – 1 ac/h* |

* ac/h stands for air changes per hour, i.e. the number of times per one hour that the entire air volume of the whole building is changed.

** The indoor temperature comfort in natural ventilated buildings in summer will be complimented with overheating benchmark criteria discussed later.

#### *A.4.3.2 Adaptive approach towards comfort*

Adaptive approach for thermal comfort developed from field studies of people in daily life with immediate relevance to ordinary living conditions. In this approach, people actively make adjustment to their clothing and activities to adapt temperature change for comfortable. Thus the comfort temperature presented below in this approach has already included the appropriate clothing insulation and metabolic rate.

Firstly, a natural conditioned space is where the thermal conditions are regulated primarily by the occupants through openings and closing of windows without any mechanical cooling but mechanical ventilation (e.g. extract fan) is allowed. Although there is a presence of heating system within the space but it is not in operation when the adaptive approach is applied.

In summer, the building is free of cooling system then the temperature in the space follows the natural wing of the weather. However, occupants also make changes to adapt to the change in indoor environment like opening windows to provide cooling effect, changing to lighter clothes, taking a shower, etc. Therefore, the guidance in operative temperature range for human comfort in natural ventilated buildings could be related to outdoor air ambient.

Figure A-5 illustrates the range of acceptable operative temperature as a function of mean monthly outdoor temperature. The research developed an adaptive model of thermal comfort derived from a global data of 21,000 measurements taken in office buildings from 4 different continents (ASHRAE, 2004).

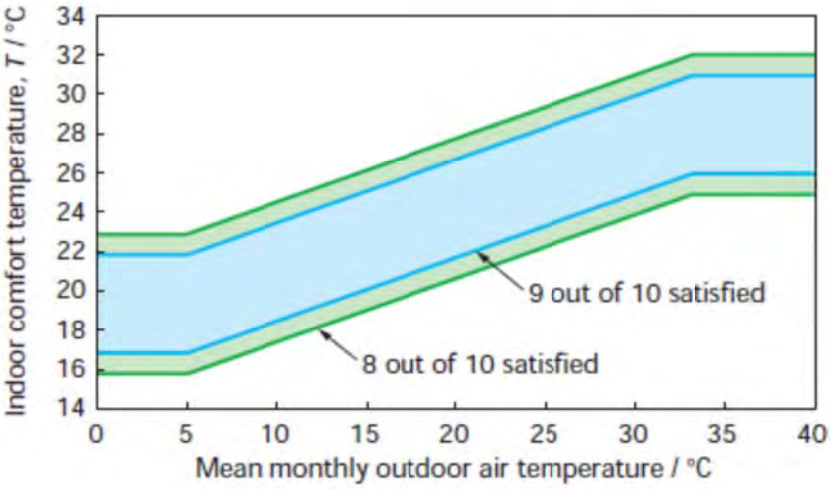


Figure A- 5: Adaptive comfort model (ASHRAE, 2004).

Meanwhile, research shows that UK weather has an important variation of outdoor temperature at shorter time than monthly intervals. It is suggested that the indoor comfort range relates to the running mean of outdoor temperature whilst taking the adaptive theory into account (CIBSE, 2006b). The adaptive theory explains in the way that people respond and adapt on the basis of their thermal experience with more recent experience being more important. Because the outdoor weighted running mean temperature considers the daily mean temperatures over the past week (or two), it would inform a more emphasis in recent temperature over the past few days than the given straight average value (CIBSE, 2006b). Figure A-6 indicates upper and lower bands for comfortable conditions in relation with the outdoor running mean temperature in office buildings for both the free running mode and for heated or cooled mode.

For residential buildings, there are insufficient data to provide a range of acceptable temperature like office buildings. Though it is suggested that people are less sensitive to temperature changes at home and in general they have more adaptive opportunities in their own home than at work (Oseland, 1995). Thus, upper and lower bands for comfortable conditions in Figure A-6 could be used with tolerance for considering comfortable conditions in residential buildings.

Besides, the degree of comfort within these bands is affected by other environmental factors as being discussed in the previous section namely radiation from surrounding surface and solar irradiation, air velocity and relative humidity. It is recommended that the acceptable range of relative humidity in buildings is between 40 and 70%, the relative humidity below 40% can be acceptable for short periods (CIBSE, 2006a). And the air velocities in an occupied space can vary within a range of 0.1 to 0.3 m/s (CIBSE, 2006b).

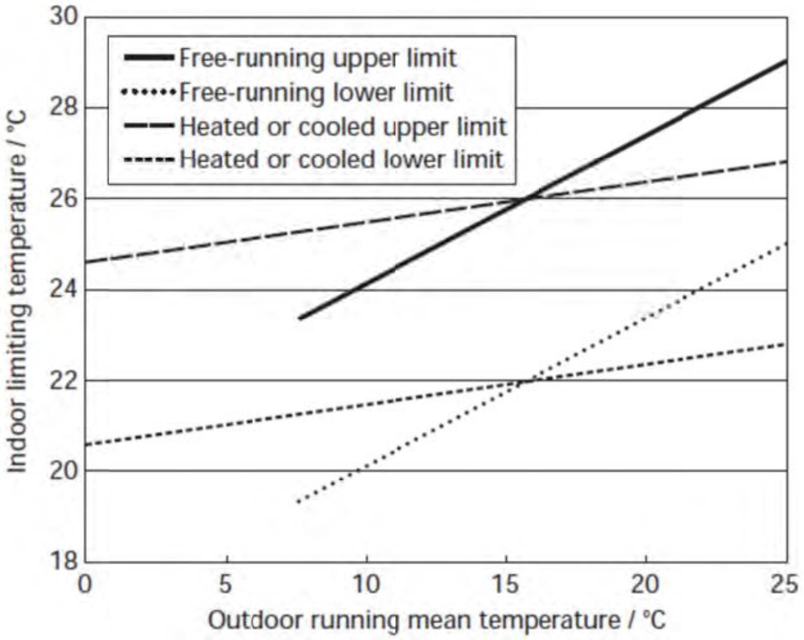


Figure A- 6: Bands of comfort temperatures related to outdoor running mean temperatures (CIBSE, 2006a)

#### A.4.3.3 *Overheating benchmark and criteria in summer*

As for a warm summer in the UK, the general operative temperature for indoor comfort for non air conditioning dwellings can be 25°C for living areas and 23°C for bedroom with indication that sleep might be impair at above 24°C (Table 1.7 in (CIBSE, 2006a)). These values are based on adaptive approach to comfort as discussed in the section above that shows few people feel uncomfortable at this temperature.

However, warmer outdoor conditions resulting in overheating in dwelling causes discomfort to occupants. This might lead to the need of installing mechanical cooling which will contribute in the increase in overall energy use and higher carbon dioxide emissions at the time when there is a pressing need to reduce this. Thus a building design needs to include risk assessment to predict the overheating that might occur and implement strategies to mitigate overheating by free or low cooling technologies. This could be achieved by employing thermal modelling with a suitable, local warm summer data.

The overheating risk assessment was introduced in CIBSE guide A that gives guidance not only about the value of peak temperature but also the length of time that temperature remain at that level. The indoor temperatures during warm periods are usually measured against a benchmark temperature and if this benchmark value is exceeded, the building is said to be “overheated”. And if this occurs for more than the designated amount of time which is expressed as a number of occupied hours or a percentage of the annual occupied period, the building is considered to have overheating issue. The benchmark temperature is operative temperature of 28°C for living areas and 26°C for bedrooms and the building is overheating if the percentage of annual occupied hours during overheated period exceeds 1% (Table 1.8 in (CIBSE, 2006a)).

In addition, another criterion for comfort in natural ventilated buildings requires that less than 5% of annual occupied hours in which the operative temperature exceeds 25°C (typically 100 hours) as being set out in CIBSE guide J (CIBSE, 2002).

Otherwise, the overheating degree hour is used to express the severity of overheating risk, that one degree hour equates to one degree over threshold temperature for an hour (EST, 2005a). For example, with the threshold temperature for living rooms is 28°C and bedrooms is 26°C, a room experiences one hour at 30°C equates to two degree hours in living rooms and four degree hours in bedrooms overheating.

#### *A.4.3.4 Other design requirement to reduce local discomfort*

The acceptable range of floor surface temperature is from 19°C to 29°C which is based on the criterion of 10% dissatisfied people wearing normal indoor footwear. This range disregards the situation in which people sit on the floor or stand on bare feet. The 29°C of floor surface temperature value is appropriate for under floor heating system (CIBSE, 2006a).

The allowable gradient temperature is up to 3°C between heads and ankles derived on criterion found only 5% dissatisfied people. In case when air velocities are higher at floor level (e.g. ventilation supply system at low level) then the maximum gradient of 2K/m is acceptable (BSI, 1995).

# Appendix B: PROOF OF CONCEPT

This section provides validation examples for calculating thermal properties of building components of the dwelling unit used in the case study. For each building element, it included a list of materials used, their thermal conductivities and thickness with the presence of air spaces, mechanical fasteners within the fabric. Appendix B.1 showed detailed calculations of thermal transmittance (U-value) of building elements as well as thermal bridges occur within the building fabric because of the geometry (i.e. connections between external walls with pitched roof and floor, around the openings). While Appendix B.1 dealt with the thermal transmittance of the building envelope as the principle factor in the determination of the steady state heat losses or gains, Appendix B.2 used admittance calculation procedure for determining the dynamic thermal behaviour of building structures. This required calculation of three parameters beside the thermal transmittance: thermal admittance, surface factor and decrement factor from heat capacity, density and conductivity of building materials. Appendix B.3 presented examples of analytical calculations for designing heating system by calculating total heat losses via building envelope and for predicting overheating risk within the spaces based on the design weather data for analytical calculation.

## *Appendix B.1 HEAT TRANSFER CALCULATION*

The steady state heat transfer is the simplified environmental conditions for building system design. It assumes that temperatures on both sides of a building envelope element (while different) are held constant for a sufficient period of time so that heat flow on both sides of the assembly is steady. It is for the purpose of determining the capacity of the heating and/or cooling system required to maintain specific internal design conditions under the external environmental conditions. The principal factor in the determination of heat losses or gain via steady state heat flow is the thermal transmittance (U-value). It is used to predict one dimensional heat transfer between two static environments through homogeneous construction of the building component. In addition, building components in real life are connected to form the envelope. Connections such as these between external walls, roofs and floors cause thermal bridges and they also occur around the openings (windows and doors) as the result of penetration breaking the element continuity. In practice, thermal bridges transfer heat via two or three dimensional flow and are responsible for 10 to 15% of the total heat losses (CIBSE, 2006). Linear thermal transmittance or Ψ–value is introduced as the simplified calculation method that facilitates building performance calculation.

This section starts with a brief introduction of calculation methods to determine thermal transmittance (U-value) and linear thermal transmittance (Ψ–value) of a building envelope (See Section B.1.1). It then considers the given building construction data, gather thermal properties of materials used for the structure and determine U-value of external walls, pitched roof, suspend floor structure and glazed fenestration of the test dwelling unit as found in Section B.1.2. It finishes with examples of Ψ–value calculation for selected locations as seen in Section B.1.3.

## B.1.1 Steady state calculation

This simplification assumes that temperatures on both sides of a building envelope element are held constant for a sufficient period of time. Such hypothesis assures the steady state heat flow from one side to another. Such calculations are useful in determining the maximum rate of heat loss or gain in order to predict heating and cooling load for sizing heating system and mechanical installations if necessary.

### *B.1.1.1 U-value calculation*

The calculation method follows the guidance from BS EN ISO 6496:2007: “Building components and building elements - Thermal resistance and thermal transmittance - Calculation method” (BSI, 2007a). For thermal transmittance calculation, it is assumed that the building component consists of thermally homogeneous layer in addition to steady state hypothesis. This means the building component consists of uniform, parallel planar layers as in reality, each constructional layer is non planar and composite.

#### *B.1.1.1.1 Building opaque elements*

For homogeneous, isotropic materials through which heat is transmitted by conduction only, the thermal resistance (R) is directly proportional to the thickness and is given by

$$R = {}^{d}\!/_{\lambda} \qquad \text{(B-1)}$$

The inside and outside surface resistances are determined by the processes of heat transfer which occur at the boundary between a building component and the air of the internal and the external environment. Calculation of surface resistances requires values of emissivity factor, heat transfer coefficient related to radiation and convection, see Equation B-2 and B-3 below:

$$R_{si} = \frac{1}{\frac{6}{5} Eh_r + h_c} \tag{B-2}$$

And

$$R_{se} = \frac{1}{Eh_r + h_c} \tag{B-3}$$

In this case where component constituted by elemental layers are of uniform thickness and the thermal conductivity is isotropic along each surface, heat flow through such component is unidirectional as indicated. The total thermal resistance ($R_T$) is calculated by combining the thermal resistance of each element and the adjacent air layers on both sides, as given in Equation B-4.

$$R_T = R_{se} + \sum R + R_{si} \tag{B-4}$$

Nevertheless, for practical structures, this is more complicated with one layer often consisting of two or more materials. For instance, mortar joints lying on brick/ block work in wall structure and timber frame in wall frame structure bridges the insulation. The thickness and thermal conductivity of component layers become dissimilar forming repeated thermal bridge (i.e. where a thermal bridge occurs at regular intervals within the construction). These thermal bridges occur when heat does not flow in a straight line of normal direction but is directed via a path least resistant to heat through the element. Commonly, the least resistant path is the one which material possesses a much higher conductivity than the surrounding materials.

The presence of a thermal bridge and its effects to U-value calculation requires a two and three dimensional heat flow analysis. However, a simpler calculation process presented as “combined method” gives satisfactory results (CIBSE, 2006). This is a simple calculation procedure based on an interval bounded by 2 limits of the thermal resistance via bridged part of the structure. The thermal resistance of the element composed of bridged layers in practice is assumed by the average value of this interval as shown in Equation B-5

$$R_T = \frac{R_U + R_L}{2} \tag{B-5}$$

The component contained bridging parts needs to be divided into thermally homogeneous parts with sections and layer thicknesses as illustrated in Figure 2.A-1.

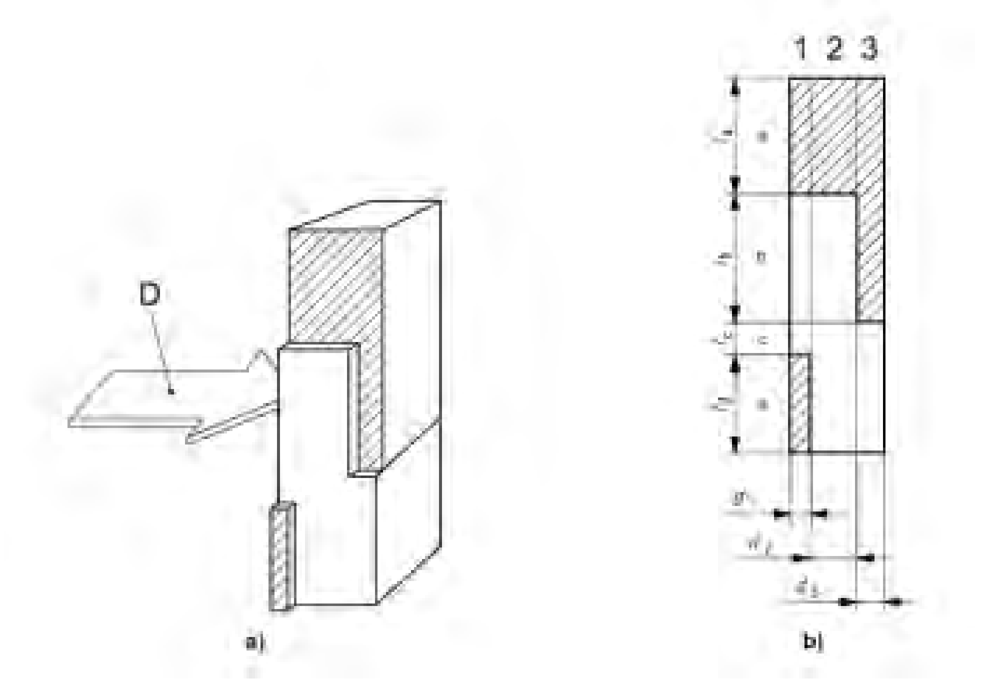


Figure B- 1: Illustration for fractional area of a construction element (BSI, 2007a).

The upper resistance limit ($R_U$) is determined by assuming one-dimensional heat flow is perpendicular to the surfaces of the component. It is obtained by the equation given below:

$$\frac{1}{R_U} = \frac{f_a}{R_{Ta}} + \frac{f_b}{R_{Tb}} + \frac{f_c}{R_{Tc}} + \frac{f_d}{R_{Td}} \tag{B-6}$$

Where: $f_a$, $f_b$ ... are fractional area of each section, that overall sum is equal to 1 (as shown in Figure B-1)

And $R_{Ta}$. $R_{Tb}$ ... are the total thermal resistances from environment to environment through each section which are calculated by Equation B-4.

And the lower limit of the total thermal resistance ($R_{L)}$ is determined by assuming that all planes parallel to the surfaces of the component are isothermal surfaces.

$$R_L = R_{se} + \sum R_i + R_{si} \tag{B-7}$$

With the equivalent thermal resistance for a thermally inhomogeneous layer ($R_i$) is obtained by using:

$$\frac{1}{R_i} = \frac{f_a}{R_{ai}} + \frac{f_b}{R_{bi}} + \frac{f_c}{R_{ci}} + \frac{f_d}{R_{di}} \tag{B-8}$$

The thermal transmittance is then calculated as:

$$U = \frac{1}{R_T} \tag{B-9}$$

Corrections shall be applied if the total correction exceeds 3% of U. These corrections take account for effects of air voids' presence within insulation and mechanical fasteners penetrating into an insulation layer.

Determine corrections to thermal transmittance for air gaps ($\Delta U_g$) and mechanical fasteners ($\Delta U_f$).

The correction for air voids is adjusted in accordance with the formula:

$$\Delta U_g = \Delta U'' \left( \frac{R_g}{R_o} \right)^2 \tag{B-10}$$

With $R_o$ is total thermal transmittance ignoring any thermal bridging occurs; $R_g$ is the thermal resistance of layer containing air gap and $\Delta U''$ is correction factor for air gap given in Table D1 in (BSI, 2007a).

The correction for mechanical fasteners is adjusted in accordance with the formula:

$$\Delta U_f = \alpha \times \frac{\lambda_f \times A_f \times n_f}{d_o} \left( \frac{R_g}{R_o} \right)^2 \tag{B-11}$$

Where:

$\alpha$ is the coefficient taken as $\alpha = 0.8.d/d_o$, with d is the length of the fastener that penetrates the insulation layer, $d_o$ the thickness of the insulation layer containing the fastener, $A_f$ is the cross-sectional area of one fastener ($m^2$), $n_f$ is the number of fasteners per square metre, $\lambda_f$ is the thermal conductivity of the fastener (W/mK)

U-value accounting for mechanical fasteners and air voids is then obtained by:

$$U = \frac{1}{R_T} + \Delta U_g + \Delta U_f \tag{B-12}$$

The standard permits $\Delta U_g$ and $\Delta U_f$ to be omitted if, taken together, their sum is no greater than 3% of the U-value.

### *B.1.1.1.2 Windows or glazed elements*

The calculation method follows the guidance from BS EN 10077-1:2006: “Thermal performance of windows, doors and shutters - Calculation of thermal transmittance - Part 1: General”. An illustration of a window composition is given in Figure B-2 below:

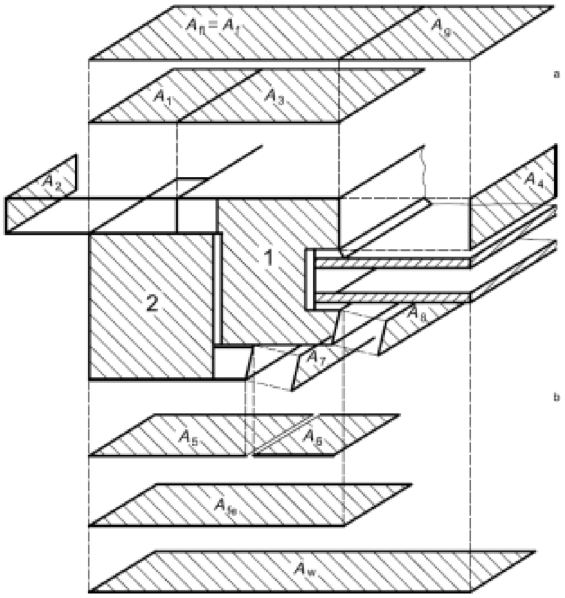


Figure B- 2: Illustration of various areas of a double glazed window (BSI, 2006b)

Note: 1- Sash (moveable)/ 2 - Frame (fixed) and a - Internal/ b- External.
Calculation of the thermal transmittance of a double glazed window, $U_w$ as a whole is given in Equation B-13.

$$U_w = \frac{\sum A_g U_g + \sum A_f U_f + \sum p_{wf} \Psi_s}{\sum A_g + \sum A_f} \tag{B-13}$$

$U_g$ – thermal transmittance of glazing (W/m$^2$K)
$U_f$ – thermal transmittance of frame (W/m$^2$K)
$\Psi_f$ – linear thermal transmittance due to combined thermal effects of glazing, spacer and frame (W/ mK)
$A_g$ - projected area of the glazing (m$^2$)
$A_f$ – projected area of the window frame or sash (m$^2$) as illustrated in Figure B-2
$A_{f,di} = A_1 + A_2 + A_3 + A_4$; $A_{f,de} = A_5 + A_6 + A_7 + A_8$. Thus $A_f = \max(A_{f,i}; A_{f,e})$

*Thermal transmittance of glazed area:*

Calculation of method of the thermal transmittance of glazing follows the BS EN 673:1998 : “Glass in building - Determination of thermal transmittance (U value) - Calculation method”(BSI, 2007b).

U-value is calculated by the following formula:

$$\frac{1}{U}=\frac{1}{h_e}+\frac{1}{h_t}+\frac{1}{h_i} \tag{B-14}$$

$h_e$ – external heat transfer coefficient (standardized to 23 W/ m$^2$K); 1/ $h_e$ = 0.04 (m$^2$K/W);
$h_i$ – internal heat transfer coefficient is equal to sum of radiation and convection conductance; 1/ $h_i$ = 0.13 (m$^2$K/W);
$h_t$ – total thermal conductance of the glazing (W/m$^2$K) which is determined by:

$$\frac{1}{h_t}=\sum_{1}^{N}\frac{1}{h_s}+\sum_{1}^{M}d_j r_j \tag{B-15}$$

$h_s$ - Thermal conductance of each gas space; $d_j$ is the thickness of each material layer;
$r_j$ is the thermal resistivity of each material (thermal resistivity of soda lime glass = 1,0 (mK/W);
N is the number of spaces, N=1; M is the number of material layers, M=2

Thermal conductance of gas space consists of radiation conductance ($h_r$) and conductance of gas filled in the space ($h_g$):

$$h_s = h_r + h_g \tag{B-16}$$

Where radiation conductance is determined by:

$$h_r = 4\sigma\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_1}-1\right)^{-1} T_m^3 \tag{B-17}$$

Gas conductance is sum of gas filled conductance and air conductance with the associated fraction. The gas conductance is given by:

$$h_g = Nu\frac{\lambda}{s} \tag{B-18}$$

With the Nusset number of argon is calculated by:

$$Nu_1 = A(Gr_1\, Pr_1)^n \tag{B-19}$$

Where: A is a constant, A=0.035; n is an component, n=0.38
Grashof number Gr of gas filled into the air space is calculated by:

$$Gr = \frac{9.81 s^3 \Delta T \rho^2}{T_m \mu^2} \qquad \text{(B-20)}$$

Prandtl number Pr of Argon is calculated by:

$$Pr = \frac{\mu c}{\lambda} \qquad \text{(B-21)}$$

*<u>Thermal transmittance of frames</u>*

Calculation of method of the thermal transmittance of window frames follows the BS EN ISO 10077-2: 2003 “Thermal performance of windows, doors and shutters - Calculation of thermal transmittance - Part 2: Numerical method for frames” (BSI, 2003b). According to Annex C (BSI, 2003b), the thermal transmittance of a frame section and the linear thermal transmittance of the interaction of frame and glazing is determined with the glazing replaced by an insulating panel (thermal conductivity $\lambda$= 0.035 W/mK).

The thermal transmittance of the glazing, $U_g$ as discussed above is applicable to the centre area of the glazing but it does not include the effect of the spacer at the edge of the glazing. The thermal transmittance of the frame, $U_f$ as presented in this section is applicable with absence of the glazing. The linear thermal transmittance $\psi$ as shown in Equation B-13 describes the additional heat flow as a result of the interaction between the frame and the glass edge that also includes the effect of the spacer.

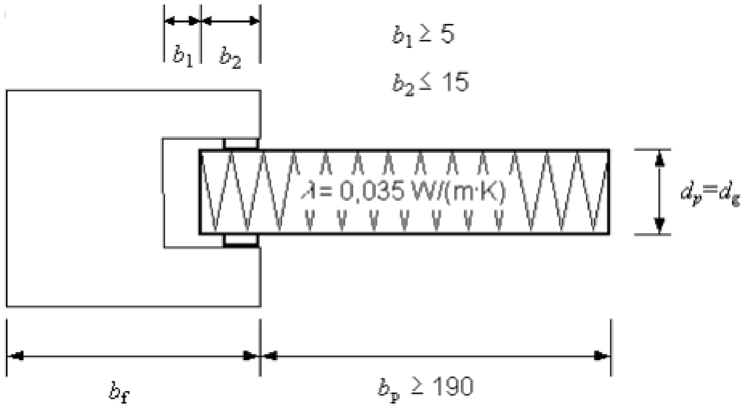


Figure B- 3: Profile section of panel installed (BSI, 2003b)

The thermal transmittance of the frame $U_f$ is determined by:

$$U_f = \frac{L_f^{2D} - U_p b_p}{b_f} \qquad \text{(B-22)}$$

Where

$U_f$ is the thermal transmittance of the frame section, in W/(m2×K);

$U_p$ is the thermal transmittance of the central area of the panel, in W/(m2×K);

$b_f$ is the projected width of the frame section, in m;

$b_p$ is the visible width of the panel, in m.

$L_f^{2D}$ is the thermal conductance of the section consisting window frame and insulating panel as shown in Figure B- 3, in W/(m×K). It is calculated from the total heat flow rate per length through the section divided by the temperature difference between both adjacent environments.

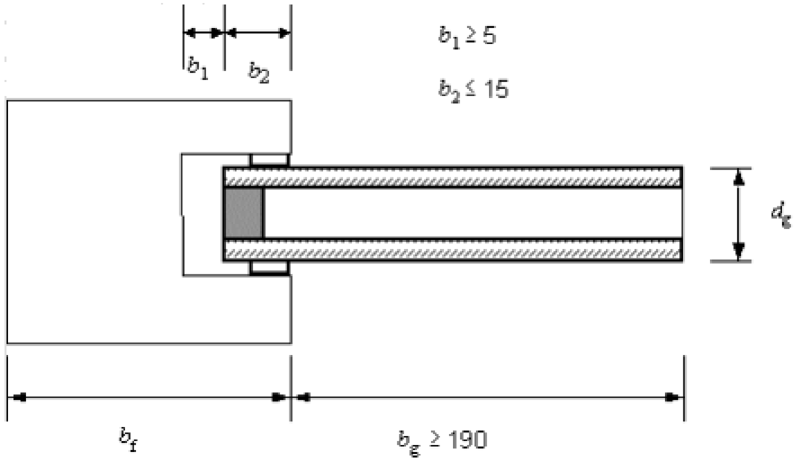


Figure B- 4: Profile section with the presence of glass panels (BSI, 2003b).

$$\psi = L_f^{2D} - U_f b_f - U_g b_g \tag{B-23}$$

Where

$\psi$ is the linear thermal transmittance, in W/(m.K);

$L_f^{2D}$ is the thermal conductance of the section shown in Figure B-4, in W/(m.K);

$U_f$ is the thermal transmittance of the frame section, in W/($m^2$K);

$U_g$ is the thermal transmittance of the central area of the glazing, in W/($m^2$K);

$b_f$ is the projected width of the frame section, in m;

$b_g$ is the visible width of the glazing, in m.

#### *B.1.1.2 Linear thermal transmittance (thermal bridging)*

Beside the thermal bridges were taken into account in the calculation of U-value (known as repeating thermal bridging), this section briefly explains the calculation of geometrical thermal bridges (known as non repeating thermal bridging). The heat flow and temperature distribution can be calculated only when boundary conditions and constructional details are known. A single geometrical model is not usually applicable for modelling a complete building. In most cases, the cut-off planes could be used for dividing the building into several parts such that the geometrical model is decomposed into a number of adjacent material cells each of which contains a homogeneous thermal conductivity (BSI, 2003a). The Standard also gives guidance regarding the location of cut-off planes: at symmetry plane if this is less than one meter from the central element or at least one meter from the central element otherwise. In order to simplify geometrical model, materials with different thermal conductivities can be replaced by material with a single thermal conductivity known as quasi homogeneous layer under several conditions discussed in Section 5.2 in (BSI, 2003a).

The calculation of the transmission heat transfer coefficient taking account of thermal bridges is given by Equation B-24

$$H_D = \sum_f A_f U_f + \sum_k l_f \psi_f + \sum_j \chi_j \tag{B-24}$$

Where:

$A_i$ is the area of element i of the building envelope, in $m^2$;
$U_i$ is the thermal transmittance of element i of the building envelope, in $W/(m^2K)$;
$l_k$ is the length of linear thermal bridge k, in m;
$\Psi_k$ is the linear thermal transmittance of linear thermal bridge k, in W/(m.K);
$\chi_j$ is the point thermal transmittance of the point thermal bridge j, in W/K.

The linear thermal bridges are formed at junctions between external elements (corner of walls, wall to roof and wall to floor), at junctions of internal walls with external walls and with roof, at junctions of intermediate floor with external wall and around openings (windows and doors). The point thermal bridges (or 3D thermal bridges) are the result of two or three intersection linear thermal bridges. In general, the influence of point thermal bridges can be neglected (BSI, 2007c).

The assumptions employed for simplified calculation approach are listed below:

- Steady-state conditions
- All physical properties are independent of temperature
- There are no heat sources within the building element
- Only one internal thermal environment applies
- One or two external thermal environments apply.

Under conditions satisfying the above assumptions, the linear thermal transmittance (Ψ-value) of the two dimensional junction is determined by the thermal coupling coefficient between the internal and external environments ($L^{2D}$) subtracted for the one dimensional heat flow through all flanking elements, expressed in W/mK as below:

$$\psi = L^{2D} - \sum (U \times l) \tag{B-25}$$

Where:

U is the U-value of the flanking element, in W/m$^2$K
l is the length over which U applies, in m

The thermal coupling coefficient is determined from:

$$L^{2D} = \frac{Q}{T_i - T_e} \tag{B-26}$$

Q is the total heat flow from the internal to the external environment.
$T_i$ and $T_e$ are the temperatures of the internal and external environments.

### *B.1.1.2.1 Temperature factor, $f_{Rsi}$*

The temperature factor $f_{Rsi}$, is used to assess the risk of surface condensation or mould growth on any detail. It is calculated under steady state conditions by the following formula:

$$f_{Rsi} = \frac{T_{si} - T_e}{T_i - T_e} \tag{B-27}$$

Where

$T_{si}$ is the surface temperature.
$T_i$ is the internal environmental temperature and $T_e$ is the temperature of the external environment.

In order to check whether surface condensation or mould growth become issue, the temperature factor should not be less than the critical temperature factors ($f_{CRsi}$) set out in Table 1 and Table 2 in BRE Information Paper IP 1/06 (Ward, 2006).

Or regarding the presence of thermal bridges within the construction, the minimum value of $f_{Rsi}$ is introduced to assess condensation free or mould free of interior surface. The calculation method is given in BS EN ISO 10211:2.

At the junctions of three intersecting linear thermal bridges, the minimum value of the temperature factor ($f_{Rsi}^{3D}$) is determined as below:

$$f_{Rsi}^{3D} = \frac{1}{\frac{1}{f_{Rsi}^{2D,x}} + \frac{1}{f_{Rsi}^{2D,y}} + \frac{1}{f_{Rsi}^{2D,z}} - \frac{2}{f_{Rsi}^{1D}}} \qquad \text{(B-28)}$$

Where:

$f_{Rsi}^{2D}$ (x, y, z - axis) is minimum temperature factor of the linear thermal bridges along the x, y or z axis.

$f_{Rsi}^{1D}$ is the arithmetic mean value of the temperature factors of the thermally homogeneous parts of the envelope adjacent to the linear thermal bridges.

When there is only two linear thermal bridges intersect, Equation B-28 can be applied, using the formula:

$$f_{Rsi}^{3D} = \frac{1}{\frac{1}{f_{Rsi}^{2D,x}} + \frac{1}{f_{Rsi}^{2D,y}} - \frac{2}{f_{Rsi}^{1D}}} \qquad \text{(B-29)}$$

The temperature factor of the thermally homogeneous construction of the building envelope is given below:

$$f_{Rsi}^{1D} = \frac{R_t + R_{se}}{R_t + R_{se} + R_{si}} \qquad \text{(B-30)}$$

## B.1.2 Non steady state calculation

The admittance method, employed in the thesis, is concerned with the internal building response to a cyclic variation in external conditions as the thermal response depends on constructional composition of the building envelope. There are several methods to assess the non-steady state of a structure. One of the simplest one is the admittance procedure which is employed in many BPS tools and this also is presented and applied in CIBSE guides of calculation. The method of calculation of dynamic thermal characteristics is given in BS EN ISO 13786:2007 (BSI, 2007d).

### *B.1.2.1 Assumptions and calculation procedure*

The admittance procedure requires the calculation of three parameters in addition to thermal transmittance: admittance factor, decrement factors and surface response factor. Each response factor has an associated time lag/lead, where the construction causes a phase shift in the periodic variation in internal temperature to the external sol-air temperature (BSI, 2007d).

Admittance factor (Y, W/m$^2$K) represents the thermal storage capacity of the constructional elements and is measured by the ratio of heat flux (environment node to internal surface) to the temperature deviation from the environmental. Decrement factor (f) shows the dynamic variation in temperatures between internal and external environments and is calculated by the ratio of external heat wave amplitude to the internal heat wave amplitude. Surface response factor (F) is the ratio of the variation of heat flow about its mean value readmitted to the space from the surface, to that about the mean value absorbed by the surface.

The above procedure applies to building components consisting of plane homogeneous layers. Thermal bridges usually present in such building components do not affect significantly the dynamic thermal characteristics, and can hence be neglected.

Some typical building components of the test building are manually calculated in respect the following calculation process:

- Identify the materials comprising the layers of the building component and the thickness of these layers, and determine the thermal characteristics of the materials (thermal conductivity (λ, W/m.K), density (ρ, kg/m$^3$) and specific heat capacity (c, J/kg.K).).
- Specify the period of the variations at the surfaces.
- Calculate the penetration depth for the material of each layer.
- Determine the elements of the heat transfer matrix for each layer.
- Multiply the layer heat transfer matrices, including those of the boundary layers, in the correct order, so as to obtain the transfer matrix of the component.

### *B.1.2.2 Calculation method*

From the Fourier Heat equation:

$$\frac{\partial^2\theta}{\partial x^2} = \frac{1}{\alpha}\frac{\partial\theta}{\partial t} \qquad \text{(B-31)}$$

α represents thermal diffusivity which takes account of thermal conductivity and heat flux. It is calculated by the formula below:

$$\alpha = \frac{\lambda}{\rho c} \qquad \text{(B-32)}$$

The admittance method assumes a periodic cycle (usually 24 hours) for external temperature and heat flux variation. The response of the internal environment to the external cyclical conditions is dependent on the diffusivity of each layer. This is described by a periodic penetration depth ($\delta$) (See Equation B-33).

Where the amplitude of the sinusoidal variation in external sol-air temperature is reduced by a factor of e (e=2.781). The sol-air temperature is a hypothetical value that represents heat flux by at the external surface by convective and radiative processes. Further details of sol-air temperature can be found in CIBSE guide J: Weather, solar and illuminance data (CIBSE, 2002).

The periodic penetration depth for the material of the layer is calculated from its thermal properties and the period T as followed:

$$\delta = \sqrt{\frac{\lambda T}{\pi \rho c}} \tag{B-33}$$

For a 24-hour cycle: T = 86400s.

The ratio of the thickness of the layer to the penetration depth is then given by:

$$p = \frac{d}{\delta} \tag{B-34}$$

With d is the thickness of the material layer, in meter.

Using Laplace transformation to solve Equation B-31 for a given construction under specific environmental conditions ($t_{1,2}$ are temperatures on side 1 or 2, °C) on two sides represented in matrix form as seen in Equation B-35. In this equation, the matrix Z represents the product of the matrices for each layer in the construction.

$$\begin{bmatrix} t_2 \\ q_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} t_1 \\ q_1 \end{bmatrix} \tag{B-35}$$

Where q, the heat flux, $q = -\lambda\, \partial\theta/\partial x$ (W/m$^2$).

The matrix elements of Z are given as:

$$
\begin{aligned}
&Z_{11} = Z_{22} = \cosh p \cdot \cos p + \sinh p \cdot \sin p;\\
&Z_{12} = -\frac{\delta}{2\lambda}\left[\sinh p \cdot \cos p + \cosh p \cdot \sin p + j\left(-\sinh p \cdot \cos p + \cosh p \cdot \sin p\right)\right]\\
&Z_{21} = -\frac{\lambda}{\delta}\left[\sinh p \cdot \cos p - \cosh p \cdot \sin p + j\left(\sinh p \cdot \cos p + \cosh p \cdot \sin p\right)\right]
\end{aligned}
\qquad \text{(B-36)}
$$

With:

$$
\cosh p = \frac{\left(e^{p} + e^{-p}\right)}{2}; \quad \sinh p = \frac{\left(e^{p} - e^{-p}\right)}{2} \qquad \text{(B-37)}
$$

The matrix elements can then be obtained as below:

$$
\begin{aligned}
&Z_{11} = Z_{22} = \frac{1}{2}\Big[\Big(e^{p} + e^{-p}\Big) \cdot \cos p + \Big(e^{p} - e^{-p}\Big) \cdot \sin p\Big];\\
&Z_{12} = -\frac{d}{4\lambda p}\Big[\Big(e^{p} - e^{-p}\Big) \cdot \cos p + \Big(e^{p} + e^{-p}\Big) \cdot \sin p + j\Big(-\Big(e^{p} - e^{-p}\Big) \cdot \cos p + \Big(e^{p} + e^{-p}\Big) \cdot \sin p\\
&Z_{21} = -\frac{\lambda p}{2d}\Big[\Big(e^{p} - e^{-p}\Big) \cdot \cos p - \Big(e^{p} + e^{-p}\Big) \cdot \sin p + j\Big(\Big(e^{p} - e^{-p}\Big) \cdot \cos p + \Big(e^{p} + e^{-p}\Big) \cdot \sin p\Big)\Big]
\end{aligned}
\qquad \text{(B-38)}
$$

The heat transfer matrix of the building component from surface to surface is given by:

$$
Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = Z_N \cdot Z_{N-1} \cdot \ldots Z_2 \cdot Z_1 \qquad \text{(B-39)}
$$

Where $Z_N, \ldots, Z_1$: are the heat transfer matrices of the various layers of the building component.

As for conventions for building envelope components, layer 1 shall be the innermost layer.

The heat transfer matrix from environment to environment through the building component is given by:

$$
Z_{ee} = Z_{a2} Z Z_{a1} \qquad \text{(B-40)}
$$

Where $Z_{s2}$ and $Z_{s1}$ are the heat transfer matrices of the boundary layers as below:

$$
Z_s = \begin{bmatrix} 1 & -R_s \\ 0 & 1 \end{bmatrix} \qquad \text{(B-41)}
$$

With $R_s$ is the surface resistance of the boundary layer.

For air cavity, the heat transfer matrix has the same form and thermal resistance of the boundary layer is replaced by $R_a$ is the thermal resistance of the air layer. Value of surface resistances and thermal resistance of air cavity can be referred to BS EN ISO 6496:2007.

The non-steady state parameters are now derived as follows:

Thermal admittance (Y) and periodic thermal conductance are calculated by:

$$Y_{11} = -\frac{Z_{11}}{Z_{12}}; \quad Y_{22} = -\frac{Z_{22}}{Z_{12}} \tag{B-42}$$

Where $Y_{11}$ is for internal side of the component and $Y_{22}$ is for the external side.

The time shift of admittance is calculated as below:

$$\omega_1 = \frac{T}{2\pi}\arctan\left(\frac{\mathrm{Im}(Y_{11})}{\mathrm{Re}(Y_{11})}\right); \quad \omega_2 = \frac{T}{2\pi}\arctan\left(\frac{\mathrm{Im}(Y_{22})}{\mathrm{Re}(Y_{22})}\right) \tag{B-43}$$

With the arctangent is evaluated within the range from 0 to 2π radius.

Periodic thermal transmittance and decrement factor (f) are determined by:

$$Y_{12} = -\frac{1}{Z_{12}} \tag{B-44}$$

$$f = \frac{|Y_{12}|}{U_o} \tag{B-45}$$

With $U_o$ is the thermal transmittance of the element whilst ignoring any thermal bridging. The decrement factor f is always less than 1.

The time shift of the periodic thermal transmittance (time lag).is given below:

$$\phi = \frac{T}{2\pi}\arctan\left(\frac{\mathrm{Im}(f)}{\mathrm{Re}(f)}\right) \tag{B-46}$$

The arctangent should be evaluated in the range –2π to 0 radians.

The surface response factor and surface factor time lag are determined below:

$$F = 1 - R_{si}\left(Y_{22}\right) \tag{B-47}$$

$$\psi = \frac{T}{2\pi}\arctan\left(\frac{\mathrm{Im(F)}}{\mathrm{Re(F)}}\right) \tag{B-48}$$

For internal partitions within a building, where the temperature variations are the same on either side of the partition, the periodic heat flow is related to the periodic temperature variations by a modified admittance.

For internal partitions, the decrement factor is combined with the admittance and surface factor. The modified admittance value is determined by:

$$Y_{11}^{*} = Y_{11} - Y_{12} = -\frac{Z_{11}-1}{Z_{12}}; \quad Y_{22}^{*} = Y_{22} - Y_{12} = -\frac{Z_{22}-1}{Z_{12}} \tag{B-49}$$

And the time shift is then obtained:

$$\omega = \frac{T}{2\pi}\arctan\left(\frac{\mathrm{Im}(Y^{*})}{\mathrm{Re}(Y^{*})}\right) \tag{B-50}$$

### B.1.3 Analytical verification method

An initial check for the model simulation is executed by comparison with a simple method, the steady state heat loss calculation which is in use for sizing the heater. The first section will present the calculation method which utilises CIBSE simple model and the second section will look at CIBSE admittance method, using cyclic model.

#### *B.1.3.1 Steady state heat loss*

The previous CIBSE guide A published in 1999 utilises the Approximate Model in which the environmental temperature was used as the steady state design temperature for heating. The total heat loss is the sum of fabric and ventilation losses is determined by:

$$\Phi_t = \left[\sum(AU) + C_v\right](t_{ei} - t_{ao}) \tag{B-51}$$

Where:

$\Phi_t$ is the total heat loss (W), Σ (A U) is sum of the products of surface area and corresponding thermal transmittance over surfaces through which heat flow occurs (W/K), $C_v$ is the ventilation conductance (W/K), $t_{ei}$ is the inside environmental temperature and $t_{ao}$ is the outside air temperature (°C).

The ventilation conductance is calculated by:

$$C_v = \frac{1}{3} \times N \times V \tag{B-52}$$

With N is the number of room air change for air entering the space at the outside air temperature (1/h) and V is the building volume ($m^3$).

In the latest version, (CIBSE, 2006a) proposes CIBSE simple model beside the previous model which enables designer to size emitters to achieve a specified operative temperature. This model adds in 2 factors $F_{1cu}$ and $F_{2cu}$ given by:

$$F_{1cu} = \frac{3\left(C_v + 6\sum A\right)}{\sum(AU) + 18\sum A + R\left[3C_v - \sum(AU)\right]} \tag{B-53}$$

$$F_{2cu} = \frac{\sum(AU) + 18\sum A}{\sum(AU) + 18\sum A + R\left[3C_v - \sum(AU)\right]} \tag{B-54}$$

And the total heat loss is determined by:

$$\Phi_t = \left[F_{1cu} \times \sum\left(AU\right) + F_{2cu} \times C_v\right]\left(t_c - t_{ao}\right) \tag{B-55}$$

$F_{1cu}$ and $F_{2cu}$ are factors related to characteristics of the heat sources with respect to the operative temperature, $t_c$ is the designed operative temperature at the centre of the room (°C).

It is also noted that in a well insulated buildings without large areas of glazing and low air change rates, there is usually very little difference between the environmental temperature, operative temperature and air temperature. Then the total heat loss in CIBSE simple model can simply determined by the Approximate Model ($F_{1cu}$ and $F_{2cu}$ are approximately unity).

Indoor air temperature is then calculated by:

$$t_{ai} = \frac{\Phi_t(1-1.5R) + C_v \times t_{ao} + 6\sum A \times t_c}{C_v + 6\sum A} \tag{B-55}$$

And mean surface temperature within the room is given by:

$$t_m = 2t_c - t_{ai} \tag{B-56}$$

In case where the fabric loss contains heat loss through internal partitions, a modified U-value should be used

$$U' = \frac{U(t_c - t_c')}{(t_c - t_{ao})} \tag{B-57}$$

Where U' is the thermal transmittance modified for heat loss through internal partitions ($W/m^2K$) and $t_c$' is the operative temperature on the opposite side of partition through which heat flow occurs (°C).

### *B.1.3.2 Calculation of cooling requirement using dynamic model*

Because the CIBSE cyclic model is "best suited" to the calculation of space cooling loads, this is selected for analytical verification of the model simulation. In the cyclic model, the analysis is carried out using a sequence of identical days for which the external conditions vary on a 24 hour cyclic basis (CIBSE, 2006a). In this section, CIBSE admittance method is in use for numerical verification.

Calculation of peak temperature in hot days applies the CIBSE Simple Model which utilises the sol air temperature. It is defined as the hypothetical outside surface temperature which, in the absence of solar and long-wave radiation, would give the same temperature distribution within and the same rate of energy transfer through a wall or roof, as exists with the actual outside air temperature, surface wind speed, incident solar radiation and incident long-wave radiation (CIBSE, 2002).

#### *B.1.3.2.1 Determination of mean heat gains from all sources:*

*Solar heat gain:*

Solar gains through glazing consist of solar radiation, which is absorbed in the glazing and transmitted to the environmental node and also the transmitted solar radiation, which is absorbed at the internal surfaces of the room and appears at the environmental node.

The mean solar heat gain to the internal environmental node is given by:

$$\bar{\Phi}_{se} = \bar{S}_e \times \bar{I}_t \times A_g \tag{B-58}$$

Where

$\bar{\Phi}_{se}$ is the mean solar heat gain to the environmental node (W),

$\overline{S}_e$ is the mean solar gain factor at the environmental node,

$\overline{I}_t$ is the mean total solar irradiance (W/m$^2$)

A$_g$ is glazing area (m$^2$)

*Internal heat gain (if applicable)*

The mean heat gain from internal sources such as occupants, lighting, computers etc. is calculated by multiplying each individual load by its duration, summing over all sources and averaging the total over 24 hours. It is assumed that all the internal gains are to the environmental node. Hence:

$$\overline{\Phi}_c = \frac{\sum \Phi_{in} \times t_{in}}{24} \tag{B-59}$$

$\overline{\Phi}_c$ is the mean internal heat gain (W)

$\Phi_{in}$ is the instantaneous heat gain from each internal heat source (W)

t$_{in}$ is the duration of each internal heat source (h).

*Mean structure heat gain*

The mean gain due to transmission through the fabric is calculated by summing the mean gains through the external opaque and glazed surfaces:

$$\overline{\Phi}_f = \sum (AU) \times \overline{t}_{eo} + \sum (A_g U_g) \times \overline{t}_{ao} \tag{B-60}$$

Where

$\overline{\Phi}_f$ is the mean fabric heat gain (W),

$\overline{t}_{ao}$ and $\overline{t}_{eo}$ is the mean air and sol air temperature (°C)

*Total gains to the environmental node:*

The total gain to the environmental node is given by:

$$\overline{\Phi}_{te} = \overline{\Phi}_{se} + \overline{\Phi}_{in} + \overline{\Phi}_f \tag{B-61}$$

*Total gain to the air node*

The total gain to air node is calculated by:

$$\overline{\Phi}_{ta} = \overline{\Phi}_{sa} + \overline{\Phi}_{av} \tag{B-62}$$

Where: $\bar{\Phi}_{ta}$ is the mean total gain to the air node (W)

$\bar{\Phi}_{sa}$ is the mean solar heat gain to the air node (W)

$\bar{\Phi}_{av}$ is the mean ventilation heat gain which is determined by: $\bar{\Phi}_{av} = C_v \bar{t}_{ao}$

With: $C_v$ is ventilation loss (W/K) and $\bar{t}_{ao}$ is the mean outside air temperature (°C).

#### *B.1.3.2.2 Mean internal operative temperature:*

For a fixed ventilation rate the difference between the mean operative temperature and the outside air temperature is given by:

$$\bar{t}_c = \frac{\bar{\Phi}_{ta} + F_{cu}\bar{\Phi}_{te}}{C_v + F_{cu}\sum(AU)} \qquad \text{(B-63)}$$

$\bar{t}_c$ is the mean operative temperature at the centre of the room (°C) and $F_{cu}$ is the room conductance corrector with respect to operative temperature and determined by:

$$F_{cu} = \frac{3\left(C_v + 6\sum A\right)}{\sum(AU) + 18\sum A} \qquad \text{(B-64)}$$

#### *B.1.3.2.3 Determination swing (deviation) mean to peak in all heat gain sources*

*Swing in solar gain:*

The swing in solar heat gain to the internal environmental node is given by:

$$\tilde{\Phi}_{se} = \tilde{S}_e \times A_g \times \left(\hat{I}_t - \bar{I}_t\right) \qquad \text{(B-65)}$$

With $\tilde{\Phi}_{se}$ is the swing in solar gain to environmental node (W)

$\tilde{S}_e$ is the cyclic solar gain factor at the environmental node

$\hat{I}_t$ is the peak total solar irradiance (W/m$^2$)

*Swing in internal gain (if applicable)*

At the assumed of peak load:

$$\tilde{\Phi}_c = \hat{\Phi}_c - \bar{\Phi}_c \qquad \text{(B-66)}$$

Where $\tilde{\Phi}_c$ is the swing in internal gain (W)

$\hat{\Phi}_c$ is the peak internal gain, taken as the sum of all internal gains within the space (W).

*Swing in structure gain*

The swing in sol air temperature is given by

$$\tilde{t}_{eo} = t_{eo} - \bar{t}_{eo} \tag{B-67}$$

Where $\tilde{t}_{eo}$ is the swing in sol air temperature (°C)

$t_{eo}$ is the sol-air temperature at the time (t – ø) (°C)

t is the time when peak temperature occurs and ø is the time lag associated with the decrement factor f of the structure (h).

The swing in effective heat input due to fabric heat gains is given by:

$$\tilde{\Phi}_f = \sum_n f_n A_n U_n \tilde{t}_{eo} + \sum_n f_{gn} A_{gn} U_{gn} \tilde{t}_{ao} \tag{B-68}$$

Where $\tilde{\Phi}_f$ the swing in fabric heat gain (W)

$f_n$ is the decrement factor for (opaque) surface n

$A_n$ is the area of (opaque) surface n ($m^2$)

$U_n$ is the thermal transmittance of (opaque) surface n ($W/m^2K$)

$\tilde{t}_{eo}$ is the swing in sol-air temperature (K)

$f_{gn}$ is the decrement factor for glazed surface n

$A_{gn}$ the area of glazed surface n which does not include frame area ($m^2$)

$U_{gn}$ is the thermal transmittance of glazed surface n ($W/m^2K$)

$\tilde{t}_{ao}$ is the swing in outside air temperature (K) at time t and determined by $\tilde{t}_{ao} = t_{ao} - \bar{t}_{ao}$.

For glass, $f_g = 1$ and time lag corresponding to decrement factor ø = 0.

*Swing in heat gain from ventilation*

The swing in heat gain is given by:

$$\tilde{\Phi}_{av} = C_v \tilde{t}_{ao} \tag{B-69}$$

*Total swing in heat gains:*

$$\tilde{\Phi}_{te} = \tilde{\Phi}_{se} + \tilde{\Phi}_{in} + \tilde{\Phi}_f \tag{B-70}$$

$$\tilde{\Phi}_{ta} = \tilde{\Phi}_{sa} + \tilde{\Phi}_{av} \tag{B-71}$$

#### B.1.3.2.4 Swing in operative temperature

The swing in internal operative temperature is determined by:

$$\tilde{t}_c = \frac{\tilde{\Phi}_{ta} + F_{cy}\tilde{\Phi}_{te}}{C_v + F_{cy}\sum(AY)} \qquad \text{(B-72)}$$

With Fcy is the room admittance factor with respective to operative temperature and calculated by:

$$F_{cy} = \frac{3\left(C_v + 6\sum A\right)}{\sum(AY) + 18\sum A} \qquad \text{(B-73)}$$

The peak temperature is then calculated by:

$$\hat{t}_c = \bar{t}_c + \tilde{t}_c \qquad \text{(B-74)}$$

#### B.1.3.2.5 Cooling load calculation

As recommended thermal comfort criteria employs operative temperature therefore cooling load is designed based on controlling of operative temperature.

The total sensible cooling is given by:

$$\Phi_k = \bar{\Phi}_a + \tilde{\Phi}_a + \Phi_{sg} + \Phi_v \qquad \text{(B-75)}$$

Where:

$\Phi_k$ is the total sensible cooling to the air node (W)

$\bar{\Phi}_a$ and $\tilde{\Phi}_a$ is the mean and swing convective cooling load (W)

$\Phi_{sg}$ is the cooling load due to windows and blind (W)

$\Phi_v$ is the cooling load related to ventilation (W).

With the mean and swing convective cooling load are determined as below:

$$\bar{\Phi}_a = \bar{\Phi}_{fa} + F_{cu} \times 1.5 \times \sum \bar{\Phi}_{rad} + \sum \bar{\Phi}_{con} - 0.5\sum \bar{\Phi}_{rad} \qquad \text{(B-76)}$$

And

$$\tilde{\Phi}_a = \tilde{\Phi}_{fa} + F_{cu} \times 1.5 \times \sum \tilde{\Phi}_{rad} + \sum \tilde{\Phi}_{con} - 0.5\sum \tilde{\Phi}_{rad} \;\; \hat{t}_c = \bar{t}_c + \tilde{t}_c \qquad \text{(B-77)}$$

Where:

$F_{cu}$ and $F_{cy}$ the room conductance and admittance factor with respect to operative temperature.

$\bar{\Phi}_{fa}$ is mean fabric heat gain to the air node (W)

$\tilde{\Phi}_{fa}$ is alternating component of the fabric gain to the air node.

$\bar{\Phi}_{rad}$ is daily mean radiant gain (W)

$\tilde{\Phi}_{rad}$ is alternating component of daily mean radiant gain (W)

$\bar{\Phi}_{con}$ is daily mean convective gain (W)

$\tilde{\Phi}_{con}$ is alternating component of daily mean convective gain (W)

And the cooling load related to ventilation is given by: $\Phi_v = C_v(t_{ao,t} - t_c)$

With $t_{ao,t}$ is the outside air temperature at the time t.

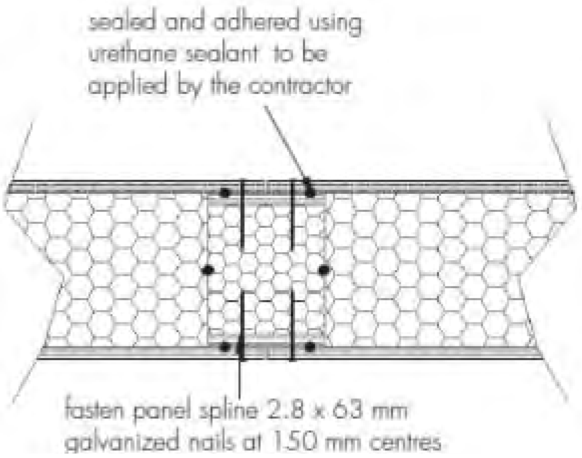
## *Appendix B.2 CALCULATION FOR THE TEST BUILDING*

This section includes a range of numerical applications for calculating the thermal transmittance of building elements. It provides information regarding building geometry, construction details and thermal properties of building materials used for the calculation of U-value, thermal bridges of external walls, pitched roof, suspended floor structure and windows.

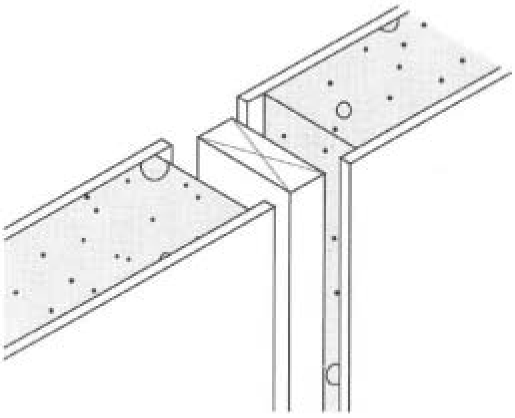
### B.2.1 U-value calculation

SIP system composed of OSB/3 (orientated strand boards grade 3 which are load bearing boards for use in humid conditions comply with the Harmonised Standard for wood-based panels (BSI, 2006a)) facings with a rigid insulation core. It is manufactured by injecting a precise blend of chemical polyurethane foam (PU) under high pressure between the OSB faces. This process autohesively bonds the OSB and the foam core together as the chemical reaction occurs, resulting in superior bond strength compared to lamination techniques, and guarantees a continuous bond across the entire surface area of the panel. Thermal conductivity of OSB in use of SIP system constructing the ErgoHome building unit is of 0.13 W/mK and that of polyurethane foam is of 0.025 W/mK (SIPCO, 2009).

For component connection, there is an amount of timber existing within the polyurethane layer where thermal bridges occur. The standard panel of SIPs structure in use is of 1200mm width therefore a total length of 11850mm of ErgoHome unit requires 10 panels connected one to another. There are two types of connection in use for the building unit: mini SIP spline (See Figure B-5a) and standard stud spline (See Figure B-5b).



a- Connection between two panels by mini SIP spline (SIPCO, 2009)



b- Connection between two panels by timber stud spline (Morley, 2000)

Figure B- 5: Two types of connections in SIP

For wall and roof structure, mini SIP splines were used for connections and standard stud splines were used for suspended timber floor structure as shown in Figure B-6.

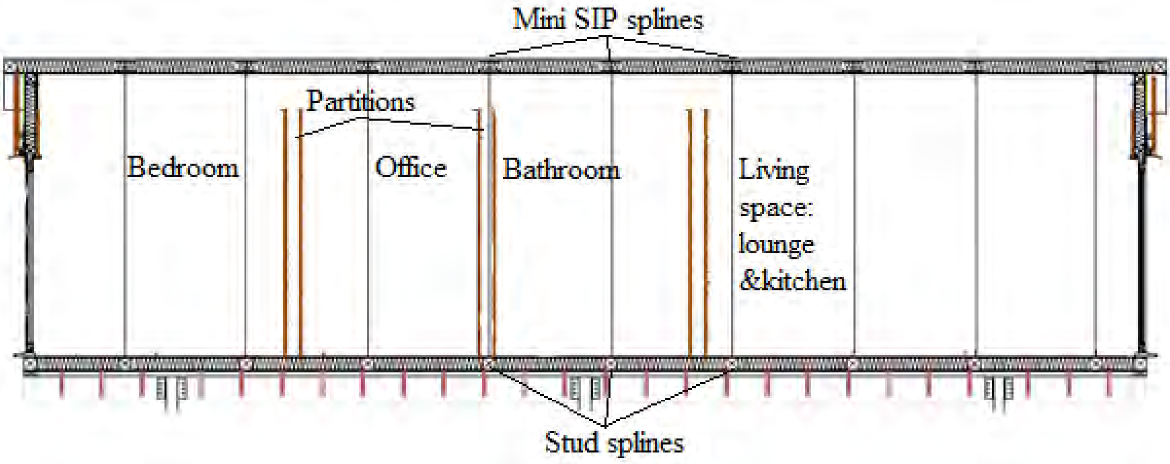


Figure B- 6: Building facade with stacked module (Chadwick, 2011).

### *B.2.1.1 External walls*

Ventilated air cavity in between the external cladding and SIPs system prevents mould growth on OSB face. Cedar timber cladding keeps the building system from wind driven rain. Vapour control layer is maintained to be continuous across the building envelope to prevent moisture entering into the structure causing condensation and mould growth. The total thermal resistance of a building component containing a well-ventilated air layer shall be obtained by disregarding the thermal resistance of the air layer and all other layers between the air layer and external environment, and including an external surface resistance corresponding to still air (BSI, 2007a).A typical wall construction of the test building unit is described in Figure B-7.

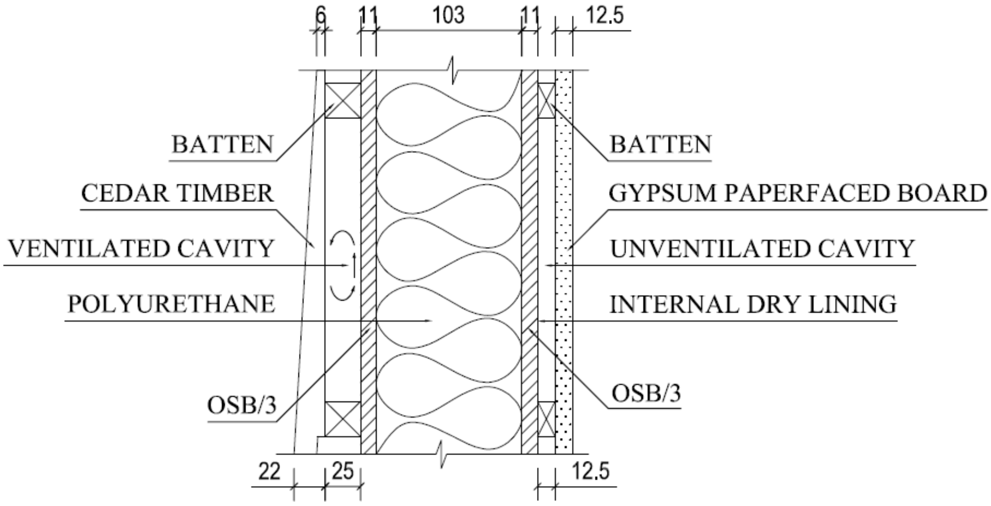


Figure B- 7: External wall construction

As the second layer with external to internal order is ventilated air cavity therefore the thermal resistance that includes external surface resistance, thermal resistance of cedar timber and air cavity is taken as same value of thermal resistance of internal surface. With regards the horizontal direction of the heat flow, the surface resistance is of 0.13 $m^2K/W$ (See Table 1 in (BSI, 2007a).

It is suggested that the timber fraction for thermal transmittance calculation of building elements excludes the amount of timber around the openings and at junctions between external walls and floor/roof according to Accredited Construction Details for timber frame construction (BRE, 2006). This also gives guidelines for calculating timber fraction that it excludes a zone around windows and doors of 50 mm at the sill and each jamb and 175mm at the top. The timber fraction includes any timber between the finished internal face of external wall/ partition, between the inside level of the ground floor and underside of the roof or ceiling of the top floor, and noggins and intermediate floor joints that are not insulated behind (BRE, 2006).

Determination of fractional area:

In order to build external wall of 11.85 meters length, SIPs system employs 10 panels of SIPs assembly one to another by 9 mini-SIPs (the connection refers to Figure B-6). SIP used for external wall structure consists of 2 OSB panels of 11mm thickness and polyurethane foam of 103mm thickness. Mini-SIPs of 300mm width constitutes of 2 OSB panels of 11mm thickness and polyurethane foam of 81 mm thickness.

Timber fraction accounting for the presence of 2 OSB of mini SIP splines within the polyurethane foam layer is determined by:

(2 x 0.011)/0.103 x (9x0.3)/11.85 = 0.05 or 5%

Timber fraction of dry lining cavity of 12.5 mm thickness is calculated taking account of 25mm timber battens at 600mm centre plus top and bottom plates for the height of 2.74 m:

0.025/0.6 + 2 x 0.025/2.74 = 0.06.

The dimensions and thermal properties of the components of the wall are given below

Table B- 1: Thermal properties of materials of external wall construction

| **N** | **Layer description** | **Thickness d** | **Conductivity λ** | **Resistance R** | **Fraction- f** |
|---|---|---|---|---|---|
| | | mm | W/m.K | $m^2K/W$ | - |
| | External air | | | $R_{se}$ = 0.13 | |
| 1. | Cedar timber | 14 | 0.19 | | |
| 2. | Ventilated cavity | 25 | | | |
| 3 | OSB | 11 | 0.13 | 0.085 | |
| 4a | Polyurethane foam | 103 | 0.025 | 4.12 | 0.95 |
| 4b | Mini SIP splines | 103 | 0.13 | 0.79 | 0.05 |
| 5 | OSB | 11 | 0.13 | 0.085 | |
| 6a | Air cavity | 12.5 | | 0.160 | 0.94 |
| 6b | Timber batten | 12.5 | 0.13 | 0.096 | 0.06 |
| 7 | Gypsum board | 12.5 | 0.16 | 0.078 | |
| | Indoor air | | | $R_{si}$ = 0.13 | |

References: Thermal conductivities of materials can be referred to Table 3.47, 3.48 in (CIBSE, 2006). Surface resistances depending on heat flow direction are referred to Table 1 and thermal resistance of air cavity as in Table 2 (BSI, 2007a).

The combined method as presented in Section B.1.1.1 was employed to calculate the upper and lower limits of the thermal resistance of the bridged part of the structure. Figure B-8 illustrates the conceptual illustration of calculating the upper resistance limit.

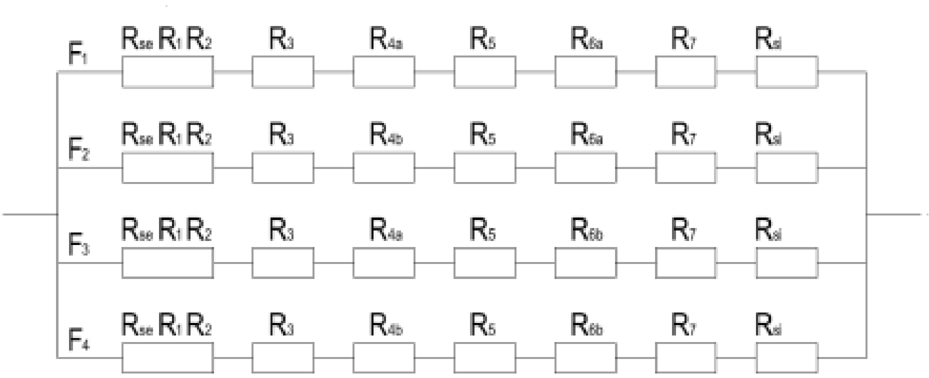


Figure B- 8: Conceptual illustration of calculating upper resistance limit.

$$R_{c1} = \left(R_{se} + R_1 + R_2 + R_3 + R_5 + R_7 + R_{si}\right) + \left(R_{4a} + R_{6a}\right) = 0.508 + (4.12 + 0.16) = 4.788\left(m^2K/W\right)$$

$F_1 = f_{4a} \times f_{6a} = 0.93 \times 0.94 = 0.87$ =0.95x0.94 =0.893

$R_{c2}$ = 1.458 ($m^2$K/W); $F_2$ = 0.047; $R_{c3}$ = 4.724($m^2$K/W); $F_3$ = 0.057

And $R_{c4}$ = 1.394($m^2$K/W); $F_4$ = 0.003. Thus obtaining: $R_U = \dfrac{1}{\sum_{i=1}^{4} \dfrac{F_i}{R_{ci}}} = 4.293\left(m^2K/W\right)$

When calculating the lower limit of thermal resistance, the resistance of a bridged layer is determined by combining in parallel the resistances of the non-bridged part and the bridged part of the layer.

Then the resistances of all elemental layers are added together to give the lower resistance limit. The conceptual illustration of this method is shown in Figure B-9.

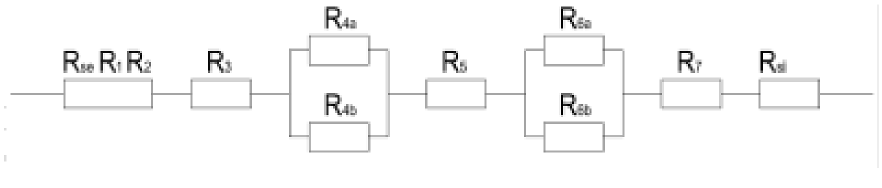


Figure B- 9: Conceptual illustration of calculating the lower limit of resistance.

The thermal resistance of the 4th layer containing 5% timber as bridging part is calculated as below:

$$R_4 = \frac{1}{\dfrac{f_{4a}}{R_{4a}} + \dfrac{f_{4b}}{R_{4b}}} = \frac{1}{\dfrac{0.95}{4.12} + \dfrac{0.05}{0.792}} = 3.40\left(m^2K/W\right)$$

For the 6th layer consisting of unventilated cavity and timber batten: $R_6$= 0.154($m^2K/W$)

$$R_L = R_{se} + \sum_1^7 R + R_{si} = 4.062\left(m^2K/W\right)$$

Total thermal resistance: $R_T = \dfrac{R_U + R_L}{2} = 4.178\left(m^2K/W\right)$

Estimation of error: $e = \dfrac{R_U - R_L}{2R_T} \times 100\% = 2.76\%$

The thermal transmittance is then obtained:

$$U = \frac{1}{R_{eq}} = 0.24\left(W/m^2K\right)$$

As α is scaling factor and equal to 0.8 if the fastener fully penetrates the insulation layer. And $d_o$ is the thickness of the insulation layer: $d_o$ = 0.103 m. $R_I$ is thermal resistance of the insulation layer and $R_T$ is the total thermal resistance ignoring any thermal bridging.

The panels are connected by the use of panel splines adhered by urethane sealant and fasten in size of 2.8 mm diameter by 63 mm, galvanised nails at 150 mm the centre (see Figure B-7).

The number of fixing per unit area: $n_f = 4 \times \dfrac{1000x1000}{300x500} \times \left(\dfrac{9 \times 300}{11850}\right) = 6$

The cross sectional area of a single fastener: $A_f = \pi\ (2.8x10^{-3})^2\ /4=6.10^{-6}\ (m^2)$ and its thermal conductivity: $\lambda_f$ = 16 (W/mK). As the fastener fully penetrates into the insulation layer, α=0.8 (BSI, 2007a). Then U-value correction for mechanical fasteners calculated by Equation B-11 is obtained:

$$\Delta U_f = \frac{0.8 \times 16 \times 6 \times 6 \times 10^{-6}}{0.103}\left(\frac{4.12}{4.788}\right)^2 = 0.0033\left(W/m^2K\right)$$

Correction for air void can be omitted because there might be minor air voids present within the construction but have no significant effect on thermal transmittance because the air bridging does not occur between the hot and cold side of the insulation. It is as a result of the cedar timber and ventilated air cavity preheats or reduces air temperature of the cold air in the external environment.

Correction for air gap and mechanical fasteners can be omitted because

$\Delta U_c = 0.003\left(W/m^2K\right) < 3\%.0.23 = 0.007\left(W/m^2K\right)$.

Thus the thermal transmittance of external wall is 0.24 W/m$^2$K.

### *B.2.1.2 Pitched roof*

In order to calculate thermal transmittance of the pitched roof SIP construction, the guideline for calculating procedure for pitched roof containing insulation at rafter level could be applied here. Figure B-10 indicates the elemental construction constituting the pitched roof of the building unit. As the second layer with external to internal order is ventilated air cavity therefore the thermal resistance that includes external surface resistance, thermal resistance of corrugated aluminium and air cavity is taken as same value of thermal resistance of internal surface (BSI, 2007a).

The pitched roof construction consists of 10 panel of SIP 150 mm (15-120-15 mm), connecting one to another by 9 mini SIP splines (15-90-15 mm) of 300mm width. Timber fraction accounting for the presence of 2 OSB panels of mini SIP splines within the polyurethane foam layer is determined by: (2 x 0.015)/0.120 x (9x0.3)/11.85 = 0.06 or 6%.

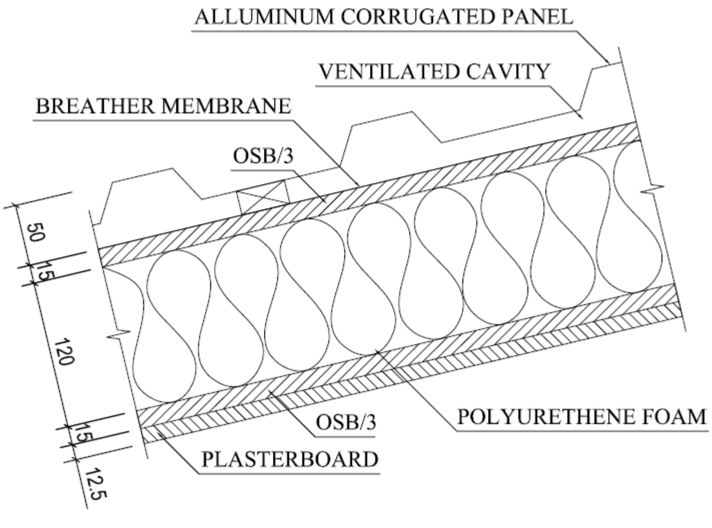


Figure B- 10: Pitched roof construction

The dimensions and thermal properties of the components of the pitched roof structure are given in Table B-2.

Table B- 2: Thermal properties of materials of pitched roof construction

| N | Layer description | Thickness, d | Conductivity, λ | Resistance, R | Fraction, f |
|---|---|---|---|---|---|
| | | mm | W/mK | $m^2K/W$ | - |
| | External air ambient | | | $R_{se}$ = 0.10 | |
| 1. | Corrugated aluminium | 3 | 160 | | |
| 2 | Air layer ventilated | 50 | | | |
| | Breather membrane | | | | |
| 3 | OSB | 15 | 0.13 | 0.115 | |
| 4a | Polyurethane foam | 120 | 0.025 | 4.80 | 0.94 |
| 4b | Mini SIP splines | 120 | 0.13 | 0.923 | 0.06 |
| 5 | OSB | 15 | 0.13 | 0.115 | |
| 6 | Plasterboard | 12.5 | 0.16 | 0.078 | |
| | Internal air | | | $R_{si}$ = 0.10 | |

Reference: Thermal conductivities of materials can be referred to Table 3.38, 3.47 and 3.48 (CIBSE, 2006). Surface resistances in Table 1 and thermal resistance of air cavity as seen in Table 2 (BSI, 2007a).

The combined method as presented in Section 1.A1.1.1 was employed to calculate the upper and lower limits of the thermal resistance of pitched roof structure. Thermal bridging takes place within the insulation layer at the location of mini SIP splines connecting the SIP system of the roof construction.

The same calculation procedure for wall structure was applied here to calculate the thermal transmittance of the pitched roof.

The upper and lower limits of thermal resistance: $R_U = 4.566$ $m^2K/W$ and $R_L = 4.338$ $m^2K/W$. The total thermal transmittance is obtained as the average values of upper and lower limits: $R_T = 4.45$ $m^2K/W$.

The thermal transmittance of the pitched roof is obtained as:

$$U = \frac{1}{R_{eq}} = 0.22\left(W/m^2K\right)$$

The thermal correction with regards to air voids and mechanical fasteners could be omitted as a result of a similar check as in previous correction.

### *B.2.1.3 Suspended floor*

Heat is transferred through suspended floor to the under floor space, from which it is then transferred to the external environment through the ground, wall of the under floor space and by ventilation of the under floor space. The thermal transmittance of a suspended floor is calculated by the formula given in (CIBSE, 2006a) as below:

$$U_{fs} = \left[ 1/U_f + 1/U_o - \left( R_{se} + R_{fu} + R_{si} \right) \right]^{-1} \quad \text{(A-31)}$$

Where:

$U_f$ is the thermal transmittance of the floor deck (W/m$^2$K),
$U_o$ is the thermal transmittance for un-insulated suspended floor (W/m$^2$K),

$R_{fu}$ is the thermal resistance of a notional un-insulated floor deck, equal to 0.2 (m$^2$K/W).

Calculation of thermal transmittance of the floor deck:

The suspended floor construction consists of 10 panel of SIP 150 mm (11-128-11 mm), connecting one to another by 9 timber stud splines (128x128 mm). The timber fraction introducing the presence of timber stud splines within the polyurethane foam layer at the panel connections of SIP system is determined by:

9x0.128/11.85 = 0.097 (9.7%) rounded as 0.10

The surface resistances on both side of this type of floor deck are taken at 0.17 (m$^2$K/W) according to CIBSE guide A: Environmental Design (CIBSE, 2006).

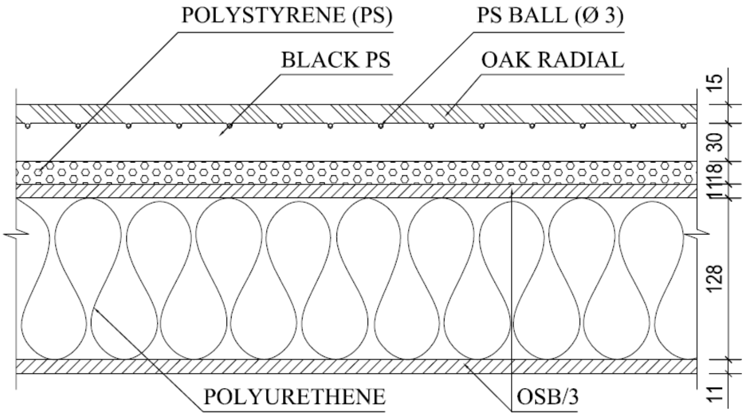


Figure B- 11: Suspended ground floor construction

The dimensions and thermal properties of the components of the suspended floor structure are given in Table B-3.

Table B- 3: Thermal properties of materials of suspended floor construction

| **N** | **Layer description** | **Thickness, d** | **Conductivity, λ** | **Resistance, R** | **Fraction, f** |
|---|---|---|---|---|---|
| | | mm | W/mK | $m^2K/W$ | - |
| | External air ambient | | | Rse = 0.17 | |
| 1 | OSB/3 | 11 | 0.13 | 0.085 | |
| 2a. | Polyurethane foam | 128 | 0.025 | 5.12 | 0.90 |
| 2b | Timber stud splines | 128 | 0.13 | 0.985 | 0.10 |
| 3 | OSB/3 | 11 | 0.13 | 0.085 | |
| 4 | Polystyrene (PS) | 18 | 0.035 | 0.514 | |
| 5a | Black PS | 30 | 0.035 | 0.857 | 0.98 |
| 5b | PS ball | 3 | 0.035 | 0.086 | 0.02 |
| 6 | Oak radial | 15 | 0.19 | 0.079 | |
| | Indoor air | | | Rsi = 0.17 | |
| Reference: Thermal conductivities of materials can be referred to Table 3.39, 3.47 and 3.48 in (CIBSE, 2006). Surface resistances refer to Table 1 (BSI, 2007a). | | | | | |

The combined method as presented in Section B.1.1.1 was employed to calculate the upper and lower limits of the thermal resistance of suspended floor structure containing two bridged layers as above.

The upper and lower limits of thermal resistance: $R_U$ = 6.187 $m^2K/W$ and $R_L$= 5.436 $m^2K/W$. The total thermal transmittance is obtained as the average values of upper and lower limits: $R_T$ = 5.81 $m^2K/W$.

Estimation of error: $e = \frac{R_U - R_L}{2R_o} \times 100\% = 6.46\%$

The connection between floor panels was performed by the use of timber inserts sealed and adhered by urethane sealant; a correction should be applied for the floor deck in order to account for air gaps. The correction for air voids is taken to level 1 describing as air gaps bridging between the hot and cold side of the insulation, but not causing air circulation between the warm and cold side of the insulation, therefore ΔU’’=0.01(BSI, 2007a). The correction of thermal transmittance for air voids is determined by:

$$\Delta U_g = \Delta U'' \times \left(\frac{R_I}{R_o}\right)^2 = 0.01 \times \left(\frac{5.12}{7.08}\right)^2 = 0.005\left(W/m^2K\right)$$

$\Delta U_g$ is not less than 3% of $(1/R_T)$ then the thermal transmittance of the floor deck is obtained as below:

$$U_f = \frac{1}{R_T} + \Delta U_g = 0.17+0.005=0.175\left(W/m^2K\right)$$

The dimension of the floor is 3.878x11.85 (m). The perimeter of the floor is calculated by $p_f$ = 2 x (3.878 + 11.85) = 31.4 (m) and the area is: $A_f$ = 3.878 x11.85 = 45.95 ($m^2$), hence the ratio $p_f/A_f$ = 0.7.

The thermal transmittance for un-insulated suspended floor $U_o$ = 0.85 ($W/m^2K$) (See Table 3.20 in (CIBSE, 2006a)).

Therefore U-value of suspended insulated floor is obtained by

$$U = \frac{1}{\left[1/0.175 + 1/0.85 - (0.17+0.2+0.17)\right]} = 0.157\left(W/m^2K\right)$$

U-value rounded = 0.16 $W/m^2K$.

### B.2.1.4 Internal partition

Figure B-12 shows the internal partition construction of the dwelling unit which consists of two plaster boards with 50mm height timber studs of 600 mm centre within the cavity of 75mm width fully filled by rock wool insulation. The party walls of 100 mm thickness separate office with bedroom, office and bathroom and with the hall.

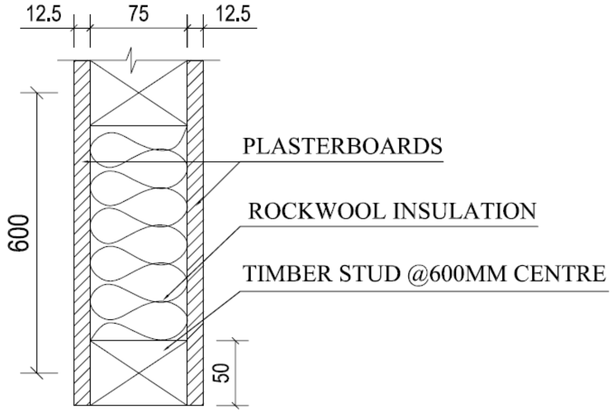


Figure B- 12: An internal partition between living space and bathroom

Timber fraction accounting for the presence of 75mm timber studs at 600mm centre plus top and bottom rail for room height 2.487 m within the insulation layer is given by:

50/600 + 2*50/2487 = 0.124 or 12%.

The dimensions and thermal properties of the party wall construction are given in Table B-4 below:

Table B- 4: Physical properties of materials of internal partition

| N | Element composition | Thickness d | Conductivity λ | Resistance R | Fraction f |
|---|---|---|---|---|---|
| | | mm | W/mK | $m^2K/W$ | - |
| | Internal air | | | $R_{si}$ = 0.13 | |
| 1. | Plaster board | 12.5 | 0.16 | 0.078 | |
| 2a | Rockwool sound insulation | 75 | 0.037 | 2.027 | 0.88 |
| 2b | Timber studding | 75 | 0.13 | 0.577 | 0.12 |
| 3. | Plaster board | 12.5 | 0.16 | 0.078 | |
| | Internal air | | | $R_{si}$ = 0.13 | |
| References: Thermal conductivities of materials refer to Table 3.37, 3.47 (CIBSE, 2006). | | | | | |

The same calculation procedure for a construction component with one layer containing thermal bridging. Thermal transmittance of the internal partition is 0.49 $W/m^2K$ rounded.

A similar calculation process is applied to determine the thermal transmittance of the partition between living space and bathroom. It is composed by two plaster boards of 12.5 mm and timber studding with 50 mm height at 600 mm centre with fully filled rock wool insulation into 147 mm cavity. The U-value is obtained as 0.28 $W/m^2K$.

### *B.2.1.5 Windows*

The building fenestration system was supplied by VELFAC Ltd. It includes double glazed windows of three different sizes and two French patio doors are also double glazed.

#### *B.2.1.5.1 Glazing*

The outsider glass pane is clear float, the inside pane is silver coated glass (known as low emissivity coating) and argon filled in the 16 mm air cavity in between two glass panes (See Figure B-13).

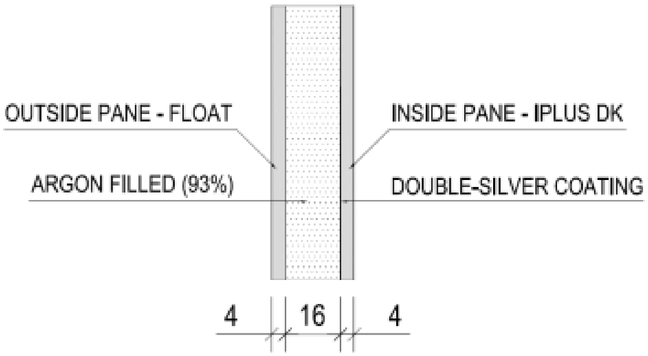


Figure B- 13: Cross section of glazed area.

Thermal properties of glazed element are given in Table B-5. External pane is clear float pane of normal emissivity. Internal pane uses I-plus type of low emissivity which is double silver coating at inner side then its emissivity applies the corrected emissivity (See Table 1.A.2 in (BSI, 2007b)).

Table B- 5: Thermal properties of glazed element

| **N°** | **Layer description** | **Thickness d** | **Conductivity λ** | **Resistivity r** | **Emissivity ε** |
|---|---|---|---|---|---|
| | | mm | W/mK | mK/W | |
| 1. | Clear float | 4 | 1.05 | 0.952 | 0.893 |
| 2. | iplus DK | 4 | 1.05 | 0.952 | 0.03 x 1.22 |
| References: | | | (CIBSE, 2006) | r = 1/ λ | (BSI, 2007b) |
| **N°** | **Gas filled in a space of 16mm width, at 10 °C** | **Density ρ** | **Conductivity λ** | **Dynamic viscosity μ** | **Specific heat capacity c** |
| | | kg/m$^3$ | W/m.K | kg/ m.s | J/ kg.K |
| 3a | Cavity –argon filled 93% | 1.699 | 1.684 x 10$^{-2}$ | 1.761 x 10$^{-5}$ | 0.519 x 10$^3$ |
| 3b | Air (7%) | 1.232 | 2.496 x 10$^{-2}$ | 2.164 x 10$^{-5}$ | 1.008 x 10$^3$ |
| Reference: Thermal properties are conducted from Table 1 and Table 1.A.2 (BSI, 2007b) | | | | | |

The calculation method of thermal transmittance of glazing alone was presented in Section B.2.1.1.2. Thermal conductance of gas space consists of radiation conductance ($h_r$) and conductance of gas filled in the space ($h_g$): $h_s = h_r + h_g$

Radiation conductance is determined by:

$$h_r = 4\sigma\left(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1\right)^{-1} T_m^3 = 4\times 5.67\times 10^{-8}\times\left(\frac{1}{0.863}+\frac{1}{0.037}-1\right)^{-1}\times 283^3 = 0.189$$

Gas conductance is sum of argon conductance and air conductance with the associated fraction.

The Grashof number (Gr) of argon is calculated by:

$$Gr_1 = \frac{9.81 s^3 \Delta T \rho^2}{T_m \mu^2} = \frac{9.81 \times 0.016^3 \times 15 \times 1.699^2}{283 \times \left(2.164 \times 10^{-5}\right)^2} = 13128.2$$

And Prandtl number Pr of argon is given by

$$Pr_1 = \frac{\mu c}{\lambda} = \frac{2.164 \times 10^{-5} \times 0.519 \times 10^3}{1.684 \times 10^{-2}} = 0.667$$

Thus Nusset number of argon is obtained:

$$Nu_1 = 0.035 \times (13128.2 \times 0.667)^{0.38} = 1.102$$

Argon conductance is determined by:

$$\left(h_g\right)_{ar} = Nu_1 \frac{\lambda_1}{s} = 1.102 \times \frac{1.684 \times 10^{-2}}{0.016} = 1.16$$

The same procedure is used for air conductance calculation as follow

$$Gr_2 = \frac{9.81 \times 0.016^3 \times 15 \times 1.232^2}{283 \times \left(1.761 \times 10^{-5}\right)^2} = 10424$$

$$Pr_2 = \frac{1.761 \times 10^{-5} \times 1.008 \times 10^3}{2.496 \times 10^{-2}} = 0.711$$

$$Nu_2 = 0.035 \times (10424 \times 0.711)^{0.38} = 1.034$$

Thus: $\left(h_g\right)_{air} = Nu_2 \frac{\lambda_2}{s} = 1.034 \times \frac{2.496 \times 10^{-2}}{0.016} = 1.613$

The gas conductance is determined by

$$h_g = \left(h_g\right)_{ar} f_{ar} + \left(h_g\right)_{air} f_{air} = 1.1598 \times 0.93 + 1.613 \times 0.07 = 1.19$$

The total thermal conductance of gas space is: $h_s$ = 1.19 + 0.189=1.38 (W/m$^2$K)

Thus, the total thermal conductance of the glazing is:

$$\frac{1}{h_t} = \frac{1}{1.38} + 2 \times 0.004 \times 0.952 = 0.732 \ \ (\text{W/m}^2\text{K})$$

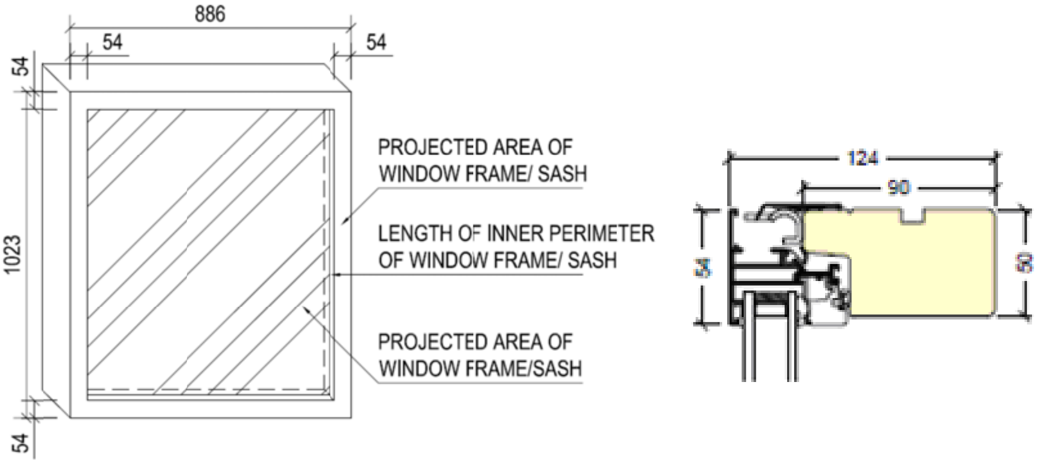
U-value of glazing is determined by:

$$\frac{1}{U} = 0.04 + 0.732 + 0.13 = 0.902 \rightarrow U = 1.11$$

U-value rounded = 1.1 W/m$^2$K.

### *B.2.1.5.2 Windows as a whole*

Due to lack of data for detailed calculation for window frame/sash, the linear thermal transmittance was derived from Informative Paper: System 200 - Performance specification in VELFAC Advance Window Design from staff of VELFAC Ltd. Dimension of large window is illustrated in Figure B-14 (a) and frame details are shown in Figure B-14 (b).



(a) Dimension of large window

Figure B- 14: Dimensions of large windows

Thermal transmittance of a whole window set is calculated by Equation B-13 in Section B.1.1.2. The glazing area is calculated by:

$$A_g = (0.886 - 2\times 0.054)\times(1.023 - 2\times 0.054) = 0.778\times 0.915 = 0.71\left(m^2\right);$$

$U_g$ = 1.1 W/m$^2$K.

Wood frame: $A_{frame} = 2\times 0.05\times(0.778 + 1.023) = 0.169\left(m^2\right)$

Thermal transmittance of window wooden frame which the average thickness is of 90mm for VELFAC 200 system is given as: $U_{frame}$ = 1.58 W/m$^2$K (VELFAC, 2009). Then $(AU)_{frame}$ = 0.267 W/K.

The area of the aluminium sash is calculated by:

$$A_{sash} = 2\times 0.054\times\left(0.778+1.023\right)+2\times 0.005\times\left(0.778+0.915\right)=0.207\left(m^2\right)$$

Thermal transmittance of aluminium sash with advanced technique of thermal break provides $U_{sash}$ = 2.0 W/m$^2$K. Then $(AU)_{sash}$ = 0.414 W/K.

Therefore, $(A_fU_f)$ = max $((AU)_{frame}, (AU)_{sash})$ = 0.414 W/K.

And the length of inner perimeter of sash: $p_{wf} = 2\times(0.778+0.915)=3.387\left(m\right)$

Linear thermal transmittance for double glazing with 1 pane coated of metal frame (sash) with thermal break: $\Psi_s$ = 0.11 (W/mK) (Table 3.26 in CIBSE (2006a)).

Thermal transmittance of VELFAC large window is calculated by:

$$U_w = \frac{0.71\times 1.1+0.414+3.387\times 0.11}{0.71+0.207}=1.709\left(W/m^2K\right)$$

U-value rounded by 1.71 W/m$^2$K.

The same calculation procedure is made to determine U-value of small, fixed windows and French patio doors and the calculated U-values are given in Table B-6. Note that the frame width of small and fixed windows is of 54mm. And the French patio door consists of 2 leaves. The sash dimension of each unit is of 0.5825 x 1.974 (m) with 66mm thickness.

Table B- 6: U-value of windows

| **Type of windows** | **Dimension WxH** | **Glazing area, $A_g$** | **Sash area, $A_s$** | **Inner perimeter, $p_{wf}$** | **U-value rounded** |
|---|---|---|---|---|---|
| | m x m | m$^2$ | m$^2$ | m | W/m$^2$K |
| Large window | 0.886 x 1.023 | 0.71 | 0.207 | 3.387 | 1.71 |
| Small window | 0.623 x 1.023 | 0.47 | 0.18 | 2.861 | 1.83 |
| Fixed window | 0.373 x 0.773 | 0.176 | 0.123 | 1.86 | 2.17 |
| Patio door | 1.173 x 1.983 | 1.66 | 0.686 | 9.17 | 1.82 |

### B.2.2 Thermal bridges at junctions

This section includes three numerical examples of calculating linear thermal transmittance at junctions between external wall and roof/floor and around window.

2D heat transfer software THERM - Version 6.3 was used for calculating the psi value ($\psi$) as it is free software with online support for users, which can be downloaded from the website: http://windows.lbl.gov/software/therm/therm.html.

Following the conventions for calculating linear thermal transmittance (Ward and Sanders, 2007), it is suggested that the boundary conditions are set as below:

- Internal boundary: temperature is usually set at 20°C and the value of thermal resistance for internal environment depends on heat flow direction.
- External boundary: temperature is usually set at 0°C and the value of thermal resistance for external environment is 0.04 $m^2K/W$.
- Adiabatic boundary refers to zero heat flow location.

### *B.2.2.1 Junction at external wall and pitched roof*

Figure B-15 describes the details of connections between the external wall and pitched roof. A model describes all materials and dimensions to be created in THERM software could be complicated while an accurate and exact thermal bridging value would not be required. The Government's Standard Assessment Procedure taking account of additional heat loss due to thermal bridging to 0.15 $W/m^2K$ without the known details or 0.08 $W/m^2K$ with construction detailing conforms to Accredited Construction Details (SAP2009, 2010). Thus, a simplified modelling taking average value of all constructional elements was established as seen in Figure B-16.

The cutting plane was set to be one meter from the central element according to BS EN ISO 10211-1:1996 (BSI, 2003a). The thermal conductivities of the considered part were taken from the total thermal resistance of the building component determined in the previous sections deducted for the surface resistances (Section B.2.1.1 – B.2.1.3). The timber used for connections at the ends of SIP elements were taken into account, of 6% of timber within SIP wall and 9% of timber within SIP roof. The new thermal conductivities for external wall and roof accounting for the timber fraction at connections were given in Table B-7. Simplified model built in THERM with thermal properties of construction elements, surface resistances and coefficient were given in Table B-7.

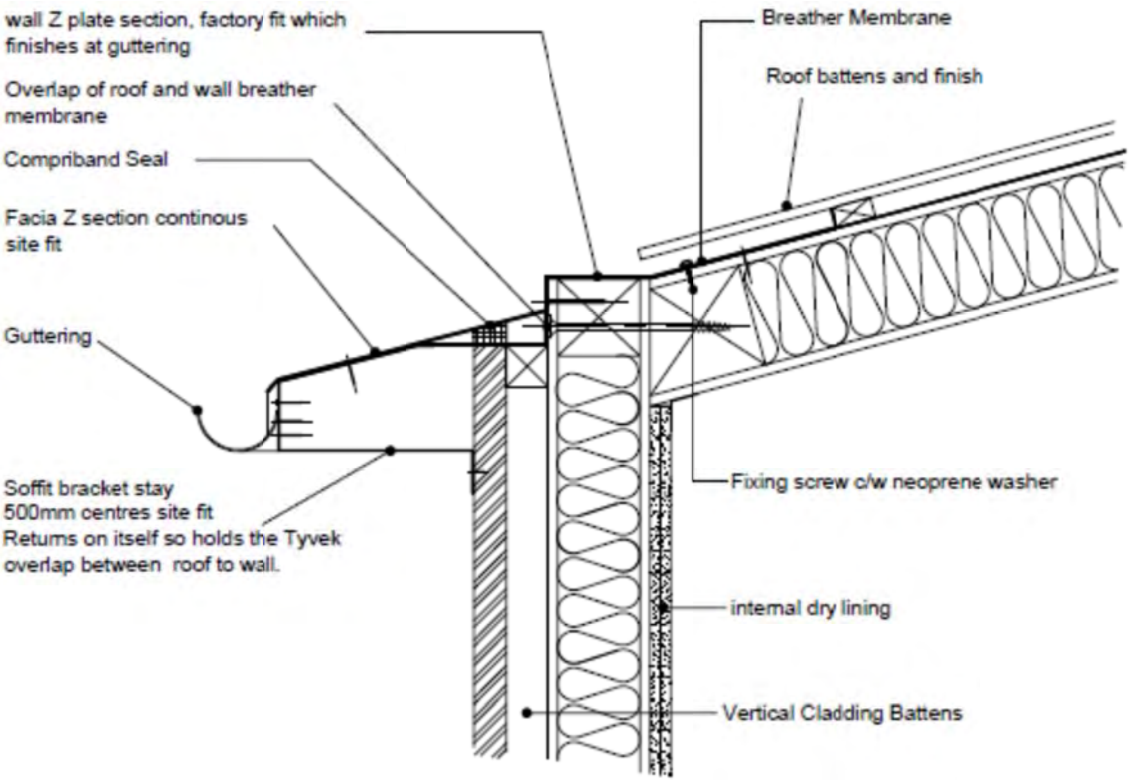


Figure B- 15: Details of connection between external wall and pitched roof (Chadwick, 2011).

Table B- 7: Information of the thermal properties of building elements and surface resistances

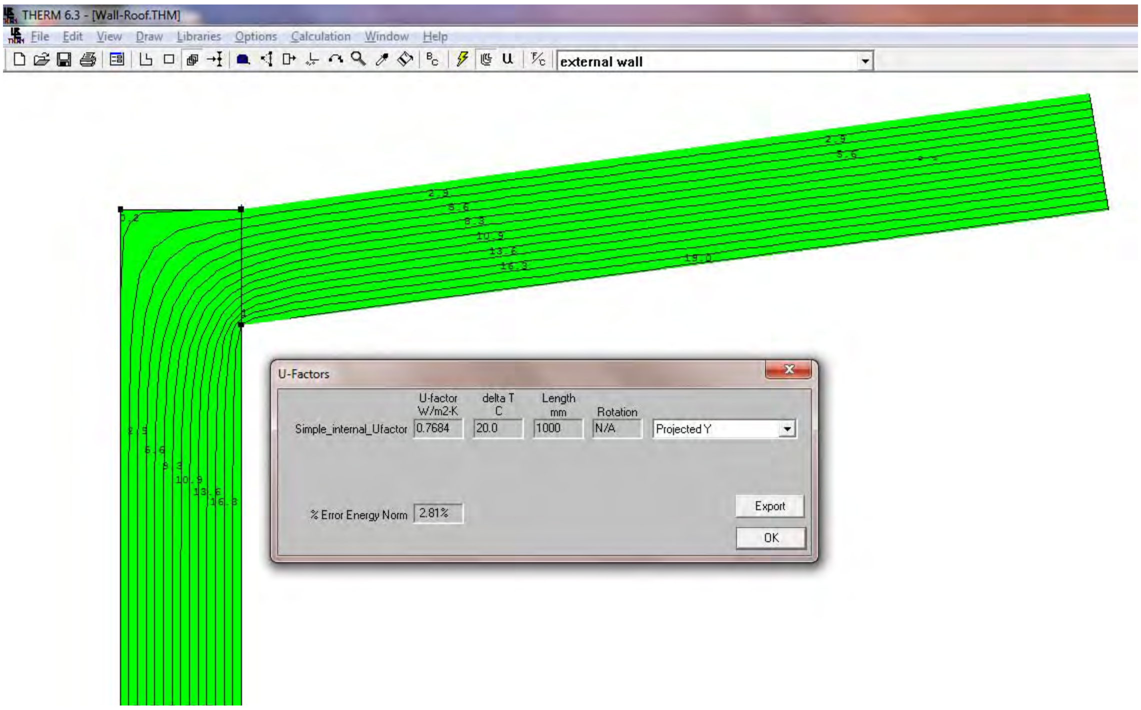
| | **Surface resistance, $R_{si}$** | **Surface resistance, $R_{se}$** | **Internal surface coefficient** | **External surface coefficient** | **Thermal conductivity, λ** | **Thickness, d** |
|---|---|---|---|---|---|---|
| | $m^2K/W$ | $m^2K/W$ | $W/m^2$ K | $W/m^2$ K | W/mK | mm |
| External wall | 0.13 | 0.04 | 7.69 | 25 | 0.053 | 189 |
| Pitched roof | 0.10 | 0.04 | 10 | 25 | 0.056 | 213 |

The boundary conditions given in Table B-8 below was derived from BRE guidance regarding calculating linear thermal transmittance (Table 1 in Ward and Sanders (2007)).

Table B- 8: Boundary conditions

| **Location** | **Temperature, °C** | **Film coefficient, $W/m^2K$** |
|---|---|---|
| Exterior | 0 | 25 |
| Internal surface of wall | 20 | 7.69 |
| Internal surface of roof | 20 | 10 |

From the result of U-factor calculated by THERM software (See Figure B-16¸ the psi value was determined by Equation B-25



| | U-factor W/m2-K | delta T C | Length mm | Rotation | |
|---|---|---|---|---|---|
| Simple_internal_Ufactor | 0.7684 | 20.0 | 1000 | N/A | Projected Y |

% Error Energy Norm 2.81%

Figure B- 16: Screenshot of calculation of U-factors for connections between wall and roof in THERM 6.3.

$\Psi$ = 0.7684 x [(0.125 + 0.150/ cos(15)) x2] – 0.24x1 – 0.22x(0.871+0.125) = -0.028 W/K.

The psi value is negative because the heat flux is less than the calculated heat loss using external areas (e.g. the sum of $U_w$’x $l_w$ and $U_r$’x $l_r$). If using internal areas then the heat flux will be higher than the calculated heat loss areas and the psi value will be positive.

### *B.2.2.2 Junction at external wall and suspended floor*

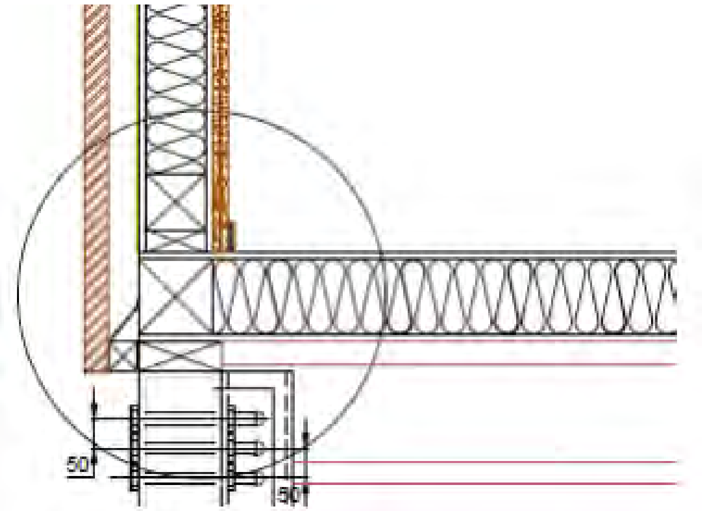


Figure B- 17: Details of connection between wall and floor.

The cutting planes were set to be one meter from the central element for the wall element and at 0.5b = 4 meters for the floor structure according to BS EN ISO 10211-

1:1996 (BSI, 2003a). The thermal conductivities of the considered part were taken from the total thermal resistance of the building component determined in the previous sections deducted for the surface resistances (Section B.2.1.1 –B.2.1.3). The timber used for connections at the ends of SIP elements were taken into account, of 6% of timber within SIP wall and 9% of timber within SIP roof. The new thermal conductivities for external wall and roof accounting for the timber fraction at connections were recalculated and given in Table B-9. Simplified model built in THERM with thermal properties of construction elements, surface resistances and heat transfer coefficients were given in Table B-9.

Table B- 9: Information of thermal properties of building elements and surface resistances

| | **Surface resistance, $R_{si}$** | **Surface resistance, $R_{se}$** | **Internal heat transfer coefficient** | **External heat transfer coefficient** | **Thermal conductivity, λ** | **Thickness, d** |
|---|---|---|---|---|---|---|
| | $m^2K/W$ | $m^2K/W$ | $W/m^2$ K | $W/m^2$ K | W/m K | mm |
| External wall | 0.13 | 0.04 | 7.69 | 25 | 0.053 | 189 |
| Ground floor | 0.17 | 0.04 | 5.88 | 25 | 0.045 | 213 |

The guidance regarding conventions for calculation of linear thermal transmittance illustrates the calculation diagram for junction between suspended floor structure and external wall as seen in Figure B-17. The under-floor of suspended floor structure is at the intermediate temperature $T_u$ between external and internal temperature. The modelling created in THERM tool followed the conceptual approach as illustrated in Figure B-18 that included modelling of ground extended to the cut off plane at a distance of 2.5b = 2.5 x 8 = 20 meters. Thus it did not require the known value of $T_u$ as part of establishing boundary conditions. The value b in the model was set at 8 meters according to clause 5.2.3 in BS EN ISO 10211 (BSI, 2003a). The distance from the edge of the floor in the two dimensional model to the opposite adiabatic boundary was then equal to 0.5b = 4 meters.

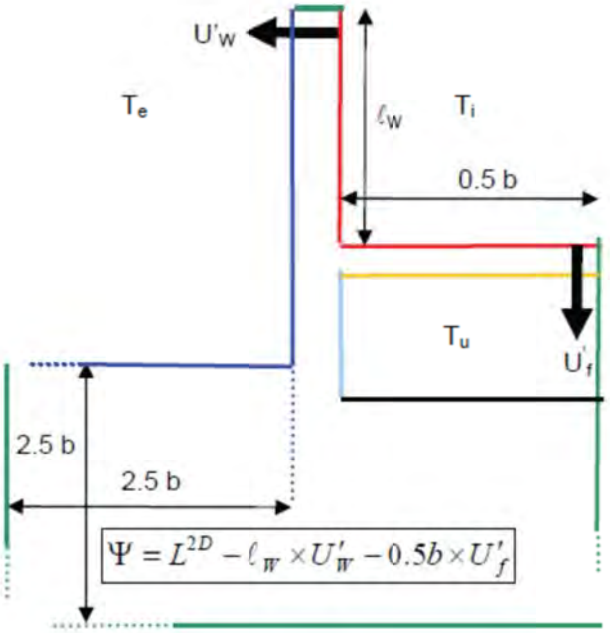


Figure B- 18: Conceptual approach of calculating thermal bridge at junction between suspended floor and wall (Ward and Sanders, 2007)

The boundary conditions given in Table B-10 below was derived from Table 1 in the calculation guidance of linear thermal transmittance (Ward and Sanders, 2007).

Table B- 10: Boundary conditions

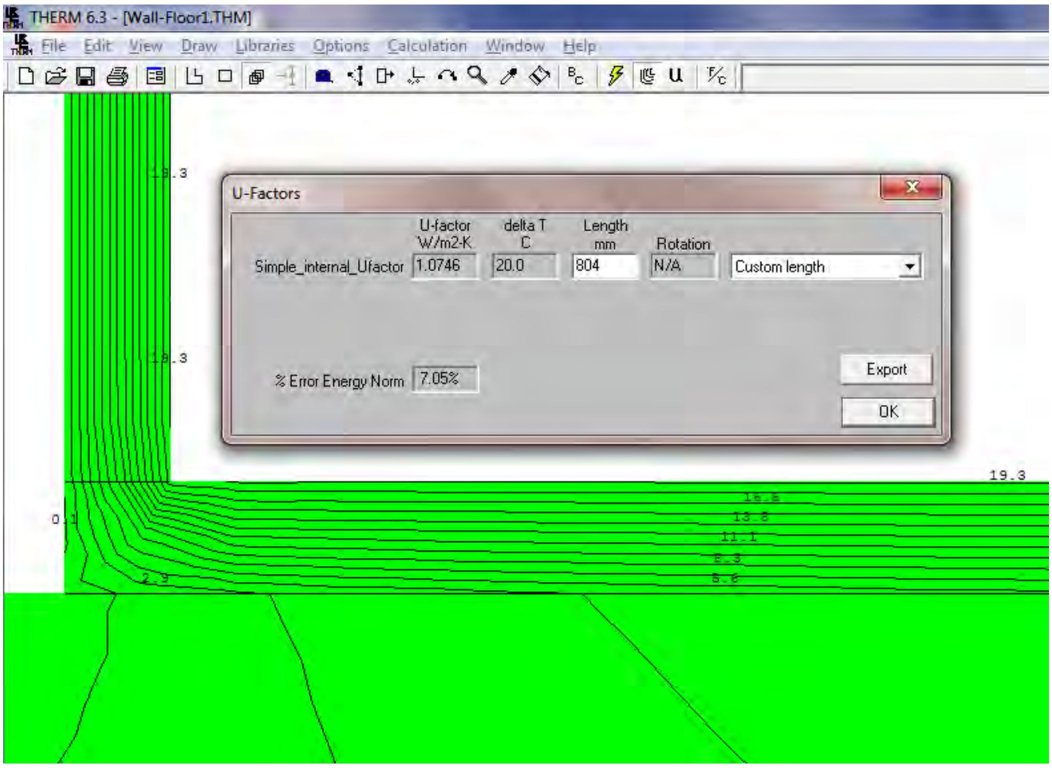
| **Location** | **Temperature, °C** | **Film coefficient, W/m$^2$K** |
|---|---|---|
| Exterior (externally to wall) | 0 | 25 |
| Internal surface of wall | 20 | 7.69 |
| Internal surface of floor | 20 | 5.88 |

From the result of U-factor calculated by THERM software (See Figure B-19) the psi value for suspended floor structure was given by the equation illustrated in Figure B-18.

Length of the 2D model in this case is calculated by 2 x (0.213+0.189)] = 0.804 m or 804 mm

The psi value or linear thermal transmittance is then obtained by:

Ψ = 1.0746 x 0.804 – 0.16 x 4.0 – 0.24 x 1.0 = -0.016 W/K.



| | U-factor W/m2-K | delta T C | Length mm | Rotation | |
|---|---|---|---|---|---|
| Simple_internal_Ufactor | 1.0746 | 20.0 | 804 | N/A | Custom length |

% Error Energy Norm 7.05%

Figure B- 19: Screenshot of U-factors calculation for connections between wall and floor in THERM 6.3.

### B.2.2.3 *Temperature factor:*

In order to assess the risk of surface condensation or mouth growth, the minimum internal surface temperature ($f_{Rsi}$) under specific internal, external environments is required. Using the models built in THERM as above in which the external temperature was set at 0°C in both cases which deems reasonable as for UK climate.

By using Equation B-28, the temperature factor is obtained as 0.97 as the model provides the surface temperature of 19.3°C. A surface temperature factor equal or above 0.75 is considered to be sufficient to avoid growth, given the range of conditions in UK buildings and the UK climate as discussed in BRE Information Paper IP 1/06 (Ward, 2006). Also, it is important to note that, a fully risk assessment regarding mould growth and surface condensation requires a known of three parameters: internal moisture supply, internal air temperature and temperature factor of internal surface $f_{Rsi}$. The internal moisture production is from tenant, fuel used, and household activities and won’t be discussed in this project.

## B.2.3 Thermal admittance values of the ErgoHome fabric

This section illustrates numerical examples of using a transient model, CIBSE admittance method to assess the thermally dynamic behaviour of building elements.

### *B.2.3.1 External wall*

A summary of the thermal properties of constructional layers of external wall can be seen in Table B-11. The corresponding values of the periodic penetration depth and ratio of the thickness to the penetration for each layer were calculated by using Equation B-31 and B-32 as seen in this table.

The matrices of internal air: $Z_1 = \begin{bmatrix} 1 & -0.13 \\ 0 & 1 \end{bmatrix}$; The matrices of air cavity: $Z_3 = \begin{bmatrix} 1 & -0.16 \\ 0 & 1 \end{bmatrix}$; The matrices of external air: $Z_{789} = \begin{bmatrix} 1 & -0.13 \\ 0 & 1 \end{bmatrix}$

Table B- 11: Thermal properties of constructional layers of external wall

| **Layer description** | **d** | **λ** | **c** | **ρ** | **R** | **δ** | **p** |
|---|---|---|---|---|---|---|---|
| | m | W/m K | J/(kg | kg/m$^3$ | m$^2$K/W | m | - |
| 1. Internal air | | | | | 0.13 | | |
| 2.Gypsum board | 0.0125 | 0.16 | 800 | 840 | | 0.081 | 0.154 |
| 3. Air cavity | 0.0125 | | | | 0.16 | | |
| 4. OSB/3 | 0.011 | 0.13 | 1700 | 600 | | 0.059 | 0.186 |
| 5. Polyurethane | 0.103 | 0.03 | 1400 | 30 | | 0.140 | 0.735 |
| 6. OSB/3 | 0.011 | 0.13 | 1700 | 600 | | 0.059 | 0.186 |
| 7. Cavity ventilated | 0.025 | | - | - | 0.13 | | |
| 8. Cedar timber | 0.014 | 0.19 | 1600 | 500 | | | |
| 9. External air | | | | | | | |
| References: Thermal properties of materials refer to Table 3.38, 3.47 (CIBSE, 2006). | | | | | | | |

The matrices of gypsum paper faced board: $Z_2 = \begin{bmatrix} m_1 & m_2 \\ m_3 & m_1 \end{bmatrix}$

With p=0.154 and e=2.718, thus obtaining: $e^p$=1.166; $e^{-p}$=0.8573; cosp=0.988; sinp= 0.1534

Thus:

$$Z_2 = \begin{bmatrix} 1+0.024j & -0.078-0.001j \\ 0.005-0.611j & 1+0.024j \end{bmatrix}$$

The matrices of OSB: $Z_4 = Z_6 = \begin{bmatrix} n_1 & n_2 \\ n_3 & n_1 \end{bmatrix}$

With p=0.186 and e=2.718, thus obtaining: $e^p$=1.204; $e^{-p}$=0.83; cosp=0.983; sinp= 0.185

Thus:

$$Z_4 = Z_6 = \begin{bmatrix} 1+0.035j & -0.085-0.001j \\ 0.009-0.816j & 1+0.035j \end{bmatrix}$$

The matrices of polyurethane foam: $Z_5 = \begin{bmatrix} p_1 & p_2 \\ p_3 & p_1 \end{bmatrix}$

With p=0.735and e=2.718, thus obtaining: $e^p$=2.085; $e^{-p}$=0.480; cosp=0.742; sinp= 0.671

Thus:

$$Z_5 = \begin{bmatrix} 0.950+0.547j & -3.456-0.638j \\ 0.058-0.311j & 0.950+0.547j \end{bmatrix}$$

The matrices total is calculated as multiplying of elemental matrices:

$$Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} -1.557+5.828j & -3.285-3.149j \\ 5.631-1.045j & -1.400+3.941j \end{bmatrix}$$

The non-steady state parameters are now derived as follow:

Thermal admittance is the amplitude of the density of heat flow rate on one side resulting from unit temperature amplitude on the same side, when the temperature amplitude on the other side is zero (BSI, 2007d). For internal side $t_1 = 0$, admittance value for external wall is determined by:

$$Y_{22} = -\frac{Z_{22}}{Z_{12}} = -\frac{-1.400+3.941j}{-3.285-3.149j} = 0.377+0.838j; \quad Y_{ex} = |Y_{22}| = 0.92$$

And the time shift: $\omega_{ex} = \frac{12}{\pi}\arctan\left(\frac{0.838}{0.377}\right) = 4.39(h)$

Periodic thermal transmittance and decrement factor are calculated as:

$$Y_{12} = -\frac{1}{Z_{12}} = \frac{1}{3.285+3.149j} = 0.159-0.152j; \quad f = \frac{|Y_{12}|}{U} = \frac{|0.159-0.152j|}{0.24} = 0.91$$

$U_o$ is the thermal transmittance of external wall ignoring all thermal bridge layers: $U_o=1/R_o=1/4.778=0.21$ W/m$^2$K (See Section B.2.1.1).

The time shift of the periodic thermal transmittance is given:

$$\phi = \frac{12}{\pi}\arctan\left(\frac{-0.724}{0.757}\right) = -2.9(h)$$

Surface response factor is calculated below:

$$F = 1 - R_{si}Y_{22} = 1 - 0.13 \times (0.377 + 0.838j) = 0.951 - 0.111j$$

F= 0.96

The surface factor time lag is determined:

$$\psi = \frac{12}{\pi}\arctan\left(\frac{-0.111}{0.951}\right) = -0.444(h)$$

### *B.2.3.2 Pitched roof*

Thermal conductivity (λ), density (ρ) and specific heat capacity (c) of elemental layers constituting pitched roof structure are given and the penetration depth calculated accordingly as shown in the order from internal to external construction layers in Table B-12.

Table B- 12: Thermal properties of constructional layers of pitched roof

| **Layer description** | **d** | **λ** | **c** | **ρ** | **R** | **δ** | **p** |
|---|---|---|---|---|---|---|---|
| | m | W/mK | J/(kgK) | kg/m$^3$ | m$^2$K/W | m | |
| 1.Internal air | | | | | 0.10 | | |
| 2.Plasterboard | 0.013 | 0.16 | 950 | 840 | | 0.074 | 0.168 |
| 3.OSB/3 | 0.015 | 0.13 | 1700 | 600 | | 0.059 | 0.253 |
| 4.Polyurethane | 0.120 | 0.03 | 1400 | 30 | | 0.142 | 0.842 |
| 5.OSB/3 | 0.015 | 0.13 | 1700 | 600 | | 0.059 | 0.253 |
| 6.Ventilated cavity | 0.050 | | 1600 | 500 | 0.10 | | |
| 7.Breather membrane | | | - | - | | | |
| 8.Corrugated aluminium | 0.003 | 160 | | | | | |
| 9.External air | | | | | | | |
| Reference: Thermal properties of materials refer to Table 3.38 and 3.47 (CIBSE, 2006a). | | | | | | | |

Following a similar calculation procedure of the walling system, the matrices total is calculated as multiplying of elemental matrices:

$$Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} -3.101 + 8.010j & -3.366 - 3.461j \\ 10.413 - 0.129j & -2.416 + 5.241j \end{bmatrix}$$

Admittance value of the pitched roof is then determined by:

$$Y_{22} = -\frac{Z_{22}}{Z_{12}} = -\frac{-2.416 + 5.241j}{-3.366 - 3.461j} = 0.429 + 1.116j; \quad Y_{ex} = |Y_{22}| = 1.20$$

And the time shift: $\omega_{ex} = \frac{12}{\pi} \arctan\left(\frac{1.116}{0.429}\right) = 4.6(h)$

Periodic thermal transmittance and decrement factor are calculated below:

$$Y_{12} = -\frac{1}{Z_{12}} = -\frac{1}{-3.366 - 3.461j} = 0.144 - 0.148j; \quad f = \frac{|Y_{12}|}{U} = \frac{0.207}{0.22} = 0.94$$

Time dependency in association with the decrement factor (or time lag)

$$\phi = \frac{12}{\pi} \arctan\left(\frac{-0.148}{0.144}\right) = -3.05(h).$$

Surface response factor is calculated below:

$$F = 1 - R_{si} Y_{22} = 1 - 0.13 \times (0.429 + 1.116j) = 0.944 - 0.145j$$

Then F= 0.96.

The surface factor time lag is determined:

$$\psi = \frac{12}{\pi} \arctan\left(\frac{-0.145}{0.944}\right) = -0.58(h)$$

#### *B.2.3.3 Suspended floor*

Thermal conductivity (λ), density (ρ) and specific heat capacity (c) of elemental layers constituting suspended timber structure are listed and the penetration depth calculated accordingly as shown in the order from internal to external construction layers in Table B-13.

Table B- 13: Thermal properties of constructional layers consisting suspended floor

| **Layer description** | **d** | **λ** | **c** | **ρ** | **R** | **δ** | **p** |
|---|---|---|---|---|---|---|---|
| | m | W/mK | J/kgK | kg/m$^3$ | m$^2$K/W | m | - |
| 1.Internal air | | | | | 0.17 | | |
| 2.Oak radial | 0.015 | 0.19 | 2390 | 700 | | 0.056 | 0.268 |
| 3. Polystyrene | 0.048 | 0.027 | 1470 | 35 | | 0.120 | 0.400 |
| 4.OSB/3 | 0.011 | 0.13 | 1700 | 600 | | 0.059 | 0.186 |
| 5.Polyurethane | 0.128 | 0.035 | 1400 | 30 | | 0.151 | 0.846 |
| 6.OSB/3 | 0.011 | 0.13 | 1700 | 600 | | 0.059 | 0.186 |
| 7.External air | | | | | 0.04 | | |
| Reference: Thermal properties of materials refer to Table 3.38, 3.39 and 3.47 (CIBSE, 2006a). | | | | | | | |

The matrices total is calculated as multiplication of elemental matrices and given below:

$$Z=\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}=\begin{bmatrix} -16.060+8.233j & 1.134-9.644j \\ 13.754+10.228j & -8.743+3.055j \end{bmatrix}$$

Admittance value of the suspended floor:

$$Y_{22}=-\frac{Z_{22}}{Z_{12}}=-\frac{-8.743+3.055j}{1.134-9.644j}=0.418+0.857j;\quad Y_{ex}=\left|Y_{22}\right|=0.95$$

And the time shift: $\omega_{ex}=\frac{12}{\pi}\arctan\left(\frac{0.857}{0.418}\right)=4.27(h)$

Periodic thermal transmittance and decrement factor are calculated as:

$$Y_{12}=-\frac{1}{Z_{12}}=-\frac{1}{1.134-9.644j}=-0.012-0.102j;\quad f=\frac{\left|Y_{12}\right|}{U_o}=\frac{0.103}{0.13}=0.79$$

Time dependency in association with the decrement factor (or time lag) (See Table C.1 in (BSI, 2007d) for Arctangent value).

$$\phi=\frac{12}{\pi}\arctan\left(\frac{-0.102}{-0.012}\right)=\frac{12}{\pi}\left[\arctan\left(\frac{-0.102}{-0.012}\right)-\pi\right]=-6.45(h).$$

Surface response factor is calculated below:

$$F=1-R_{si}Y_{22}=1-0.13\times(0.418+0.579j)=0.946-0.075j$$

Then F= 0.95. The surface factor time lag is determined:

$$\psi = \frac{12}{\pi}\arctan\left(\frac{-0.579}{0.418}\right) = -3.61(\mathrm{h})$$

### B.2.3.4 *Internal partition*

Thermal conductivity (λ), density (ρ) and specific heat capacity (c) of elemental layers constituting internal partition are given and the penetration depth calculated accordingly as shown in the order from internal to external construction layers in Table B-14.

Table B- 14: Thermal properties of constructional layers of internal partition

| **Element composition** | **d** | **λ** | **c** | **ρ** | **R** | **δ** | **p** |
|---|---|---|---|---|---|---|---|
| | m | W/mK | J/(kgK) | kg/m$^3$ | m$^2$K/W | m | - |
| 1. Internal air | | | | | 0.13 | | |
| 2. Plaster board | 0.013 | 0.16 | 840 | 950 | | 0.074 | 0.168 |
| 3. Rockwool insulation (stud included) | 0.075 | 0.048 | 1030 | 25 | | 0.226 | 0.331 |
| 4. Plaster board | 0.013 | 0.16 | 840 | 950 | | 0.074 | 0.168 |
| 5. Internal air | | | | | 0.13 | | |
| Reference: Thermal properties of materials refer to Table 3.37 and 3.47 (CIBSE, 2006a). | | | | | | | |

The matrices total is calculated as multiplying of five elemental matrices

$$Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} 0.762 + 1.564\mathrm{j} & -1.928 - 0.550\mathrm{j} \\ 1.048 - 1.536\mathrm{j} & 0.762 + 1.564\mathrm{j} \end{bmatrix}$$

For internal partitions within a building, where the temperature variations are the same on either side of the partition, the periodic heat flow is related to the periodic temperature variations by a modified admittance (BSI, 2007d). For internal partitions, the decrement factor is combined with the admittance and surface factor.

The modified admittance value is determined by:

$$Y_{22}^{*} = Y_{22} - Y_{12} = -\frac{Z_{22}}{Z_{12}} + \frac{1}{Z_{12}} = \frac{1 - Z_{22}}{Z_{12}} = \frac{1 - (0.762 + 1.564\mathrm{j})}{-1.928 - 0.550\mathrm{j}} = -0.328 + 0.718\mathrm{j}$$

$$Y^{*} = \left|Y_{c}^{*}\right| = 0.79; \quad \omega = \frac{12}{\pi}\arctan\left(\frac{0.718}{-0.328}\right) = \frac{12}{\pi}\left[\arctan\left(\frac{0.718}{-0.328}\right) + \pi\right] = 7.64(\mathrm{h})$$

Periodic thermal transmittance and decrement factor are calculated as:

$$Y_{12} = -\frac{1}{Z_{12}} = -\frac{1}{-1.928 - 0.550\mathrm{j}} = 0.48 - 0.137\mathrm{j}; \quad f = \frac{\left|Y_{12}\right|}{U} = \frac{0.49}{0.49} = 1$$

Time dependency in association with the decrement factor (time lag):

$$\phi = \frac{12}{\pi}\arctan\left(\frac{-0.137}{0.48}\right) = -1.06(\mathrm{h}).$$

Surface response factor is calculated below:

$$F = 1 - R_{si}Y_{22} = 1 - 0.13 \times (0.762 + 1.564j) = 0.901 - 0.203j$$

F= 0.92.

The surface factor time lag is determined:

$$\psi = \frac{12}{\pi}\arctan\left(\frac{-0.203}{0.901}\right) = -0.85(\mathrm{h})$$

### *B.2.3.5 Windows*

Thermal conductivity (λ), density (ρ) and specific heat capacity (c) of elemental layers of the window are listed in the order from internal to external side as shown in Table B-15. The conductance of gas (argon and air) is of 1.38 W/m$^2$K then its thermal resistance is calculated as 1/1.38 = 0.724 m2K/W (See Section B.2.1.5). Within the window, the glazing plays a major role in thermal response so the frame factor could be ignored.

Table B- 15: Physical properties of construction layers of windows

| **Layer description** | **d** | **λ** | **c** | **ρ** | **R** | **δ** | **p** |
|---|---|---|---|---|---|---|---|
| | m | W/mK | J/kgK | kg/m$^3$ | m$^2$K/W | m | |
| 1.Internal air | | | | | 0.13 | | |
| 2.Iplus-DK | 0.004 | 1.05 | 840 | 2500 | | 0.117 | 0.034 |
| 3.Air cavity filled with argon | 0.016 | | | | 0.724 | | |
| 4.Clear float | 0.004 | 1.05 | 840 | 2500 | | 0.117 | 0.034 |
| 5.External air | | | | | 0.04 | | |
| References: Thermal properties of materials refer to Table 3.38, 3.39, and 3.47 (CIBSE, 2006a). | | | | | | | |

The matrices total is calculated as multiplying of elemental matrices:

$$Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} 0.988 + 0.496j & -0.900 - 0.084j \\ 0.272 - 1.222j & 0.964 + 0.606j \end{bmatrix}$$

Thermal admittance value of the glazed window is

$$Y_{22} = -\frac{Z_{22}}{Z_{12}} = -\frac{0.964 + 0.606\,j}{-0.900 - 0.084\,j} = 1.124 + 0.568\,j; \quad Y_{ex} = \left|Y_{22}\right| = 1.26$$

And the time shift: $\omega_{ex} = \frac{12}{\pi}\arctan\left(\frac{0.568}{1.124}\right) = 1.79\left(h\right)$

Periodic thermal transmittance and decrement factor are calculated as:

$$Y_{12} = -\frac{1}{Z_{12}} = -\frac{1}{-0.896 - 0.084\,j} = 1.097 - 0.103j; \quad f = \frac{\left|Y_{12}\right|}{U_o} = \frac{1.102}{1.1} = 1$$

Time shift within the periodic thermal transmittance (time lag)

$$\phi = \frac{12}{\pi}\arctan\left(\frac{-0.103}{1.097}\right) = -0.36\left(h\right).$$

Surface response factor is calculated below:

$$F = 1 - R_{si}Y_{22} = 1 - 0.13 \times (1.124 + 0.568\,j) = 0.854 - 0.074\,j$$

F= 0.86.

The surface factor time lag is determined:

$$\psi = \frac{12}{\pi}\arctan\left(\frac{-0.074}{0.854}\right) = -0.33\left(h\right)$$

## *B.3 ANALYTICAL VERIFICATION*

### B.3.1 Steady state heat loss

The site is subjected to normal condition of exposure. Designed operative temperature should be reasonably selected as it fundamentally affects the estimation of heating loads hence heating system operation. The test unit is to be heated to an operative temperature of 20°C, see Table 1.5 in (CIBSE, 2006)for recommended comfort design for dwelling. Besides, ventilation rate recommended for comfort in living space is within the range of 0.4 – 1 ac/h, N=1 ac/h is selected for calculation.

The estimation of heat loss depends largely on the difference between outdoor and indoor temperature so the area of internal building elements is excluded. It is suggested that the external design temperature for heat loss calculation in the UK is -5°C.

The building fabric data calculated in Section B.2, with the building dimension were given in Chapter 5, Figure 5. And 5., the areas of building components and the multiple results of AU and AY were calculated, given in Tables B-15 to B-17 for 5 thermal zones shown in Figure B-20

It is noted that for simplifying the manual calculation, the U-value of internal partition and internal door is equal to the international partition.

Applying the calculation procedure in Section B.1.3,

, calculation for different thermal space is provided in Table 1.A-20

With data provided in Tables 1.A-17 – 1.A-19,. The

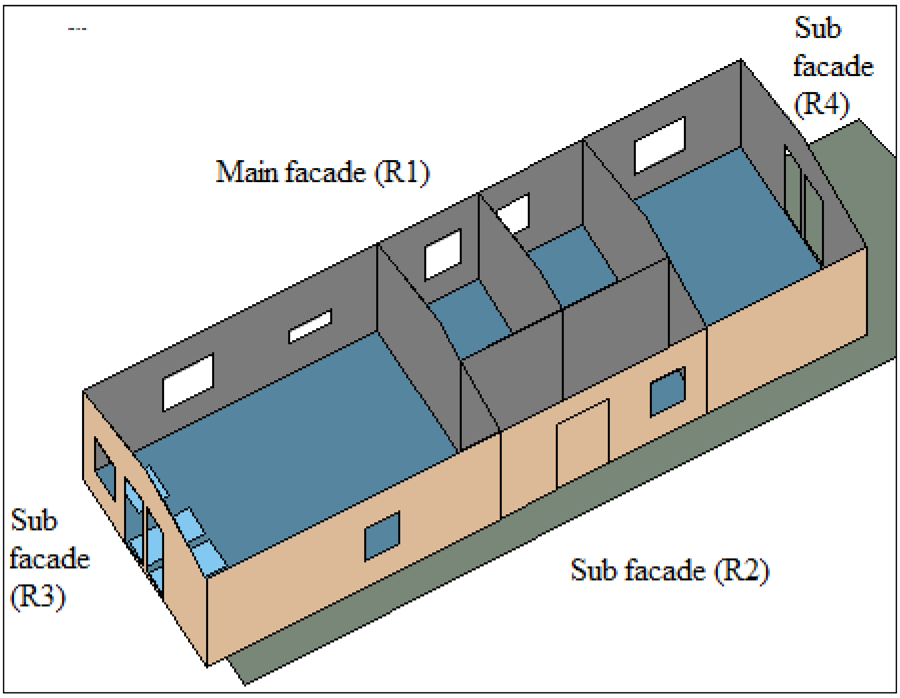


Figure B- 20: 3D model to illustrate five thermal zones and facade indication

Table B- 16: Thermal properties and areas of building elements for the living space

| **Surface** | **Area** | **U-value** | **A x U** | **Y-value** | **A x Y** | **Decrement factor, f** | **Time lag , ø** |
|---|---|---|---|---|---|---|---|
| | $m^2$ | $W/m^2K$ | W/K | $W/m^2K$ | W/K | $m^2K/W$ | hours |
| External wall (R1) | 13.00 | 0.24 | 3.12 | 0.92 | 12.20 | 0.91 | 2.90 |
| External wall (R2) | 13.54 | 0.24 | 3.25 | 0.92 | 12.71 | 0.91 | 2.90 |
| External wall (R3) | 8.69 | 0.24 | 2.09 | 0.92 | 6.93 | 0.91 | 2.90 |
| Pitched roof | 21.15 | 0.22 | 4.65 | 1.20 | 23.04 | 0.94 | 3.05 |
| Ground floor | 20.43 | 0.16 | 3.27 | 0.95 | 19.64 | 0.79 | 6.45 |
| Windows (R1) | 1.194 | 1.71\|2.17 | 2.17 | 1.26 | 1.50 | 1 | 0.36 |
| Windows (R2) | 0.637 | 1.83 | 1.17 | 1.26 | 0.80 | 1 | 0.36 |
| Windows (R3) | 2.963 | 1.82\|1.83 | 5.40 | 1.26 | 3.73 | 1 | 0.36 |
| Internal partition + door* | 11.42 | 0.49 | 5.60 | 0.79 | 7.76 | | 1.06 |
| Total *(including\| not including internal partition) | 93.02\| 81.60 | - | 30.71\| 25.12 | - | 92.26\| 83.24 | - | - |

Table B- 17: Thermal properties and areas of building component for bedroom and office

| **Surface** | **Area** | **U-value** | **A x U** | **Y-value** | **A x Y** | **Decrement factor, f** | **Time lag , ø** |
|---|---|---|---|---|---|---|---|
| | $m^2$ | $W/m^2K$ | W/K | $W/m^2K$ | W/K | - | hour |
| **Bedroom** | | | | | | | |
| External wall (R1) | 6.72 | 0.24 | 1.61 | 0.92 | 6.18 | 0.91 | 2.9 |
| External wall (R2) | 7.62 | 0.24 | 1.83 | 0.92 | 7.01 | 0.91 | 2.9 |
| External wall (R4) | 9.09 | 0.24 | 2.18 | 0.92 | 8.36 | 0.91 | 2.9 |
| Pitched roof | 11.37 | 0.22 | 2.50 | 1.20 | 13.64 | 0.94 | 3.05 |
| Ground floor | 10.98 | 0.16 | 1.76 | 0.95 | 10.43 | 0.79 | 6.45 |
| Windows (R1) | 0.906 | 1.71 | 1.55 | 1.26 | 1.14 | 1 | 0.36 |
| Windows (R4) | 2.326 | 1.82 | 4.23 | 1.26 | 2.93 | 1 | 0.36 |
| Internal partition + door | 11.42 | 0.49 | 5.60 | 0.79 | 9.02 | 1 | 1.06 |
| Total * | 60.43\| 49.01 | | 21.26\|15.66 | | 58.72\|49.70 | | |
| **Office** | | | | | | | |
| External wall (R1) | 4.46 | 0.24 | 1.07 | 0.92 | 4.01 | 0.91 | 2.9 |
| Pitched roof | 5.18 | 0.22 | 1.14 | 1.20 | 6.22 | 0.94 | 3.05 |
| Ground floor | 5.0 | 0.16 | 0.80 | 0.95 | 4.75 | 0.79 | 6.45 |
| Windows (R1) | 0.637 | 1.83 | 1.17 | 1.26 | 0.80 | 1 | 0.36 |
| Internal partition + door | 21.53 | 0.49 | 10.55 | 0.79 | 17.01 | 1 | 1.06 |
| Total * | 36.81\|15.28 | | 14.73\|4.18 | | 32.88\|15.87 | - | - |

Table B- 18: Thermal properties and areas of building components for bathroom and hall entrance

| **Surface** | **Area** | **U-value** | **A x U** | **Y-value** | **A x Y** | **Decrement factor, f** | **Time lag , ø** |
|---|---|---|---|---|---|---|---|
| | m$^2$ | W/m$^2$K | W/K | W/m$^2$K | W/K | - | hours |
| **Bathroom** | | | | | | | |
| External wall (R1) | 4.31 | 0.24 | 1.03 | 0.92 | 3.97 | 0.91 | 2.9 |
| Pitched roof | 5.03 | 0.22 | 1.11 | 1.20 | 6.04 | 0.94 | 3.05 |
| Ground floor | 4.86 | 0.16 | 0.78 | 0.95 | 4.62 | 0.79 | 6.45 |
| Windows (R1) | 0.637 | 1.83 | 1.17 | 1.26 | 0.80 | 1 | 0.36 |
| Internal partition + door | 21.37 | 0.49 | 10.47 | 0.79 | 16.88 | 1 | 1.06 |
| Total (Same as Table 1.A-15) | 36.21\| 14.84 | | 14.56\|4.08 | | 32.30\|15.42 | - | - |
| **Hall entrance** | | | | | | | |
| External wall (R2) | 7.56 | 0.24 | 1.81 | 0.92 | 6.96 | 0.91 | 2.9 |
| Pitched roof | 4.77 | 0.22 | 1.05 | 1.20 | 5.72 | 0.94 | 3.05 |
| Ground floor | 4.60 | 0.16 | 0.74 | 0.95 | 4.37 | 0.79 | 6.45 |
| Windows (R2) | 0.637 | 1.83 | 1.17 | 1.26 | 0.80 | 1 | 0.36 |
| Internal partition + doors | 18.31 | 0.49 | 8.97 | 0.79 | 14.46 | 1 | 1.06 |
| External door | 1.84 | 0.92 | 1.69 | - | - | - | - |
| Total (Same as Table 1.A-15) | 37.72\|19.41 | | 15.43\|6.46 | | 32.32\|17.85 | | |

Table B- 19: Calculation of design steady state heat loss

| **Thermal space** | **∑A** | **∑AU** | **Volume, V** | **$C_v$** | **$F_{1cu}$** | **$F_{2cu}$** | **$t_c$** | **$t_{ao}$** | **$t_c$ - $t_{ao}$** | **$\Phi_t$** | **$t_{ai}$** | **$t_m$** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $m^2$ | W/K | $m^3$ | $m^3$ | - | - | °C | °C | °C | W | °C | °C |
| Living space | 81.60 | 25.11 | 60.25 | 20.08 | 1.006 | 0.983 | 20 | -5 | 25 | 1124.76 | 19.57 | 20.43 |
| Bedroom | 49.01 | 15.66 | 32.38 | 10.79 | 1.005 | 0.986 | 20 | -5 | 25 | 659.41 | 19.66 | 20.34 |
| Office | 15.28 | 4.18 | 14.98 | 4.99 | 1.009 | 0.972 | 20 | -5 | 25 | 226.80 | 19.30 | 20.70 |
| Bathroom | 15.18 | 4.08 | 14.55 | 4.85 | 1.009 | 0.972 | 20 | -5 | 25 | 220.85 | 19.31 | 20.69 |
| Hall entrance | 19.41 | 6.46 | 13.14 | 4.38 | 1.005 | 0.986 | 20 | -5 | 25 | 270.23 | 19.65 | 20.35 |
| Total | 180.48 | 55.49 | | | | | | | | 2502.04 | | |

$\Phi_t$ – The total heat loss (W)

$t_{ai}$, $t_m$ is indoor air temperature and mean radiant temperature (°C)

$t_c$ is operative temperature to be achieved and $t_{ao}$ is outdoor air temperature °C

$C_v$ is the ventilation loss (W), $C_v$ = 1/3NV or 0.33NV with N is number of air change per hour and V is volume of the space ($m^3$). Here N was selected to be of 1 air change

## B.3.2 Calculation of cooling load and peak temperature

Design data for heat gain calculation of the test building referring to measured solar radiation data and sol air temperatures derived from surface observation are available only for 3 UK locations: London (Bracknell), Manchester (Aughton) and Edinburg (Mylnefield) (CIBSE, 2006). Regarding the purpose of analytical verification, London external design data were selected for calculation of summer peak temperature and space cooling loads.

The calculation is based on the following assumption:

- The operative temperature of the total unit is maintained equal room to room therefore heat flow occurs only through external element (windows, roof, suspended floor and external walls).
- There are internal blinds hence the solar gain to the air node is zero.

### *B.3.2.1 Determination of mean heat gains from all sources:*

The calculation follows the procedure in Section B.1.3.2

#### *B.3.2.1.1 Solar heat gain:*

The façade R1 (shown in Figure B-20) of the test unit faces due south. It is observed from the summer design date data in Table 2.30 and Table 2.34 with regards to orientation of the test building that the building will reach its peak temperature and cooling load in August. Solar gain factor at the environmental node for double glazing windows which are clear-low emissivity: $\bar{S}_e = 0.62$ (Table 5.7 in (CIBSE, 2006a)).The mean solar heat gain to the environmental node for different rooms is given in Table B-19 with mean solar irradiance data given in Table 2.30 in (CIBSE, 2006a).

Table B- 20: Mean solar irradiance and solar heat gain in different rooms

| **Thermal space** | **Net glazing area, $A_g$** | **Mean total solar irradiance, $\bar{I}_t$** | **Mean solar heat gain $\bar{\Phi}_{se}$** |
|---|---|---|---|
| | $m^2$ (Table B-6) | $W/m^2$ | W |
| Living space (R1) | 0.886 | $\left(\bar{I}_t\right)_S = 177$ | 345.22 |
| (R2) | 0.47 | $\left(\bar{I}_t\right)_N = 67$ | |
| (R3) | 2.13 | $\left(\bar{I}_t\right)_E = 173$ | |
| Bedroom (R1) | 0.71 | $\left(\bar{I}_t\right)_S = 177$ | 248.76 |
| (R4) | 1.66 | $\left(\bar{I}_t\right)_W = 166$ | |
| Study room (R1) | 0.47 | $\left(\bar{I}_t\right)_S = 177$ | 51.58 |
| Bathroom (R1) | 0.47 | $\left(\bar{I}_t\right)_S = 177$ | 51.58 |
| Hall (R2) | 0.47 | $\left(\bar{I}_t\right)_N = 67$ | 19.52 |

### *B.3.2.1.2 Mean structure heat gain*

Mean structure heat gain, $\bar{\Phi}_f$ is the total heat gain through the opaque ($\left[\bar{\Phi}_f\right]_{op}$) and glazing surfaces ($\left[\bar{\Phi}_f\right]_g$). The multiplication results (AxU) of glazing element (including frame) are given in Tables B-16 – B-18. Mean air temperature for calculating fabric gain from glazing: $\bar{t}_{ao}$ =19.8°C (Table 2.34 in (CIBSE, 2006a)). With the mean sol air temperature for structure heat gain calculation is given in Table 2.34 in (CIBSE, 2006a), the mean fabric heat gains of different rooms are determined in Tables B-21 and B-22

Table B- 21: Mean fabric heat gain for living space and bedroom

| **Thermal zone** | **AxU** | **Mean sol air temperature** $\overline{t}_{eo}$ | **Mean fabric heat gain,** $\left[\overline{\Phi}_f\right]_{op}$ |
|---|---|---|---|
| Living space | W/K | K | W |
| Wall (R1) | 3.12 | $\left(\overline{t}_{eo}\right)_S = 26.9$ | 80.50 |
| Wall (R2) | 3.25 | $\left(\overline{t}_{eo}\right)_N = 21.8$ | 72.79 |
| Wall (R3) | 2.09 | $\left(\overline{t}_{eo}\right)_E = 27.5$ | 57.98 |
| Roof | 4.65 | $\left(\overline{t}_{eo}\right)_{hor} = 22.3$ | 105.16 |
| Ground floor | 3.27 | $\left(\overline{t}_{eo}\right)_{hor} = 26.6$ | 89.24 |
| Glazing | 8.74 | $\overline{t}_{ao} = 19.8$ | 173.03 |
| $\overline{\Phi}_f = \left[\overline{\Phi}_f\right]_{op} + \left[\overline{\Phi}_f\right]_g$ =575.87(W) | | | |
| Bedroom | W/K | K | W |
| Wall (R1) | 1.61 | $\left(\overline{t}_{eo}\right)_S = 26.9$ | 43.38 |
| Wall (R2) | 1.83 | $\left(\overline{t}_{eo}\right)_N = 21.8$ | 39.87 |
| Wall (R4) | 2.18 | $\left(\overline{t}_{eo}\right)_W = 25.8$ | 56.29 |
| Roof | 2.50 | $\left(\overline{t}_{eo}\right)_{hor} = 22.3$ | 55.78 |
| Ground floor | 1.76 | $\left(\overline{t}_{eo}\right)_{hor} = 26.6$ | 46.73 |
| Glazing | 5.78 | $\overline{t}_{ao} = 19.8$ | 114.50 |
| $\overline{\Phi}_f = \left[\overline{\Phi}_f\right]_{op} + \left[\overline{\Phi}_f\right]_g$ =356.54(W) | | | |

Table B- 22: Mean fabric heat gain for the office, bathroom and hall entrance

| **Thermal zone** | **AxU** | **Mean sol air temperature** $\bar{t}_{eo}$ | **Mean fabric heat gain,** $\left[\bar{\Phi}_f\right]_{op}$ |
|---|---|---|---|
| Office | W/K | K | W |
| Wall (R1) | 1.07 | $\left(\bar{t}_{eo}\right)_S = 26.9$ | 28.79 |
| Roof | 1.14 | $\left(\bar{t}_{eo}\right)_{hor} = 22.3$ | 25.41 |
| Ground floor | 0.80 | $\left(\bar{t}_{eo}\right)_{hor} = 26.6$ | 21.28 |
| Glazing | 1.17 | $\bar{t}_{ao} = 19.8$ | 23.08 |
| $\bar{\Phi}_f = \left[\bar{\Phi}_f\right]_{op} + \left[\bar{\Phi}_f\right]_g$ =98.57 (W) | | | |
| Bathroom | W/K | K | W |
| Wall (R1) | 1.03 | $\left(\bar{t}_{eo}\right)_S = 26.9$ | 27.83 |
| Roof | 1.11 | $\left(\bar{t}_{eo}\right)_{hor} = 22.3$ | 24.68 |
| Ground floor | 0.78 | $\left(\bar{t}_{eo}\right)_{hor} = 26.6$ | 20.68 |
| Glazing | 1.17 | $\bar{t}_{ao} = 19.8$ | 23.08 |
| $\bar{\Phi}_f = \left[\bar{\Phi}_f\right]_{op} + \left[\bar{\Phi}_f\right]_g$ =96.27 (W) | | | |
| Hall entrance | W/K | K | W |
| Wall (R1) | 1.81 | $\left(\bar{t}_{eo}\right)_N = 21.8$ | 39.55 |
| Roof | 1.05 | $\left(\bar{t}_{eo}\right)_{hor} = 22.3$ | 23.40 |
| Ground floor | 0.74 | $\left(\bar{t}_{eo}\right)_{hor} = 26.6$ | 19.58 |
| External door | 1.69 | $\left(\bar{t}_{eo}\right)_N = 21.8$ | 36.90 |
| Glazing | 1.17 | $\bar{t}_{ao} = 19.8$ | 23.08 |
| $\bar{\Phi}_f = \left[\bar{\Phi}_f\right]_{op} + \left[\bar{\Phi}_f\right]_g$ = 142.52 (W) | | | |

#### *B.3.2.1.3 Total gains to the environmental node:*

The total gain to the environmental node, $\bar{\Phi}_{te}$ is the sum of solar, internal and fabric heat gain

Living space: 345.22 + 575.87 = 921.09(W)

Bedroom: 248.76 + 356.54 = 605.30(W)

Office: 51.58 + 98.57 = 150.15 (W)

Bathroom: 51.58 + 96.27 =147.85 (W)

And hall entrance: 19.52 + 142.52 = 162.04 (W)

#### *B.3.2.1.4 Total gain to the air node*

The total gain to air node is then obtained as $\bar{\Phi}_{ta} = \bar{\Phi}_{sa} + \bar{\Phi}_{av}$ with $\bar{\Phi}_{sa} = 0$ because there is neither shading device nor internal blind on any windows, and $\bar{\Phi}_{av} = \bar{t}_{ao} \times C_v$ is solar heat gain as a result of ventilation with the ventilation loss is determined by: $C_v$ = 1/3 x N x V.

A ventilation rate of 1ACH is assumed for whole building area. Ventilation loss value $C_v$ was calculated from the previous section 1.A3

The total gains to air node in different rooms are calculated below:

Living space: $C_v$ = 20.08 (W/K) and $\bar{\Phi}_{ta}$ = 19.8 x 20.08 = 397.67 (W)

Bedroom: $C_v$ = 10.79 (W/K) and $\bar{\Phi}_{ta}$ = 19.8 x 10.79 = 213.72 (W)

Study room: $C_v$ = 4.99 (W/K) and $\bar{\Phi}_{ta}$ = 19.8 x 4.99= 98.87 (W)

Bathroom: $C_v$ = 4.85 (W/K) and $\bar{\Phi}_{ta}$ = 19.8 x 4.85 = 96.0(W)

And hall entrance: $C_v$ = 4.38 (W/K) and $\bar{\Phi}_{ta}$ = 19.8 x 4.38 = 86.71(W)

### *B.3.2.2 Mean internal operative temperature:*

The room conductance corrector with respect to operative temperature is then calculated by:

Living space: $F_{cu} = \dfrac{3(20.08 + 6 \times 81.60)}{25.12 + 18 \times 81.60} = 1.024$

Bedroom: $F_{cu} = \dfrac{3(10.79 + 6 \times 49.01)}{15.66 + 18 \times 49.01} = 1.019$

Office: $F_{cu} = \frac{3(4.99 + 6\times 15.28)}{4.18 + 18\times 15.28} = 1.039$

Bathroom: $F_{cu} = \frac{3(4.85 + 6\times 14.84)}{4.08 + 18\times 14.84} = 1.039$

And hall entrance: $F_{cu} = \frac{3(4.38 + 6\times 19.41)}{6.46 + 18\times 19.41} = 1.019$

Mean peak operative temperature at the centre of the room is obtained:

Living space: $\bar{t}_c = \frac{397.67 + 1.024\times 921.09}{20.08 + 1.024\times 25.12} = 29.27\left({}^{o}C\right)$

Bedroom: $\bar{t}_c = \frac{213.72 + 1.019\times 605.30}{10.79 + 1.019\times 15.66} = 31.04\left({}^{o}C\right)$

Office: $\bar{t}_c = \frac{98.87 + 1.039\times 150.15}{4.99 + 1.039\times 4.176} = 27.31\left({}^{o}C\right)$

Bathroom: $\bar{t}_c = \frac{96.0 + 1.039\times 147.85}{4.85 + 1.039\times 4.08} = 27.45\left({}^{o}C\right)$

And hall entrance: $\bar{t}_c = \frac{86.71 + 1.019\times 162.04}{4.38 + 1.019\times 6.46} = 22.98\left({}^{o}C\right)$

### *B.3.2.3 Determination deviation mean to peak in all heat gain sources*

The response factor of the test unit is determined by: $f_r = \frac{\sum(AY) + C_v}{\sum(AU) + C_v}$

$\Sigma(AY) = 83.24 + 49.70 + 15.87 + 14.42 + 17.85 = 181.08$

$\Sigma(AU) = 25.12 + 15.66 + 4.18 + 4.08 + 6.46 = 55.5$

$\Sigma C_v = 20.08 + 10.79 + 4.99 + 4.85 + 4.38 = 45.09$

$$f_r = \frac{181.08 + 45.09}{55.5 + 45.09} = 2.25$$

Structure with low thermal response factor $f_r < 4$ is considered as fast thermal response building (lightweight structure). For this type of construction, the time at which the peak space temperature occurs with zero lag within the peak hour for solar irradiation ((Table 5.6 in CIBSE, 2006).

#### *B.3.2.3.1 Swing in solar gain*

The peak value of solar irradiance and time peak vary with orientation that the glazing area of the room facing. For a lightweight structure, the cyclic solar gain factor $\tilde{S}_e = 0.57$ (Table 5.7 in CIBSE, 2006a).

Peak of solar irradiance, $\hat{\mathrm{I}}_{\mathrm{t}}$, is determined from Table 2.30 (CIBSE, 2006a) in correspondence with the peak time in LAT and the swing in solar irradiance is given by peak minus mean values ($\tilde{\mathrm{I}}_{\mathrm{t}} = \hat{\mathrm{I}}_{\mathrm{t}} - \bar{\mathrm{I}}_{\mathrm{t}}$). It is observed in the previous solar heat gain section, for the living space and bedroom, the facades R3 and R4 respectively have more important factor than other facades therefore peak, swing and time is determined by those facades. Then the calculated swings in solar heat gain in different rooms on the design day 4th August are given in Table B-23

Table B- 23: Mean to peak solar gain through glazing structure

| **Thermal space** | **Glazed area, $A_g$** | **Time** | **Peak and swing in solar irradiance, $\hat{\mathrm{I}}_{\mathrm{t}} \mid \tilde{\mathrm{I}}_{\mathrm{t}}$** | **Swing in solar gain $\tilde{\Phi}_{se}$** |
|---|---|---|---|---|
| | m$^2$ | 00:00 | W/m$^2$ | W |
| Living space (R1) | 0.886 | 8:30 | $\left(\mathrm{I}_{\mathrm{t}}\right)_{\mathrm{S}} = 305 \mid 128$ | 682.01 |
| (R2) | 0.47 | 8:30 | $\left(\mathrm{I}_{\mathrm{t}}\right)_{\mathrm{N}} = 101 \mid 34$ | |
| (R3) | 2.13 | 8:30 | $\left(\mathrm{I}_{\mathrm{t}}\right)_{\mathrm{E}} = 674 \mid 501$ | |
| Bedroom (R1) | 0.71 | 15:30 | $\left(\mathrm{I}_{\mathrm{t}}\right)_{\mathrm{S}} = 295 \mid \left(\tilde{\mathrm{I}}_{\mathrm{t}}\right)_{\mathrm{S}} = 118$ | 501.0 |
| (R4) | 1.66 | 15:30 | $\left(\hat{\mathrm{I}}_{\mathrm{t}}\right)_{\mathrm{W}} = 645 \mid \left(\tilde{\mathrm{I}}_{\mathrm{t}}\right)_{\mathrm{W}} = 479$ | |
| Office (R1) | 0.47 | 11:30 | $\left(\hat{\mathrm{I}}_{\mathrm{t}}\right)_{\mathrm{S}} = 603 \mid \left(\tilde{\mathrm{I}}_{\mathrm{t}}\right)_{\mathrm{S}} = 426$ | 114.1 |
| Bathroom (R1) | 0.47 | 11:30 | $\left(\hat{\mathrm{I}}_{\mathrm{t}}\right)_{\mathrm{S}} = 603 \mid \left(\tilde{\mathrm{I}}_{\mathrm{t}}\right)_{\mathrm{S}} = 426$ | 114.1 |
| Hall (R2) | 0.47 | 12:30 | $\left(\hat{\mathrm{I}}_{\mathrm{t}}\right)_{\mathrm{S}} = 135 \mid \left(\tilde{\mathrm{I}}_{\mathrm{t}}\right)_{\mathrm{S}} = 68$ | 18.22 |

### *B.3.2.3.2 Swing in structure gain*

Swing in structural gain through glazed elements is calculated by $\left[\tilde{\Phi}_f\right]_g = \sum_n f_{gn} A_{gn} U_{gn} \tilde{t}_{ao}$

With glass, the decrement factor $f_g$ =1 and air temperature consulted in Table 2.34 (CIBSE, 2006a), swing or mean to peak in fabric heat gain through glazed elements calculated at the hour ending of the peak hour for different rooms is given in table below:

Table B- 24: Mean to peak heat gain through building glazed elements

| **Thermal zone** | **$(AxU)_g$** | **Time peak** | **Air temperature at the peak hour $\hat{t}_{ao}$** | **Mean to peak $\tilde{t}_{ao}$** | **Swing in glazed element gain $\left[\tilde{\Phi}_f\right]_g$** |
|---|---|---|---|---|---|
| | W/K | 00:00 | °C | °C or K | W |
| Living space | 8.74 | 09:00 | 19.4 | -0.4 | -3.50 |
| Bedroom | 5.78 | 16:00 | 25.7 | 5.9 | 34.10 |
| Office | 1.17 | 12:00 | 23.9 | 4.1 | 4.78 |
| Bathroom | 1.17 | 12:00 | 23.9 | 4.1 | 4.78 |
| Hall entrance | 1.17 | 13:00 | 24.8 | 5.0 | 5.83 |

The swing in the sol-air temperature $\tilde{t}_{eo}$ is determined by subtracting the mean sol-air temperature from the sol air temperature at a time preceding the peak hour by the value of the time lag associated with the decrement factor of the structure (CIBSE, 2006). For example, the time lag of external wall is of 3 hours then in the living space: t – ø =8:30 – 3:00=5:30, thus 6:00 is used for calculation of the sol air temperature of wall and roof structure of living space; and for the floor with time lag ø=6.5, the sol air temperature at 3:00 is in use (See Table B-25).

Swing in structure heat gain through opaque elements is calculated by:

$$\left[\tilde{\Phi}_f\right]_{op} = \sum_n f_n A_n U_n \tilde{t}_{eo}$$

Calculation of swing structural heat gain for different rooms in the test building is shown in Table B-25 and B-26 .Values of sol air temperature at different design time can be referred to Table 5.34 in CIBSE (2006). Thermal properties of building elements (e.g. U-value and decrement factor, f) can be found in Tables B-16- B-18.

Table B- 25: Swing in fabric gain through the living space and bedroom

| **Thermal zone** | **AxU** | **Decrement factor f** | **Sol air temperature at (t- ø) and swing value, \|** $t_{eo} \mid \tilde{t}_{eo} = t_{eo} - \bar{t}_{eo}$ | **Mean fabric heat gain,** $\left[\tilde{\Phi}_f\right]_{op}$ |
|---|---|---|---|---|
| Living space | W/K | - | K \| at 06:00 for wall and roof; at 03:00 for floor | W |
| Wall (R1) | 3.12 | 0.91 | $\left(t_{eo}\right)_S = 14.8 \mid \left(\tilde{t}_{eo}\right)_S = -12.1$ | -34.35 |
| Wall (R2) | 3.25 | 0.91 | $\left(t_{eo}\right)_N = 19.1 \mid \left(\tilde{t}_{eo}\right)_N = -2.7$ | -7.98 |
| Wall (R3) | 2.09 | 0.91 | $\left(t_{eo}\right)_E = 30.7 \mid \left(\tilde{t}_{eo}\right)_E = 3.2$ | 6.07 |
| Roof | 4.65 | 0.94 | $\left(t_{eo}\right)_{hor} = 13.3 \mid \left(\tilde{t}_{eo}\right)_{hor} = -9$ | -39.36 |
| Ground floor | 3.27 | 0.79 | $\left(t_{eo}\right)_{hor} = 15.1 \mid \left(\tilde{t}_{eo}\right)_{hor} = -11.5$ | -29.70 |
| $\Phi_f = \left(\Phi_f\right)_{op} + \left(\Phi_f\right)_g$ = -75.63 – 3.50=-79.13(W) | | | | |
| Bedroom | W/K | - | K\| at (t- ø) = 13:00 and 10:00 for floor | W |
| Wall (R1) | 1.61 | 0.91 | $\left(t_{eo}\right)_S = 52 \mid \left(\tilde{t}_{eo}\right)_S = 25.1$ | 36.84 |
| Wall (R2) | 1.83 | 0.91 | $\left(t_{eo}\right)_N = 31.9 \mid \left(\tilde{t}_{eo}\right)_N = 10.1$ | 16.81 |
| Wall (R4) | 2.18 | 0.91 | $\left(t_{eo}\right)_W = 36.5 \mid \left(\tilde{t}_{eo}\right)_W = 10.7$ | 21.24 |
| Roof | 2.50 | 0.94 | $\left(t_{eo}\right)_{hor} = 36 \mid \left(\tilde{t}_{eo}\right)_{hor} = 13.7$ | 32.21 |
| Ground floor | 1.76 | 0.79 | $\left(t_{eo}\right)_{hor} = 42.2 \mid \left(\tilde{t}_{eo}\right)_{hor} = 15.6$ | 21.65 |
| $\Phi_f = \left(\Phi_f\right)_{op} + \left(\Phi_f\right)_g$ =128.75+34.12 =162.87(W) | | | | |

Table B- 26: Swing in fabric gain through the office, bathroom and hall entrance

| **Thermal zone** | **AxU** | **Decrement factor, f** | **Sol air temperature at (t- ø) and swing value,** $t_{eo} \mid \tilde{t}_{eo} = t_{eo} - \bar{t}_{eo}$ | **Mean fabric heat gain,** $\left[\Phi_f\right]_{op}$ |
|---|---|---|---|---|
| Office | W/K | - | °C\| at 09:00 for wall and roof; 06:00 for floor | W |
| Wall (R1) | 1.07 | 0.91 | $\left(t_{eo}\right)_S = 36 \mid \left(\tilde{t}_{eo}\right)_S = 9.1$ | 8.86 |
| Roof | 1.14 | 0.94 | $\left(t_{eo}\right)_{hor} = 28.2 \mid \left(\tilde{t}_{eo}\right)_{hor} =$ | 6.32 |
| Ground floor | 0.80 | 0.79 | $\left(t_{eo}\right)_{hor} = 15.1 \mid \left(\tilde{t}_{eo}\right)_{hor} =$ | -7.27 |
| $\Phi_f = \left(\Phi_f\right)_{op} + \left(\Phi_f\right)_g$ = 7.92 + 4.78= 12.70 (W) | | | | |
| Bathroom | W/K | - | K\| 9:00 and 6:00 | W |
| Wall (R1) | 1.03 | 0.91 | $\left(t_{eo}\right)_S = 36 \mid \left(\tilde{t}_{eo}\right)_S = 9.1$ | 8.86 |
| Roof | 1.11 | 0.94 | $\left(t_{eo}\right)_{hor} = 28.2 \mid \left(\tilde{t}_{eo}\right)_{hor} =$ | 6.14 |
| Ground floor | 0.78 | 0.79 | $\left(t_{eo}\right)_{hor} = 15.1 \mid \left(\tilde{t}_{eo}\right)_{hor} = -$ | -7.06 |
| $\Phi_f = \left(\Phi_f\right)_{op} + \left(\Phi_f\right)_g$ =7.63 +4.78 =12.41 (W) | | | | |
| Hall entrance | W/K | - | K\| 10:00 and 7:00 | W |
| Wall (R1) | 1.81 | 0.91 | $\left(t_{eo}\right)_N = 27.7 \mid \left(\tilde{t}_{eo}\right)_N = 5.$ | 9.74 |
| Roof | 1.05 | 0.94 | $\left(t_{eo}\right)_{hor} = 31.7 \mid \left(\tilde{t}_{eo}\right)_{hor} =$ | 9.27 |
| Ground floor | 0.74 | 0.79 | $\left(t_{eo}\right)_{hor} = 22.3 \mid \left(\tilde{t}_{eo}\right)_{hor} = -$ | -2.5 |
| $\Phi_f = \left(\Phi_f\right)_{op} + \left(\Phi_f\right)_g$ =16.51 + 5.83 =22.34 (W) | | | | |

#### *B.3.2.3.3 Total swing in heat gains to environmental node:*

Living space: $\tilde{\Phi}_{te} = 682.01 - 79.13 = 602.88 (W)$

Bedroom: $\tilde{\Phi}_{te} = 501.0 + 162.87 = 663.87 (W)$

Office: $\tilde{\Phi}_{te} = 114.1 + 12.70 = 126.80 (W)$

Bathroom: $\tilde{\Phi}_{te} = 114.1 + 12.41 = 126.51(W)$

And hall entrance: $\tilde{\Phi}_{te} = 18.22 + 22.34 = 40.56(W)$

#### *B.3.2.3.4 Total swing in heat gains to air node*

Swing in heat gains to the air node is equal to swing in heat gains from ventilation as the result of absence of internal blinds hence value solar heat gain to air node is assumed to be nil.

Living space: $\tilde{\Phi}_{ta} = C_v \tilde{t}_{ao} = 20.08 \times (-0.4) = -8.03W)$

Bedroom: $\tilde{\Phi}_{ta} = C_v \tilde{t}_{ao} = 10.79 \times 5.9 = 63.68(W)$

Office: $\tilde{\Phi}_{ta} = C_v \tilde{t}_{ao} = 4.993 \times 4.1 = 20.47(W)$

Bathroom: $\tilde{\Phi}_{ta} = C_v \tilde{t}_{ao} = 4.85 \times 4.1 = 19.88(W)$

And hall entrance: $\tilde{\Phi}_{ta} = C_v \tilde{t}_{ao} = 4.38 \times 5 = 21.90(W)$

### *B.3.2.4 Swing in operative temperature*

The room admittance factor with respective to operative temperature $F_{cy}$ is determined by $F_{cy} = \dfrac{3\left(C_v + 6\sum A\right)}{\sum (AY) + 18\sum A}$ thus:

Living space: $F_{cy} = \dfrac{3\left(20.08 + 6 \times 81.60\right)}{83.24 + 18 \times 81.60} = 0.985$

Bedroom: $F_{cy} = \dfrac{3\left(10.79 + 6 \times 49.01\right)}{49.70 + 18 \times 49.01} = 0.977$

Office: $F_{cy} = \dfrac{3\left(4.99 + 6 \times 15.28\right)}{15.87 + 18 \times 15.28} = 0.997$

Bathroom: $F_{cy} = \dfrac{3\left(4.85 + 6 \times 14.84\right)}{15.42 + 18 \times 14.84} = 0.997$

And hall entrance: $F_{cy} = \dfrac{3\left(4.38 + 6 \times 19.41\right)}{17.85 + 18 \times 19.41} = 0.987$

The swing in internal operative temperature is then calculated by $\tilde{t}_c = \dfrac{\tilde{\Phi}_{ta} + F_{cy}\tilde{\Phi}_{te}}{C_v + F_{cy}\sum(AY)}$

Living space: $\tilde{t}_c = \dfrac{-8.03 + 0.985 \times 602.88}{20.08 + 0.985 \times 83.24} = 5.74\left({}^{o}C\right)$

Bedroom: $\tilde{t}_c = \dfrac{63.68 + 0.977 \times 663.87}{10.79 + 0.977 \times 49.70} = 12\left({}^{o}C\right)$

Office: $\tilde{t}_c = \dfrac{20.47 + 0.997 \times 126.80}{4.99 + 0.997 \times 15.87} = 7.06\left({}^{o}C\right)$

Bathroom: $\tilde{t}_c = \dfrac{19.88 + 0.997 \times 126.51}{4.85 + 0.997 \times 14.84} = 7.22\left({}^{o}C\right)$

And hall entrance: $\tilde{t}_c = \dfrac{21.90 + 0.987 \times 40.56}{4.38 + 0.987 \times 17.85} = 2.82\left({}^{o}C\right)$

### *B.3.2.5 Peak in operative temperature*

For living space: $\hat{t}_c = 29.27 + 5.74 = 35.01\left({}^{o}C\right)$ at 9:00

For bedroom: $\hat{t}_c = 31.04 + 12 = 43.04\left({}^{o}C\right)$ at 16:00

For office $\hat{t}_c = 27.31 + 7.06 = 34.37\left({}^{o}C\right)$ at 12:00

And bathroom: $\hat{t}_c = 27.45 + 7.22 = 34.67\left({}^{o}C\right)$ at 12:00

And hall entrance: $\hat{t}_c = 22.98 + 2.82 = 25.79\left({}^{o}C\right)$ at 13:00

### *B.3.2.6 Cooling load with operative temperature control*

For comfort reason, the operative temperature in dwelling is set at 24°C. Due to absence of internal heat gain for simplification, the mean convective cooling load is equal to mean fabric heat gain (i.e. $\overline{\Phi}_a = \overline{\Phi}_{fa}$ while referring to the formula in Section 4.1.5)

The mean fabric heat gain to the air node is calculated by $\overline{\Phi}_{fa} = F_{cu} \times (AU) x \left(\overline{t}_{eo} - 24\right)$ as shown in Tables 1.A-28 and 1.A-29.

Table B- 27: Mean fabric heat gain to the air node in the living space and the bedroom

| **Thermal zone** | **Conductive factor** $F_{cu}$ | **AxU** | **Mean sol air temperature,** $\bar{t}_{eo}$ **(°C) and** $\bar{t}_{eo}-24$ | **Mean fabric heat gain,** $\bar{\Phi}_{fa}$ |
|---|---|---|---|---|
| Living space | 1.024 | W/K | K | W |
| Wall (R1) | | 3.12 | $\left(\bar{t}_{eo}\right)_S = 26.9 \mid \bar{t}_{eo} - 24 = 2.9$ | `9.26 |
| Wall (R2) | | 3.25 | $\left(\bar{t}_{eo}\right)_N = 21.8 \mid \bar{t}_{eo} - 24 = -2.2$ | -7.32 |
| Wall (R3) | | 2.09 | $\left(\bar{t}_{eo}\right)_E = 27.5 \mid \bar{t}_{eo} - 24 = 3.5$ | 7.47 |
| Roof | | 4.65 | $\left(\bar{t}_{eo}\right)_{hor} = 22.3 \mid \bar{t}_{eo} - 24 = -1.7$ | -8.10 |
| Ground floor | | 3.27 | $\left(\bar{t}_{eo}\right)_{hor} = 26.6 \mid \bar{t}_{eo} - 24 = 2.6$ | 8.70 |
| Glazing | | 8.74 | $\bar{t}_{ao} = 19.8 \mid \bar{t}_{eo} - 24 = -4.2$ | -37.57 |
| $\bar{\Phi}_{fa} = -27.55\left(W\right)$ | | | | |
| Bedroom | - | W/K | K | W |
| Wall (R1) | 1.019 | 1.61 | $\left(\bar{t}_{eo}\right)_S = 26.9 \mid \bar{t}_{eo} - 24 = 2.9$ | 4.72 |
| Wall (R2) | | 1.83 | $\left(\bar{t}_{eo}\right)_N = 21.8 \mid \bar{t}_{eo} - 24 = -2.2$ | -4.06 |
| Wall (R4) | | 2.18 | $\left(\bar{t}_{eo}\right)_W = 25.8 \mid \bar{t}_{eo} - 24 = 1.8$ | 3.97 |
| Roof | | 2.50 | $\left(\bar{t}_{eo}\right)_{hor} = 22.3 \mid \bar{t}_{eo} - 24 = -1.7$ | -4.30 |
| Ground floor | | 1.76 | $\left(\bar{t}_{eo}\right)_{hor} = 26.6 \mid \bar{t}_{eo} - 24 = 2.6$ | 4.61 |
| Glazing | | 5.78 | $\bar{t}_{ao} = 19.8 \mid \bar{t}_{eo} - 24 = -4.2$ | -24.53 |
| $\bar{\Phi}_{fa} = -19.59\left(W\right)$ | | | | |

Table B- 28: Mean fabric heat gain in the office, bathroom and hall entrance

| **Thermal zone** | **Conductive factor** $F_{cu}$ | **AxU** | **Mean sol air temperature,** $\overline{t}_{eo}$ **(°C) and** $\overline{t}_{eo} - 24$ | **Mean fabric heat gain,** $\overline{\Phi}_{fa}$ |
|---|---|---|---|---|
| Office | | W/K | K | W |
| Wall (R1) | 1.039 | 1.07 | $(\overline{t}_{eo})_S = 26.9 \mid \overline{t}_{eo} - 24 = 2.9$ | 3.26 |
| Roof | | 1.14 | $(\overline{t}_{eo})_{hor} = 22.3 \mid \overline{t}_{eo} - 24 = -1.$ | -2.01 |
| Ground floor | | 0.80 | $(\overline{t}_{eo})_{hor} = 26.6 \mid \overline{t}_{eo} - 24 = 2.6$ | 2.16 |
| Glazing | | 1.17 | $\overline{t}_{ao} = 19.8 \mid \overline{t}_{eo} - 24 = -4.2$ | -5.09 |
| $\overline{\Phi}_{fa} = -1.71(W)$ | | | | |
| Bathroom | | W/K | K | W |
| Wall (R1) | 1.039 | 1.03 | $(\overline{t}_{eo})_S = 26.9 \mid \overline{t}_{eo} - 24 = 2.9$ | 3.11 |
| Roof | | 1.11 | $(\overline{t}_{eo})_{hor} = 22.3 \mid \overline{t}_{eo} - 24 = -1.$ | -1.95 |
| Ground floor | | 0.78 | $(\overline{t}_{eo})_{hor} = 26.6 \mid \overline{t}_{eo} - 24 = 2.6$ | 2.10 |
| Glazing | | 1.17 | $\overline{t}_{ao} = 19.8 \mid \overline{t}_{eo} - 24 = -4.2$ | -5.08 |
| $\overline{\Phi}_{fa} = -1.82(W)$ | | | | |
| Hall entrance | | W/K | K | W |
| Wall (R1) | 1.019 | 1.03 | $(\overline{t}_{eo})_N = 21.8 \mid \overline{t}_{eo} - 24 = -2.2$ | -4.07 |
| Roof | | 1.11 | $(\overline{t}_{eo})_{hor} = 22.3 \mid \overline{t}_{eo} - 24 = -1.$ | -1.82 |
| Ground floor | | 0.78 | $(\overline{t}_{eo})_{hor} = 26.6 \mid \overline{t}_{eo} - 24 = 2.6$ | 1.95 |
| Glazing | | 1.17 | $\overline{t}_{ao} = 19.8 \mid \overline{t}_{eo} - 24 = -4.2$ | -4.99 |
| $\overline{\Phi}_{fa} = -8.92(W)$ | | | | |

The alternating component of the fabric gain to the air node is given by $\Phi_{fa} = F_{cy} \times \Phi_f$, where $\Phi_f$, the swing in structure gains can be referred to Table B-25 and B-26, and $F_{cy}$ was determined in Section B.3.2.4

Living space: $\Phi_{fa} = F_{cy} \times \Phi_f = 0.985 \times (-79.13) = -77.95(\mathrm{W})$

Bedroom: $\Phi_{fa} = 0.977 \times 162.87 = 159.13(\mathrm{W})$

Office: $\Phi_{fa} = 0.997 \times 12.70 = 12.66(\mathrm{W})$

Bathroom: $\Phi_{fa} = 0.997 \times 12.42 = 12.38(\mathrm{W})$

And hall entrance: $\Phi_{fa} = 0.987 \times 22.34 = 22.06(\mathrm{W})$

The cooling loads related to the ventilation in different rooms are to be determined as below:

Living space: $C_v$ = 20.08 (W/K) and $\Phi_v$= 20.08 x (19.8 – 24) = -84.35 (W)

Bedroom: $C_v$ = 10.79 (W/K) and $\Phi_v$= 10.79 x (19.8 – 24) = -45.33 (W)

Office: $C_v$ = 4.99 (W/K) and $\Phi_v$= 4.99 x (19.8 – 24) = -20.97 (W)

Bathroom: $C_v$ = 4.85 (W/K) and $\Phi_v$= 4.85 x (19.8 – 24) = -20.36(W)

And hall entrance: $C_v$ = 4.38 (W/K) and $\Phi_v$= 4.38 x (19.8 – 24) = -18.39(W)

Solar gain factor at the environmental node for double glazing windows which are clear-low emissivity: $S_e = 0.62$ (Table 5.7 in CIBSE, 2006a).

The cooling loads due to glazing structure are given by $\Phi_{sg} = S_e \times A_g \times \hat{I}$ as shown in Table B-29

As the total sensible cooling load is given by $\Phi_k = \overline{\Phi}a + \Phi_a + \Phi_v + \Phi_{sg}$, cooling loads for different rooms are calculated as below:

Living space: $\Phi_k$ = -27.55 – 77.95 - 84.35 + 1072.01=882.15 (W) (VE=0.88)

Bedroom: $\Phi_k$ =-19.59 +159.13 -45.33 +678.13=772.3 (W)

Office: $\Phi_k$ = -1.65+ 12.66 -20.97+175.71 = 165.75 (W)

Bathroom: $\Phi_k$ =-1.82 + 12.3 -20.36 + 175.71 = 165.90 (W).

And hall entrance: $\Phi_k$ =-8.92 + 22.06 – 18.39 + 83.70 = 78.44 (W).

Table B- 29: Mean to peak solar gain through glazing structure

| **Thermal space** | **Net glazed area, $A_g$** | **Time** | **Peak in solar irradiance, $\hat{I}_t$** | **Peak solar gain $\Phi_{sg}$** |
|---|---|---|---|---|
| | $m^2$ | 00:00 | $W/m^2$ | W |
| Living space (R1) | 0.886 | 8:30 | $\left(I_t\right)_S = 305$ | 1072.01 |
| (R2) | 0.47 | 8:30 | $\left(I_t\right)_N = 101$ | |
| (R3) | 2.13 | 8:30 | $\left(\hat{I}_t\right)_E = 674$ | |
| Bedroom (R1) | 0.71 | 15:30 | $\left(I_t\right)_S = 295$ | 678.13 |
| (R4) | 1.66 | 15:30 | $\left(\hat{I}_t\right)_W = 645$ | |
| Study room (R1) | 0.47 | 11:30 | $\left(\hat{I}_t\right)_S = 603$ | 175.71 |
| Bathroom (R1) | 0.47 | 11:30 | $\left(\hat{I}_t\right)_S = 603$ | 175.71 |
| Hall entrance (R2) | 0.47 | 12:30 | $\left(\hat{I}_t\right)_N = 135$ | 83.70 |

# Appendix C- SAP CALCULATION

The Government's Standard Assessment Procedure (SAP), which was used to assess the energy performance of the test building, is presented in this section. The indicators of energy performance are: energy consumption per unit floor area; an energy cost rating (the SAP rating); an Environmental Impact rating based on $CO_2$ emissions (the EI rating); and a Dwelling $CO_2$ Emission Rate (DER). The SAP rating is based on the energy cost per square metre which is calculated using a simplified form of SAP. The energy costs take into account the costs of space and water heating, ventilation and lighting, less any cost savings from energy generation technologies. The rating is expressed on a scale of 1-100, where a dwelling with a rating of 1 has poor energy efficiency (high costs) and a dwelling with a rating of 100, represents a completely energy efficient dwelling (zero net energy costs per year). The EI rating is related to the annual $CO_2$ emissions, and on its rating scale, EI 100 means that the dwelling achieves zero net emissions. It can rise above 100 if the dwelling is a net exporter of energy. The Building Regulations refer to $CO_2$ emissions, as calculated by SAP (DER), as a method of demonstrating compliance with regulations regarding conservation of fuel and power. It sets out the limitation on the permissible annual $CO_2$ emissions from new dwellings, expressed in kilograms per square metre of floor area (kg/m²).

## *C.1 SAP REPORT*

In order to provide a SAP rating, the most recent version to comply with 2010 Building Regulation is SAP2009 developed by JPA Designer Version 5.03a1 011, SAP Version 9.90. Licensed to Demo Version © JPA Technical Literature Jul 2012. Approval of JPA Designer by BRE, applies only to the software. Data is not subject to quality control procedures and users are themselves responsible for the accuracy of the data. The information in this report is for information checking/reference purpose and not an official document assigned for the EH dwelling unit provided by 3rd party.

### *1. Overall dwelling dimensions*

| | **Area (m²)** | **Average Storey height (m)** | **Volume (m³)** | |
|---|---|---|---|---|
| Ground floor (1) | 45.87 | 2.95 | 135.32 | (3a) |
| Total floor area | 45.87 | | | (4) |
| Dwelling volume (m³) | | | 135.32 | (5) |

### *2. Ventilation rate*

| | **Main + secondary + other heating** | | **$m^3$ per hour** | |
|---|---|---|---|---|
| Number of chimneys | 0 + 0 + 0 | x 40 | 0.00 | (6a) |
| Number of open flues | 0 + 0 + 0 | x 20 | 0.00 | (6b) |
| Number of intermittent fans | 2 | x 10 | 20.00 | (7a) |
| Number of passive vents | 0 | x 10 | 0.00 | (7b) |
| Number of flueless gas fires | 0 | x 40 | 0.00 | (7c) |
| | | | Air changes per hour | |
| Infiltration due to chimneys, fans and flues | | | 0.15 | (8) |
| Pressure test, result q50 | | | *1.82* | (17) |
| Air permeability | | | 0.24 | (18) |
| Number of sides on which sheltered | | | 4.00 | (19) |
| Shelter factor | | | 0.70 | (20) |
| Infiltration rate incorporating shelter factor | | | 0.17 | (21) |

Infiltration rate modified for monthly wind speed:

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|

Monthly average wind speed

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5.40 | 5.10 | 5.10 | 4.50 | 4.10 | 3.90 | 3.70 | 3.70 | 4.20 | 4.50 | 4.80 | 5.10 |

54.10 (22)

Wind factor

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.35 | 1.27 | 1.27 | 1.13 | 1.02 | 0.98 | 0.93 | 0.93 | 1.05 | 1.13 | 1.20 | 1.27 |

13.53 (22a)

Adjusted infiltration rate (Allowing for shelter and wind speed)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.23 | 0.21 | 0.21 | 0.19 | 0.17 | 0.16 | 0.15 | 0.15 | 0.18 | 0.19 | 0.20 | 0.21 |

2.26 (22b)

Ventilation: natural ventilation, intermittent extracting fans

Effective air change rate

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.53 | 0.52 | 0.52 | 0.52 | 0.51 | 0.51 | 0.51 | 0.51 | 0.52 | 0.52 | 0.52 | 0.52 | (25) |

### *3. Heat losses and heat loss parameter*

| **Element** | **Net area m$^2$** | **U-value W/m$^2$K** | **A x U W/K** | **K-value kJ/m$^2$K** | **A x K kJ/K** | |
|---|---|---|---|---|---|---|
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (East), Living space | **1.05** | **1.70 (1.82)** | 1.78 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (East) Living space | **1.05** | **1.70 (1.82)** | 1.78 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (East) Living space | **0.64** | **1.70 (1.82)** | 1.09 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (North) Living space | **0.64** | **1.70 (1.82)** | 1.09 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South), Living space | **0.91** | **1.70 (1.82)** | 1.54 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South) Living space | **0.29** | **1.70 (1.82)** | 0.49 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South), Bathroom | **0.64** | **1.70 (1.82)** | 1.09 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South) Office | **0.64** | **1.70(1.82)** | 1.09 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South), Bedroom | **0.91** | **1.70 (1.82)** | 1.54 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (West), Bedroom | **1.05** | **1.70 (1.82)** | 1.78 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (West), Bedroom | **1.05** | **1.70 (1.82)** | 1.78 | | | (27) |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat , (North), Hall | **0.64** | **1.70(1.82)** | 1.09 | | | (27) |
| Solid door | **1.84** | **0.90** | 1.66 | | | (26) |

**External walls and pitched roof**

| **Element** | **Net area m²** | **U-value W/m²K** | **A x U W/K** | **K-value kJ/m²K** | **A x K kJ/K** | |
|---|---|---|---|---|---|---|
| Walls, NCM typical external wall, Living space | 13.54 | 0.24 | 3.25 | 9.00 | 121.86 | (29) |
| Walls, NCM typical external wall, Living space | 8.69 | 0.24 | 2.09 | 9.00 | 78.21 | (29) |
| Walls, NCM typical external wall, Living space | 12.99 | 0.24 | 3.12 | 9.00 | 116.91 | (29) |
| Walls, NCM typical external wall, Bathroom | 4.31 | 0.24 | 1.03 | 9.00 | 38.79 | (29) |
| Walls, NCM typical external wall, Office | 4.46 | 0.24 | 1.07 | 9.00 | 40.14 | (29) |
| Walls, NCM typical external wall, Bedroom | 7.62 | 0.24 | 1.83 | 9.00 | 68.58 | (29) |
| Walls, NCM typical external wall, Bedroom | 9.33 | 0.24 | 2.24 | 9.00 | 83.97 | (29) |
| Walls, NCM typical external wall, Bedroom | 6.72 | 0.24 | 1.61 | 9.00 | 60.48 | (29) |
| Walls, NCM typical external wall, Hall | 7.56 | 0.24 | 1.81 | 9.00 | 68.04 | (29) |
| Pitched roofs insulated between joists, Living space | 10.54 | 0.22 | 2.32 | 9.00 | 94.86 | (30) |
| Pitched roofs insulated between joists, Living space | 10.61 | 0.22 | 2.33 | 9.00 | 95.49 | (30) |
| Pitched roofs insulated between joists, Bathroom | 3.68 | 0.22 | 0.81 | 9.00 | 33.12 | (30) |
| Pitched roofs insulated between joists, Bathroom | 1.35 | 0.22 | 0.30 | 9.00 | 12.15 | (30) |
| Pitched roofs insulated between joists, Office | 3.79 | 0.22 | 0.83 | 9.00 | 34.11 | (30) |
| Pitched roofs insulated between joists, Office | 1.39 | 0.22 | 0.31 | 9.00 | 12.51 | (30) |
| Pitched roofs insulated between joists, Bedroom | 5.70 | 0.22 | 1.25 | 9.00 | 51.30 | (30) |
| Pitched roofs insulated between joists, Bedroom | 5.67 | 0.22 | 1.25 | 9.00 | 51.03 | (30) |
| Pitched roofs insulated between joists, Hall | 4.77 | 0.22 | 1.05 | 9.00 | 42.93 | (30) |

**Ground floor**

| **Element** | **Net area m²** | **U-value W/m²K** | **A x U W/K** | **K-value kJ/m²K** | **A x K kJ/K** | |
|---|---|---|---|---|---|---|
| Ground floor, NCM typical floor, Living space, | 20.43 | 0.16 | 3.26 | 20.00 | 408.60 | (28) |
| Ground floor, NCM typical floor, Bathroom | 4.86 | 0.16 | 0.78 | 20.00 | 97.20 | (28) |
| Ground floor, NCM typical floor, Study room, | 5.00 | 0.16 | 0.80 | 20.00 | 100.00 | (28) |
| Ground floors, NCM typical floor, Bedroom | 10.98 | 0.16 | 1.76 | 20.00 | 219.60 | (28) |
| Ground floors, NCM typical floor, Hall | 4.60 | 0.16 | 0.74 | 20.00 | 92.00 | (28) |

| | | |
|---|---|---|
| Total area of external elements Sigma A | 179.94 m² | (31) |
| Fabric heat loss | 50.08 W/K | (33) |
| Thermal mass parameter, (user-specified TMP) | 100 kJ/m²K | (35) |
| Effect of thermal bridges | 1.26 | (36) |
| Total fabric heat loss | 51.34 | (37) |

Ventilation heat loss calculated monthly:

Number of days in a month

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | 28 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |

Ventilation heat loss calculated monthly:

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23.46 | 23.34 | 23.34 | 23.12 | 22.98 | 22.92 | 22.86 | 22.86 | 23.02 | 23.12 | 23.23 | 23.34 | (38) |

Heat transfer coefficient, W/K

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 74.80 | 74.68 | 74.68 | 74.45 | 74.32 | 74.26 | 74.20 | 74.20 | 74.35 | 74.45 | 74.56 | 74.68 |

74.47 (39)

Heat loss parameter (HLP), W/m²K

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.63 | 1.63 | 1.63 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.62 | 1.63 | 1.63 |

HLP (average) 1.62 (40)

### *4. Water heating energy requirements* **kWh/year**

Annual occupancy, N 1.57 (42)

Annual average hot water usage in litres per day Vd, average 75.24 (43)

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|

Hot water usage in litres per day for each month

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 82.76 | 79.75 | 76.74 | 73.74 | 70.73 | 67.72 | 67.72 | 70.73 | 73.74 | 76.74 | 79.75 | 82.76 | (44) |

Energy content of hot water used

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 123.03 | 107.60 | 111.04 | 96.80 | 92.89 | 80.15 | 74.27 | 85.23 | 86.25 | 100.51 | 109.72 | 119.15 |

Energy content (annual) 1186.65 (45)

Distribution loss

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18.45 | 16.14 | 16.66 | 14.52 | 13.93 | 12.02 | 11.14 | 12.78 | 12.94 | 15.08 | 16.46 | 17.87 | (46) |

| | | |
|---|---|---|
| Hot water storage volume (litres) | 50.00 | (50) |
| Hot water cylinder loss factor (kWh/day) | 0.0094 | (51) |
| Volume factor | 1.3389 | (52) |
| Temperature factor | 0.5400 | (53) |
| Energy lost from hot water cylinder (kWh/year) | 0.34 | (55) |

Storage loss

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10.57 | 9.55 | 10.57 | 10.23 | 10.57 | 10.23 | 10.57 | 10.57 | 10.23 | 10.57 | 10.23 | 10.57 | (57) |

Primary circuit loss (annual) 360.00 (58)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 30.58 | 27.62 | 30.58 | 29.59 | 30.58 | 29.59 | 30.58 | 30.58 | 29.59 | 30.58 | 29.59 | 30.58 | (59) |

Total heat required for water heating calculated for each month

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 164.2 | 144.8 | 152.2 | 136.6 | 134.0 | 120.0 | 115.4 | 126.4 | 126.1 | 141.7 | 149.5 | 160.3 | (62) |

Output from water heater for each month, kWh/month

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 164.2 | 144.8 | 152.2 | 136.6 | 134.0 | 120.0 | 115.4 | 126.4 | 126.1 | 141.7 | 149.5 | 160.3 | (62) |

1671.15 (64)

Heat gains from water heating, kWh/month

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 73.83 | 65.51 | 69.84 | 64.04 | 63.80 | 58.51 | 57.62 | 61.26 | 60.53 | 66.34 | 68.34 | 72.54 | (65) |

### ***5. Internal gains***

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |

Metabolic gains, Watts

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 94.18 | 94.18 | 94.18 | 94.18 | 94.18 | 94.18 | 94.18 | 94.18 | 94.18 | 94.18 | 94.18 | 94.18 | (66) |

Lighting gains

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 30.43 | 27.03 | 21.98 | 16.64 | 12.44 | 10.50 | 11.35 | 14.75 | 19.80 | 25.14 | 29.34 | 31.27 | (67) |

Appliances gains

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 203.8 | 205.9 | 200.6 | 189.2 | 174.9 | 161.4 | 152.4 | 150.3 | 155.7 | 167.0 | 181.3 | 194.8 |

Cooking gains

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 45.99 | 45.99 | 45.99 | 45.99 | 45.99 | 45.99 | 45.99 | 45.99 | 45.99 | 45.99 | 45.99 | 45.99 |

Pumps and fans gains

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Losses e.g. evaporation (negative values)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -62.78 | -62.78 | -62.78 | -62.78 | -62.78 | -62.78 | -62.78 | -62.78 | -62.78 | -62.78 | -62.78 | -62.78 |

Water heating gains

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 99.23 | 97.49 | 93.87 | 88.95 | 85.76 | 81.26 | 77.44 | 82.34 | 84.08 | 89.17 | 94.92 | 97.49 |

Total internal gains

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 410.8 | 407.8 | 393.8 | 372.2 | 350.5 | 330.6 | 318.6 | 324.8 | 336.9 | 358.7 | 383.0 | 400.9 |

### 6. *Solar gains (calculation for January)*

| **Element** | **Area and Flux** | **g & FF** | **Shading** | **Gains** |
|---|---|---|---|---|
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (East), Living space | 0.9x1.1<br>19.87 | 0.63x0.70 | 1.00 | 8.28 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (East) Living space | 0.9x1.1 1<br>9.87 | 0.63x0.70 | 1.00 | 8.28 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (East) Living space | 0.9x0.6<br>19.87 | 0.63x0.70 | 1.00 | 5.05 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (North) Living space | 0.9x0.6<br>10.73 | 0.63x0.70 | 1.00 | 2.72 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South), Living space | 0.9x0.9<br>47.32 | 0.63x0.70 | 1.00 | 17.09 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South) Living space | 0.9x0.3<br>47.32 | 0.63x0.70 | 1.00 | 5.45 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South), Bathroom | 0.9x0.6<br>47.32 | 0.63x0.70 | 1.00 | 12.02 |

| | | | | |
|---|---|---|---|---|
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South) Office | 0.9x0.6<br>47.32 | 0.63x0.70 | 1.00 | 15.65 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South), Bedroom | 0.9x0.9<br>47.32 | 0.63x0.70 | 1.00 | 17.09 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (West), Bedroom | 0.9x1.1<br>19.87 | 0.63x0.70 | 1.00 | 8.28 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (West), Bedroom | 0.9x1.1<br>19.87 | 0.63x0.70 | 1.00 | 8.28 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat , (North), Hall | 0.9x0.6<br>10.73 | 0.63x0.70 | 1.00 | 2.10 |
| Solid door, Hall | 0.9x1.8<br>0.00 | 0.00 x 0.70 | 0.77 | 0.00 |

Total solar gains, January 106.67 (83-1)

Solar gains

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 106.7 | 187.0 | 260.1 | 341.6 | 393.5 | 407.3 | 396.1 | 355.8 | 294.4 | 216.0 | 128.9 | 90.53 |

(83)

Total gains

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 517.5 | 594.8 | 653.8 | 713.8 | 744.0 | 737.8 | 714.7 | 680.6 | 631.3 | 574.7 | 511.8 | 491.5 |

(84)

***Lighting calculations***

| **Element** | **Area** | **g** | **FF x Shading** | **Gains** |
|---|---|---|---|---|
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat<br>(East), Living space | 0.9x1.05 | 0.82 | 0.70x0.83 | 0.44 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (East) Living space | 0.9x1.05 | 0.82 | 0.70x0.83 | 0.44 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (East) Living space | 0.9x0.64 | 0.82 | 0.70x0.83 | 0.27 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat<br>(North) Living space | 0.9x0.64 | 0.82 | 0.70x0.83 | 0.27 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft | 0.9x0.91 | 0.82 | 0.70x0.83 | 0.38 |

| | | | | |
|---|---|---|---|---|
| coat (South), Living space | | | | |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South) Living space | 0.9x0.29 | 0.82 | 0.70x0.83 | 0.12 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South), Bathroom | 0.9x0.64 | 0.82 | 0.70x0.83 | 0.27 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South) Office | 0.9x0.64 | 0.82 | 0.70x0.83 | 0.27 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (South), Bedroom | 0.9x0.91 | 0.82 | 0.70x0.83 | 0.38 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (West), Bedroom | 0.9x1.05 | 0.82 | 0.70x0.83 | 0.44 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat (West), Bedroom | 0.9x1.05 | 0.82 | 0.70x0.83 | 0.44 |
| Window Double-glazed, air-filled, low-E, En=0.1, soft coat , (North), Hall | 0.9x0.64 | 0.82 | 0.70x0.83 | 0.27 |

GL = 4.74 / 45.87 = 0.103

C1 = 0.500

C2 = 0.960

El = 215

### *7. Mean of internal temperature*

Temperature during heating periods in the living area(°C) 21.00 (85)

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|

tau

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 17.03 | 17.06 | 17.06 | 17.11 | 17.14 | 17.16 | 17.17 | 17.17 | 17.14 | 17.11 | 17.09 | 17.06 |

Alpha

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 | 2.14 |

Utilisation factor for gains for living area

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.90 | 0.87 | 0.83 | 0.76 | 0.66 | 0.52 | 0.38 | 0.40 | 0.60 | 0.77 | 0.88 | 0.91 |

(86)

Mean internal temperature in living area T1

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18.44 | 18.74 | 19.26 | 19.75 | 20.32 | 20.71 | 20.90 | 20.89 | 20.60 | 19.94 | 19.01 | 18.47 | (87) |

Temperature during heating periods in rest of dwelling Th2

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20.18 | 20.19 | 20.19 | 20.19 | 20.19 | 20.19 | 20.19 | 20.19 | 20.19 | 20.19 | 20.19 | 20.19 | (88) |

Utilisation factor for gains for rest of dwelling

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.89 | 0.86 | 0.81 | 0.74 | 0.62 | 0.48 | 0.32 | 0.33 | 0.55 | 0.75 | 0.86 | 0.90 | (89) |

Mean internal temperature in the rest of dwelling T2

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 17.81 | 18.11 | 18.62 | 19.10 | 19.63 | 19.98 | 20.14 | 20.13 | 19.89 | 19.28 | 18.38 | 17.85 | (90) |

Living area fraction (45.87 / 45.87) 1.00 (91)

Mean internal temperature (for the whole dwelling)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18.44 | 18.74 | 19.26 | 19.75 | 20.32 | 20.71 | 20.90 | 20.89 | 20.60 | 19.94 | 19.01 | 18.47 | (92) |

Apply adjustment to the mean internal temperature, where appropriate

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18.44 | 18.74 | 19.26 | 19.75 | 20.32 | 20.71 | 20.90 | 20.89 | 20.60 | 19.94 | 19.01 | 18.47 | (93) |

### *8. Space heating requirement*

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Utilisation factor for gains | | | | | | | | | | | | |
| 0.87 | 0.84 | 0.79 | 0.73 | 0.63 | 0.51 | 0.38 | 0.39 | 0.58 | 0.74 | 0.84 | 0.88 | (94) |
| Useful gains | | | | | | | | | | | | |
| 451.79 | 499.67 | 517.24 | 520.12 | 468.43 | 374.86 | 268.63 | 265.84 | 363.50 | 423.61 | 431.69 | 431.37 | (95) |
| Monthly average external temperature | | | | | | | | | | | | |
| 4.50 | 5.00 | 6.80 | 8.70 | 11.70 | 14.60 | 16.90 | 16.90 | 14.30 | 10.80 | 7.00 | 4.90 | (96) |
| Heat loss rate for mean internal temperature | | | | | | | | | | | | |
| 1042.65 | 1026.20 | 930.45 | 823.06 | 640.68 | 453.36 | 296.74 | 296.12 | 468.15 | 680.52 | 895.35 | 1013.52 | (97) |
| Space heating requirement for each month, kWh/month | | | | | | | | | | | | |
| 439.6 | 353.8 | 307.4 | 218.1 | 128.2 | - | - | - | - | 191.1 | 333.8 | 433.1 | |

Total space heating requirement per year (kWh/year) (October to May) 2405.22 8)

Space heating requirement per m² (kWh/m²/year) 52.44 9)

| ***9. Energy requirements*** | **kWh/year** | |
|---|---|---|
| Fraction of heat from secondary system | 0.1000 | (201) |
| Fraction of space heat from main system(s) | 0.9000 | (202) |
| Efficiency of main heating system | 91.00% | (206) |
| Efficiency of secondary heating system | 100.00% | (208) |

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|

Space heating requirement

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 439.60 | 353.83 | 307.43 | 218.11 | 128.15 | - | - | - | - | 191.14 | 333.84 | 433.12 | (98) |

Appendix Q - monthly energy saved (main heating system 1)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | - | - | - | - | 0.00 | 0.00 | 0.00 | (210 |

Space heating fuel (main heating system 1)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 434.77 | 349.94 | 304.05 | 215.72 | 126.74 | - | - | - | - | 189.04 | 330.17 | 428.36 | (211 |

Appendix Q - monthly energy saved (main heating system 2)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | - | - | - | - | 0.00 | 0.00 | 0.00 | (212 |

Space heating fuel (main heating system 2)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | - | - | - | - | 0.00 | 0.00 | 0.00 | (213 |

Appendix Q - monthly energy saved (secondary heating system)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | - | - | - | - | 0.00 | 0.00 | 0.00 | (214 |

Space heating fuel (secondary)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 43.96 | 35.38 | 30.74 | 21.81 | 12.81 | - | - | - | - | 19.11 | 33.38 | 43.31 | (215 |

Water heating requirement

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 164.18 | 144.77 | 152.19 | 136.63 | 134.04 | 119.98 | 115.42 | 126.38 | 126.07 | 141.66 | 149.54 | 160.30 | (64) |

Efficiency of water heater 55.30 (216

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 55.3 | 55.3 | 55.3 | 55.3 | 55.3 | 55.3 | 55.3 | 55.3 | 55.3 | 55.3 | 55.3 | 55.3 | (217 |

Water heating fuel

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 296.89 | 261.79 | 275.20 | 247.06 | 242.38 | 216.95 | 208.72 | 228.53 | 227.98 | 256.17 | 270.42 | 289.87 | (219 |

| Annual totals | kWh/year | |
|---|---|---|
| Space heating fuel used, main system | 12378.79 | (211) |
| Space heating fuel (secondary) | 240.52 | (215) |
| Water heating fuel | 3021.97 | (219) |
| Electricity for pumps, fans and electric keep-hot | | |
| central heating pump | 130.00 | (230c) |
| boiler with a fan-assisted flue | 45.00 | (230e) |
| Total electricity for the above, kWh/year | 175.00 | (231) |
| Electricity for lighting (100.00% fixed LEL) | 214.95 | (232) |
| Energy saving/generation technologies: Appendix Q - | | |
| Energy saved or generated (): | 0.000 | (236a) |
| Energy used () | 0.000 | (237a) |

### *10. Fuel costs*

| | **KWh/year** | **Fuel price, p/kWh** | **£/year** | |
|---|---|---|---|---|
| Space heating - main system 1 | 2378.786 | 3.100 | 73.74 | (240) |
| Space heating - main system 2 | 0.000 | 0.000 | 0.00 | (241) |
| Space heating - secondary system | 240.522 | 12.820 | 30.83 | (242) |
| Water heating | | | | |
| Water heating cost | 3021.97 | 3.100 | 93.68 | (247) |
| Mech vent fans cost | 0.000 | 11.460 | 0.00 | (249) |
| Pump/fan energy cost | 175.000 | 11.460 | 20.06 | (249) |
| Energy for lighting | 214.950 | 11.460 | 24.63 | (250) |
| Additional standing charges | | | 133. 00 | (251) |
| Electricity generated - PVs | 0.000 | 0.000 | 0.00 | (252) |
| Appendix Q - | | | | |
| Energy saved or generated (): | 0.000 | 0.000 | 0.00 | (253) |
| Energy used (): | 0.000 | 0.000 | 0.00 | (254) |
| Total energy cost | | | 375.95 | (255) |

### *11. SAP rating*

| | | |
|---|---|---|
| Energy cost deflator | 0.47 | (256) |
| Energy cost factor (ECF) | 1.94 | (257) |
| SAP value | 0.00 | |
| **SAP rating** | **81** | (258) |
| **SAP band** | **C** | |

### *12. Carbon dioxide emissions*

| | **Energy kWh/year** | **Emission factor, kg $CO_2$/kWh** | **Emissions kg$CO_2$/year** | |
|---|---|---|---|---|
| Space heating - main system 1 | 2378.786 | 0.198 | 471.00 | (261) |
| Space heating - main system 2 | 0.000 | 0.000 | 0.00 | (262) |
| Space heating - secondary system | 240.522 | 0.517 | 124.35 | (263) |
| Water heating | 3021.97 | 0.198 | 598.35 | (264) |
| Space and water heating | | | 1193.70 | (265) |

| | | | | |
|---|---|---|---|---|
| Electricity for pumps and fans | 175.000 | 0.517 | 90.48 | (267) |
| Electricity for lighting | 214.950 | 0.517 | 111.13 | (268) |
| Electricity generated - PVs | 0.000 | 0.529 | 0.00 | (269) |
| Appendix Q - | | | | |
| Energy saved or generated (): | 0.000 | 0.000 | 0.00 | (270) |
| Energy used (): | 0.000 | 0.000 | 0.00 | (271) |
| Total $CO_2$, kg/year | | | 1395.30 | (272) |
| | | | **$kg/m^2$/year** | |
| $CO_2$ emissions per $m^2$ | | | 30.42 | (273) |
| EI value | | | 79.42 | (273a) |
| **EI rating** | | | **79** | (274) |
| **EI band** | | | **C** | |

### ***13. Primary energy***

| | **Energy kWh/year** | **Primary factor** | **Primary energy kWh/year** | |
|---|---|---|---|---|
| Space heating - main system 1 | 2378.786 | 1.020 | 2426.36 | (261 |
| Space heating - main system 2 | 0.000 | 0.000 | 0.00 | (262 |
| Space heating - secondary system | 240.522 | 2.920 | 702.32 | (263 |
| Water heating | 3021.97 | 1.020 | 3082.40 | (264 |
| Space and water heating | | | 6211.09 | (265 |
| Electricity for pumps and fans | 175.000 | 2.920 | 511.00 | (267 |
| Electricity for lighting | 214.950 | 2.920 | 627.66 | (268 |
| Electricity generated - PVs | 0.000 | 2.920 | 0.00 | (269 |
| Electricity generated - CHP | 0.000 | 0.000 | 0.00 | (269 |
| Electricity generated - Wind | 0.000 | 2.920 | 0.00 | (269 |
| Appendix Q - | | | | |
| Energy saved or generated (): | 0.000 | 0.000 | 0.00 | (270 |
| Energy used (): | 0.000 | 0.000 | 0.00 | (271 |
| **Primary energy kWh/year** | | | **7349.74** | (272 |
| **Primary energy $kWh/m^2$/year** | | | **160.23** | (273 |

## *C.2 COMPLIANCE WITH BUILDING REGULATIONS*

Building Compliance check list was produced by using the software IES <VE> version 6.4.0.6: <VE Compliance>.

| N° | Parameters | IES Model output | Pass/ Fail |
|---|---|---|---|
| 1 | **TER and DER** expressed in kg $CO_2$ /$m^2$year | Fuel for main heating system: Gas: mains gas<br>Fuel for secondary heating system: Electricity 7hour tariff (off-peak)<br>(fuel factor = 1.00)<br>Target Carbon Dioxide Emission Rate TER = 30.21<br>Dwelling Carbon Dioxide Emission Rate DER = 26.62 | Pass |
| 2.1 | **Fabric U-values** expressed in W/$m^2$K | Element Average U-value Highest U-value<br>Wall 0.24 (max 0.35) 0.24 (max 0.70)<br>Floor 0.16 (max 0.25) 0.16 (max 0.70)<br>Roof 0.22 (max 0.25) 0.22 (max 0.35)<br>Openings 1.71 (max 2.20) 2.17 (max 3.30) | Pass |
| 2.2 | **Common areas** | (Builder's submission) | |
| 2.3 | **Heating efficiency** | Main heating system: Combi-condensing<br>Efficiency: 93.5<br>Minimum: 86.0%<br>Secondary heating system:<br>Electric room heaters<br>Panel convector or radiant heater | Pass<br>Pass |
| 2.4 | **Cylinder insulation** | Hot water storage<br>Provide by space heating system<br>Storage combination boiler from database, primary store<br>Primary pipe work insulated N/A | N/A<br>N/A |
| 2.5 | **Controls:** Space heating controls (main heating system) | Time and temperature zone control | Pass |
| | Hot water controls | Boiler interlock: Yes<br>Independent timer for DHW: Yes | Pass |
| | Solar hot water cylinder | Solar water heating used? No | N/A |
| 2.6 | **Other provisions for heating** | (builder's submission) | |
| 2.7 | **Fixed internal and external lighting** | (builder's submission) | |
| 3.1 | **Summertime temperature** | Overheating risk: Not significant<br>Based on:<br>Region: Midlands, East Anglia, East Pennines, West Pennines<br>Thermal mass parameter: 8.70 | Pass |

| | | | |
|---|---|---|---|
| 4.1 | **Key features** | -Wall U-value 0.24 W/m²K.<br>- Floor U-value 0.16 W/m²K.<br>- Window or Door U-value 0.92 W/m²K.<br>- Thermal bridging less than the default value for accredited details.<br>- Design air permeability 1.82 m³/m²h. | |
| 4.2 | **Accredited details** | (builder's submission) | |
| 4.3 | **Non-accredited details** | (builder's submission) | |
| 4.4 | **Site inspection checks** | (builder's submission) | |
| 4.5 | **Design air permeability** | Value at 50 Pascals: 1.83 | Pass |
| 4.6 | **Sample pressure tests** | (builder's submission) | |
| 4.7 | **Commissioning** | (builder's submission) | |
| | **Overall result:** | | **Pass** |
| 5.1 | **Provision of information** | O&M instructions (builder's submission)<br>SAP rating 81 | |