Thermal Performance of Low-carbon Prefabricated Timber Housing in the UK

By

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Abstract

The research investigates thermal performance of prefabricated timber housing in the UK due to a growing concern regarding the increase in summertime temperatures, which are expected to occur regularly as global temperatures increase. Furthermore, modern houses are built to meet improved regulations with additional insulation and are more sensitive to potential summertime overheating than older houses. This study examines three UK prefabricated timber housing developments (Bridport, Oxley Woods and Stadthaus) built in the last decade by evaluating the environmental conditions of the internal spaces and the occupants' comfort. The research employs a combination of different methods such as post-occupancy surveys, environmental monitoring, and thermal comfort surveys to assess the occupants' comfort in different seasons. Moreover, dynamic thermal modelling and simulations of the buildings to get more data over a long period are used. The outcomes of this study align with the research aim and sustain the research propositions. The research contributes to the on-going discussions on overheating in dwellings and provides first set of data on occupants' thermal comfort in prefabricated timber housing. Overall, Oxley Woods appears to be warmer than Bridport and Stadthaus. Using the adaptive thermal comfort model to evaluate the risk of overheating at the buildings suggests overheating occurs in 70% of the spaces monitored at Oxley Woods; while the analysis suggests warm discomfort in 50% of the spaces monitored at Bridport and Oxley Woods in the summer. The preferred temperature is 1.8ºC higher at Bridport than Oxley Woods indicating comfort is within a wide range for the occupants at Oxley Woods. The neutral temperature is higher at Oxley Woods by 0.8ºC suggesting higher adaptation of the occupants to the internal temperatures. The results from the research suggest the occupants of the houses with smaller internal floor area adapt better than the houses with bigger internal floor area. The occupants that indicate low level of control are less satisfied with the thermal conditions of the buildings. The results from the surveys and dynamic thermal simulations suggest that summertime overheating occurs in the buildings and high internal temperatures are likely to be more frequent in UK modern houses with reduced internal floor spaces than houses with increased internal floor spaces.

Dedication

I dedicate this research to the
Almighty God, my Creator, my Helper, my Father, and my
All in All.

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Chapter 1 General Overview

1.1 Background to the Research

"For a generation, the supply of new homes has not kept up with rising demand. [....] That is why the Government is now setting a new housing target for 2016 of 240,000 additional homes a year to meet the growing demand as well as address affordability issues. The level of housing supply needs to be increased over time towards this target and we believe that a total of three million new homes are required by 2020, two million of them by 2016. [....] We don't just want to build more homes. We want them to be better homes, built to high standards, both in terms of design and environmental impact and homes that are part of mixed communities with good local facilities. Our new homes need to be part of the solution to climate change; not part of the problem".

- DCLG (2007b: pp.5,7,9)

Over the last few decades, planet earth has been facing recurrent excessive exploitation of its natural resources through various actions carried out by human beings. These actions have led to a rise in external temperature due to climate change, air pollution with potential reduction in fossil fuel deposits used for energy driven machines in manufacturing, operation of automobiles, aviation, and marine as well as for running buildings.

Since the 1970s oil crisis, energy conservation has become a major issue in every sector including housing (IPCC, 2007; DECC, 2012). From 1970 to 2004, carbon emissions generated mainly from various actions by people have increased by at least 70% (IPCC, 2007). The amount of energy used across the world is anticipated to rise for the next three decades (that is, from 2010 to 2040), by at least 56% (US EIA, 2013). More attention needs to be paid on energy usage in all sectors especially in buildings as human beings spend most part of their everyday life indoor.

In the UK, there are on-going efforts to minimise carbon emissions and limit further exploitation of fossil fuels for various purposes by at least 60% in the 2050s (DTI, 2003). Also, energy consumption in housing is targeted to be reduced by at least 80% in 2050 when compared to the emission rate in the 1990s as stated in the Climate Change Act 2008 (OPSI, 2008). However, the targets set to cut carbon emissions are yet to be met. In the past few years, the UK building regulations (Part L) have considered fuel and energy conservation (ODPM, 2006), with recommendations for provision of low energy controls and services in buildings and the need for energy efficient fabrics to regulate internal conditions since performance of buildings is very crucial in reducing energy usage and limit carbon emissions.

Thermal performance of a house is assessed by its capability for energy conservation while providing comfortable internal conditions for its occupants at different times of the year. The overall heat transfer coefficient value (U-value) determines the ability of a material to transfer thermal energy and it is often used as an indicator for assessing the ability of a fabric thermal performance with a lower U-value fabric indicating a better performance than fabrics with a higher U-value. As a result, highly insulated fabrics are expected to perform better than poorly insulated fabrics. However, recent investigations on UK dwellings have indicated a potential of summertime overheating (Jowett, 2011; Rijal & Stevenson, 2010; Lomas & Kane, 2012, 2013). There are on-going efforts to improve the energy-efficiency level of UK houses with the introduction of highly insulated envelopes (Sustainable building, 2008). In addition, houses with smaller internal spaces are built to minimise energy usage without considering the impact of global warming that has led to rising external temperature during summer period every year and performance of newly built houses need to be investigated especially timber houses due to its limited thermal capacity to store and retain heat.

Considering prefabrication construction methods, recent developments in the UK housing sector have shown a steady growth in the use of prefabrication due to its various benefits (Gorgolewski, 2008). Prefabrication is a faster building method. It limits waste of materials, gives quick return on investment and requires a limited number of workers and equipment on site. Prefabrication methods of construction can be used at different seasons and for sites with various constraints. The housing sector has also witnessed an increase in the use of lightweight materials with low thermal mass for construction (Kendrick *et al.,* 2012).

Timber housing is selected for this study because of timber's ability to be used for different kinds of construction. It is considered as the most widely used natural building material (Thompson, 2009); with different species used for various purposes and can be locally sourced in most regions of the world. Timber construction is economical in terms of cost with low energy required for production. It is environmentally friendly and sustainable. Generally, timber is sourced from various environmentally sustained forests in the UK and across other European nations such as Austria, Germany, Finland, Sweden, Denmark and Norway otherwise known as wooded nations (TRADA, 2009a; Thompson, 2009). It can be manufactured off-site with potential for necessary adjustments on site. Timber has a wider application and can be used for solid (structural) construction, cladding, finishes and furniture as well as a raw material for other products such as wood fibre tiles. It provides appealing views when used for buildings. Timber is durable in withstanding harsh weather conditions when properly treated, processed and installed.[1] In terms of performance, the developments of solid timber materials such as cross laminated timber (CLT) have indicated its ability for sound and fire resistance. However, timber is limited as it has a shorter lifespan when compared to other building materials like concrete, bricks. It takes many years to grow. Timber is not readily available in some parts of the world which could contribute to additional cost to transport the material to site. It has a low thermal mass. Lightweight materials are predicted to provide lower thermal comfort for occupants with minimum use of winter solar gains during winter period due to low thermal mass of lightweight materials (Szalay, 2004; Kendrick *et al.*, 2012). However, the actual thermal performance of timber houses has not been investigated and this will be the main focus of the research.

This study considers housing due to the fuel poverty reported in many UK houses (POST, 2005). The recommendation for all recently constructed UK houses to attain zero carbon status by 2016 (DCLG, 2007). This is a challenging task for the housing sector. Currently, well above 2 million houses in the UK are ranked as 'poor' in terms of fuel and energy conservation (POST, 2005). Moreover, at least 60% of total energy consumed in UK dwellings per year is used for regulating indoor environment in terms of heating and cooling (POST, 2005; DECC, 2012). This suggests that thermal performance of housing

[1] Timber decay can be minimised when it is impregnated with preservatives or processed as laminated timber panels.

is an important issue to address if UK's target of reducing overall carbon emissions over the next few decades must be met. Previous studies mentioned lack of data on thermal comfort of occupants in dwellings (Orme *et al.,* 2003; Firth & Wright, 2008; Lowe & Oreszczyn, 2008; Rijal & Stevenson, 2010; Porritt, *et al.,* 2012). As a result, it is necessary to carry out more investigations on housing in order to understand the thermal conditions of houses and occupants' comfort.

Based on the above, this research focuses on investigating the performance of timber houses in the UK. The study is solely focusing on thermal performance of timber houses and thermal comfort of occupants in timber dwellings.

1.2 Problem Statement and Research Propositions

Currently, at least 26% of the overall UK carbon emissions are generated from the housing sector (DEFRA, 2007). The findings indicate carbon emissions of 2.5tonnes per occupant with overall carbon emissions of 149 million tonnes from the sector (McManus et al., 2012). Taking into consideration the existing housing stock of 26.2 million (ONS, 2011); and the 61 million people with anticipated 65.4 million in 2016 (RICS, 2012 p.73). This suggests construction of additional low-carbon emissions dwellings using sustainable materials with appropriate renewable energy integration to minimise carbon emissions in housing is very important. In order to build additional houses, sustainable housing designs from planning phase to occupancy of residents need to be taken into consideration by professionals including architects, engineers and building scientists in the built environment industry.

Several innovations to achieve energy-saving houses have been included in many developments by different designers. These innovations are introduced to improve internal conditions of houses. Sustainable materials have been increasingly used for construction of various structures in recent years. Structural or engineered timber products have been considered for construction over traditional timber due to the possibility for improved thermal behaviour, low U-values and better application of modern construction methods (Thompson, 2009). Use of timber for houses has contributed to overall low-carbon emissions and created a potential for growing timber housing stock market share index especially in terms of houses developed in recent years. Increase in price and demand for more housing has encouraged investors to consider construction of more timber houses (Offsite Housing Review, 2013). Also, timber is considered for construction of housing due to its tendency to be built within a limited timeframe considering the overall cost benefit when compared to houses built with conventional materials (Thompson, 2009). However, an evaluation of the performance of the houses built with improved timber materials has not been considered to understand indoor thermal comfort conditions in the houses.

Improvement has been made to achieve airtightness of fabrics in order to reduce condensation and penetration of water in modern timber houses. The houses are built with the expectation to be operated as free-running (naturally ventilated) in summer and consuming low energy in winter. However, there are crucial limitations in terms of design in timber houses as the various interventions mainly focus on airtightness and high level of insulation to reduce heat loss.

It is important to evaluate the effectiveness of timber houses, in different seasons. Since the 2003 heat wave that resulted in many deaths across Europe (NHS, 2006; WHO, 2007; ONS, 2010). More studies have been conducted on the thermal performance of dwellings in summertime (Wright, et al., 2005; Firth & Wright, 2008; Rijal & Stevenson, 2010; Lomas & Kane, 2012, 2013; Beizaee et al., 2013). In addition, internal spaces of lightweight structures are predicted to observe high internal temperatures than houses built with heavyweight materials for the future years (Kendrick *et al.,* 2012) due to the possibility of an increase in external temperature (Lowe & Oreszczyn, 2008; Kendrick *et al.,* 2012) with no study indicating the actual performance of timber houses and no mention of the current situation. More studies have predicted extremely high internal temperatures within UK houses in the future (Orme *et al,* 2003; Kendrick *et al.,* 2010) and suggest further studies on thermal comfort of occupants in different houses (Beizaee *et al.,* 2013). As a result of the various outcomes and recommendations from previous studies, this study identifies the research gap and thus, investigates the performance of timber houses in the UK.

In order to set a clear focus for this study, the research intends to investigate:

- If summertime overheating occurs in modern timber houses.
- If internal conditions of timber houses provides thermally dissatisfied environment for occupants throughout the whole year.

- If decrease in size of internal spaces contribute to frequent high internal temperatures during summertime in modern timber houses which could affect occupants' comfort and overall well-being.

1.3 Aims and Objectives

The principal aim of the research is to investigate the summertime overheating in low-carbon prefabricated timber housing in the UK.

The research objectives include:

- To investigate thermal performance of different timber houses in the UK through environmental monitoring and dynamic thermal modelling.
- To investigate overheating potential in timber houses.
- To investigate comfort conditions in timber houses.
- To understand people's adaptation to the thermal environment of newly built houses using post-occupancy and comfort surveys.

1.4 Research Methodology

Methodology is an important part of any research as its application determines the quality of data to be collected and the overall success of the research (Nicol, 2008). The research methodology includes post-occupancy survey, environmental monitoring, comfort survey as well as dynamic thermal modelling and simulation. For the research to be conducted, the steps to be taken include:

- Identify modern houses in the UK that are built with prefabricated timber materials, rated high in terms of sustainability and have won several awards, located in south and southeast of England, purposely built for housing and completed within the last decade that can be investigated for identifying potential of overheating.
- Carry out post-occupancy surveys including thermal comfort evaluation and environmental monitoring to gather data at the case studies.
- Examine data collected from post-occupancy survey, thermal comfort survey and environmental monitoring for analysis to understand thermal behaviour of the case study buildings and also generate data from environmental monitoring that will be used for validation of computer modelling.

- Employ dynamic thermal modelling technique using DesignBuilder software to model the case study buildings and carry out computer simulations.
- Examine the thermal conditions of the internal spaces at the case study buildings to know if the occupants are thermally dissatisfied during summertime which will help the research to understand how the occupants improve the thermal conditions of their houses during hot summer period.

Based on findings from previous studies, results are more reliable when combining different methods to investigate building performance and majority of the comfort field studies in UK dwellings tend to consider environmental monitoring over post-occupancy survey (Bordass & Leaman, 2005); with the intention to use the method to carry out building assessment in general instead of evaluating the actual building performance in relation to the outdoor environment (Energy Saving Trust, 2008). This suggests that the combination of different methods to evaluate building performance provides a wide range of information regarding feeling of the occupants, understanding of the occupants' interaction with the building and their natural ability to adapt to the thermal environment. Also the approach provides the opportunity to understand differences in occupants behavioural actions, access measured data from environmental monitoring of parameters as well as getting data from the participants which are considered the most difficult and responsive indicators in field studies (Stevenson & Rijal, 2010). While the use of dynamic thermal simulation helps to capture more data on both current and future situation for further analysis. As a result, a combination of different methods will be considered.

1.5 Outline of the Thesis

The thesis has been structured into eight chapters. The first chapter provides a concise general overview on background of the research. The following two chapters of the thesis are grouped into a literature review that focuses on the research state of art on thermal comfort and housing in the UK. The other chapters consider the data protocol detailing how the data was collected and techniques used for analysis. The report on the case study buildings investigated is provided. The analysis and discussion of findings from various field surveys and dynamic thermal simulations are presented and possible comparisons are made as well as conclusion of the research is discussed at the last chapter. The outline of the thesis is presented as follows.

Chapter 1: Introduces the research topic and presents a background to the research. It highlights the problem statement as well as presents the research aims and objectives. It outlines the research methodology and provides justification for the methodology. The chapter briefly outlines the importance of the research.

Chapter 2: Examines the background study on thermal comfort in dwellings and reviews relevant studies on parameters that influence occupants' comfort in dwellings. The chapter discusses overheating as a growing concern in UK houses and presents the approved CIBSE 'static' criteria and the dynamic adaptive model (BSEN15251) used for evaluation of overheating risk in buildings. Furthermore, a review of various factors affecting thermal comfort of occupants in dwellings is presented. It briefly examines thermal comfort in lightweight dwellings. The review provides the background focus for the research that is used in the thesis.

Chapter 3: Focuses on contemporary housing in the UK and provides an architectural historic overview of UK housing development in the 20th century (especially, in the 1980s and the 1990s). It presents a comparison between different minimum space standards in the UK and across Europe. The chapter examines current developments and future prospects of prefabricated timber housing in the UK and the world.

Chapter 4: Provides a detailed account of the data protocol and techniques used for analysis. The development and distribution of the questionnaires are presented. It explains procedures taken to collect the questionnaires filled by the participants. Also, dynamic thermal modelling and simulation are discussed. The chapter explains the simulation software and outdoor weather data considered for simulation.

Chapter 5: Discusses all the three housing developments (Bridport House, Oxley Woods and Stadthaus) considered in this research. It provides detailed description of the buildings and explains the minimum space standards used for construction. The chapter discusses materials and construction methods used for the buildings as well as the environmental sustainability.

Chapter 6: Presents detailed analysis of gathered data and findings on post-occupancy surveys, environmental monitoring and comfort surveys conducted at the three case studies during the summer of 2012 and the winter of 2013. The findings from post-occupancy surveys and analysis of the statistical tests to understand the level of significance and correlation between the variables are presented. The chapter also discusses findings from environmental monitoring carried out to compare the monitored results on an equal basis. It presents findings from comfort surveys. Overheating analysis using the CIBSE static criteria and the dynamic thermal comfort criteria (BSEN15251) are presented. Comparative analysis of findings and discussions from the surveys (post-occupancy evaluation, environmental monitoring and comfort surveys) is provided. The similarities and difference between the outcomes across the case studies investigated are discussed and further comparative analysis will be examined in Chapter 7.

Chapter 7: Considers findings on dynamic thermal modelling and simulation. The chapter briefly explains thermal modelling and calibration. The modelling of the case studies is done based on the thermal properties and the materials used for construction as discussed in Chapter 5 to accurately predict the performance. Also, the chapter explains the scope and method used for computer modelling and assumptions made for predicting the current performance of the case studies. It considers overheating analysis using the static criteria and the dynamic thermal comfort criteria across the case studies for the simulated data. It provides discussion and comparative analysis of findings from the surveys and dynamic thermal simulation.

Chapter 8: Highlights the focus of each chapter and provides the conclusion on findings from the surveys. The chapter examines the research focus and re-appraises each research question raised at the beginning of this thesis to understand if the aims of the research have been met. The objectives of the research are briefly mentioned to understand if the research is carried out in line with the objectives set at the start of this study. In addition, it suggests potential areas for further research.

1.6 Summary

This chapter provided the background work to the research. It explained reasons for considering a study on the performance of prefabricated timber housing. The chapter examined on-going efforts that have been made by UK government to reduce energy consumption in buildings especially in the housing sector as it generates more than a quarter of the overall annual carbon emission in the UK. The research propositions indicate the ability of the research to contribute to on-going studies on overheating and provide new form of knowledge to the field of thermal comfort in dwellings. The research aims and objectives were highlighted to provide a clear direction for this study. The research methodology was presented and the steps taken to carry out the research were outlined. It presented the outline of the report which gave a clear understanding of the thesis focus, its structure and brief overview of each chapter of this thesis. The chapter provided a clear focus of the research and presented the importance of the research to the field of thermal comfort in dwellings.

Chapter 2 Thermal Comfort in Dwellings

2.1 Introduction

"Thermal comfort standards are required to help building designers provide an indoor climate that building occupants will find thermally comfortable. The definition of a good indoor climate is important to the success of a building, not only because it will make its occupants comfortable, but also because it will decide its energy consumption and thus influence its sustainability".

- Nicol & Humphreys (2002, p.563).

This chapter reviews literature on thermal comfort in dwellings. As widely reported, thermal comfort is important to occupants' health and overall well-being within the thermal environment. Several studies on thermal comfort in dwellings in recent years will be considered in this chapter. Various definitions of thermal comfort as well as a general way of defining thermal comfort will be discussed. Recent studies on occupants' perception of thermal sensation, thermal acceptability, satisfaction and their importance to the study of thermal comfort will be examined. Differences in occupants' perception of thermal sensation due to age, gender, occupants' behaviour will also be presented.

The two major approaches to the study of thermal comfort will be examined. The heat-balance approach will be discussed using climate chamber tests; while adaptive comfort approach will be explained using field studies. The advantages and limitations of the approaches will be highlighted.

Overheating as a growing concern in UK houses will be discussed. Overheating will be defined based on relevant literature. The evaluation of overheating risk in dwellings using different thermal comfort criteria will be explained. The indicators that will be considered include the static CIBSE criteria (CIBSE, 2006) and the dynamic adaptive comfort model as discussed in BSEN15251 (BSI, 2008).

The last part of this chapter discusses different factors affecting indoor occupants' comfort in dwellings as well as thermal comfort in lightweight dwellings. The literature that has examined thermal comfort in lightweight dwellings will be reviewed. This is important since prefabricated timber houses considered in this study are lightweight dwellings; therefore, it is necessary to understand what previous investigations have considered and the gap that this research fills.

2.2 Overview of Thermal Comfort in Dwellings

The study of thermal comfort in dwellings has been given more attention in recent years (Perreti & Schiavon, 2011) due to few studies focusing on dwellings and lack of data on thermal comfort of their occupants in the past (Firth & Wright, 2008; Lowe & Oreszczyn, 2008; Perreti & Schiavon, 2011); while various definitions have been provided by literature to the term 'thermal comfort'. According to ASHRAE (2004), thermal comfort is described as *'the condition of the mind in which satisfaction is expressed within the thermal environment'*. It also stated parameters such as personal and socio-cultural affect occupants' comfort within the thermal environment. Thermal comfort is a *'mental condition that expresses satisfaction with the thermal environment'* and factors such as physical, cultural as well as environment are likely to influence range of temperature at which indoor occupants consider to be comfortable (ISO 7730, 2005). In a study on the thermal interaction of building structure and heating and ventilating system, thermal comfort is described as '*a state in which there are no driving impulses to correct the environment by the behaviour'* (Hensen, 1991). Thermal comfort is defined as *'the state reached when heat flows to and from the human body is balanced and skin temperature and sweat rate are within a comfort range, which depends only on metabolism'* (Hoppe, 2002). Thermal comfort is the state of mind when occupants are psychologically and physiologically satisfied with the thermal environment (Nikolopoulou, 2004). Based on previous definitions of thermal comfort, it is considered as '*not a state condition, but rather a state of mind'* (Lin & Deng, 2008). Thermal comfort is also described in a wider context as a *'sense of relaxation and freedom from worry or pain'* (Darby & White, 2005) while parameters such as psycho-physiological, physical and others influence occupants' comfort (Djongyang *et al.*, 2010). The various definitions suggest occupants are comfortable when they are thermally satisfied with the thermal conditions of the spaces they are currently occupying.

In thermal comfort surveys, the relationship between thermal acceptability and thermal sensation is indirectly related while the relationship between thermal acceptability and satisfaction is interrelated (ASHRAE Standard 55, 2004). The Standard 55 mentioned further that for indoor climate to be considered acceptable, at least 80% of indoor occupants must be thermally satisfied with the indoor environmental conditions. Human responses to indoor climate is subjective and being influenced by different parameters within the indoor environment (Ogbonna & Harris, 2008); while their responses on thermal acceptability indicate a good understanding of the limits of indoor temperatures they consider acceptable (Zhang *et al.*, 2011). Hence, it is important to examine thermal acceptability, thermal sensation and thermal satisfaction of occupants as well as relationship between the parameters.

Both environmental and personal parameters influence how occupants perceive and rate their feeling of warm or cold (ASHRAE, 2004). Environmental parameters such as air temperature, relative humidity are major indicators to consider within the indoor climate when evaluating thermal comfort (Chiang & Lai, 2002). The important parameter to consider when evaluating occupants' comfort in dwellings is the indoor temperature (Ormandy & Ezratty, 2012). This is important to understand the thermal conditions of the indoor environment. Also, measurement of indoor temperature of different dwellings provide a platform to compare and understand different indoor environmental conditions of dwellings that are acceptable to different occupants especially the occupants that are vulnerable (Lomas & Kane, 2013). This indicates indoor temperature is a crucial environmental parameter to consider for understanding thermal conditions of an environment and measurement of indoor temperature in different dwellings will be considered in this study.

Thermal adaptation in people declined in terms of their physiological responses when they occupied the same thermal environment for a long period (Nikolopoulou & Steemers, 2003). However, thermal sensation differs from one occupant to another, even when the indoor temperature is measured at the same location, with the people sharing the same culture (Djongyang & Tchinda, 2010; Wang *et al.*, 2010; Alders *et al.*, 2011; Cao *et al.*, 2011) due to differences in how an individual occupant perceives and rate indoor environmental conditions (Djongyang & Tchinda, 2010; Wang *et al.*, 2010; Cao *et al.*, 2011). Gender influences thermal sensation as female occupants are more sensitive to change in temperature by 1.1ºC higher within indoor environment than male occupants (Wang, 2006). However, the study did not indicate if the difference is the same between the vulnerable female occupants and male occupants such as elderly persons and sick people. Female occupants are likely to open windows more often than male occupants when they perceive a change in lighting level (Andersen *et al.*, 2009). In addition, the authors linked occupants' perception to lighting level with thermal sensation and suggest that male occupants are expected to use light more frequently than female occupants when feeling cold or warm within indoor spaces.

Thermal discomfort is a subjective response and thermal sensation is an objective response (Brager & de Dear, 2001; Alders *et al.*, 2011). While thermal comfort depends on the environmental, subjective as well as objective factors (Ormandy & Ezratty (2012). Increase in occupants' preference for higher air movement influences occupants' thermal sensation within the indoor environment (Brager *et al.*, 2004). Age influences occupants' feeling as the younger people feel moderately higher than elderly persons with a higher preference vote within the thermal environment (Indraganti & Rao, 2010; Takahashi & Takahashi, 2012) and younger occupants' perception of comfort is higher than the elderly occupants and vice versa (Alders *et al.*, 2011). Furthermore, occupants are thermally comfortable when indoor temperatures are within comfort range with no preference for more air movement (Indraganti & Rao, 2010); while they perceived lack of fresh air with preference for higher air movement when the thermal environment is too hot (Wang *et al.*, 2011). Occupants' actions like use of openings, clothing insulation, level of activity involved, type of drinks consumed (hot or cold) (Ackerly & Brager, 2013; Goins & Moezzi, 2013; Teleghani *et al.*, 2013) and occupants' movement from one space to another also determine their level of comfort within the indoor environment (Nicol, 2008). Indoor occupants' thermal comfort and satisfaction within indoor climate can not only be affected by high temperatures but also by high content of moisture within the thermal environment (Dili *et al.*, 2010; Takahashi & Takahashi, 2012) indicating humidity also influences occupants' comfort within the thermal environment.

Indoor occupants are more comfortable and accomplished their tasks quickly when perceived they have high level of controls to adjust the thermal environment (Bordass *et al.*, 1993; BRI, 2001). Occupants' responses due to poor level of controls often suggest their inability to regulate the indoor environment (Baird & Lechat, 2009; Stevenson *et al.*, 2013). Indoor occupants are likely to perform well when perceived they have high level of controls to regulate their indoor environment in terms of heating, cooling, ventilation and sound (Baird *et al.*, 2008). Occupants' perception on how they rate comfort and overall well-being gradually declined with decrease in level of control to regulate the thermal environment (Baird & Lechat, 2009). Moreover, indoor occupants should have a good knowledge of control in dwellings as it remains a missing link on how to improve occupants' interaction with dwellings (Stevenson *et al.*, 2013) suggesting the need for further study to establish the link between gender and how occupants perceive and rate the environmental controls in dwellings.

Comfort is a major factor influencing human health and well-being within the indoor environment (Wagner *et al.*, 2007; Chappells, 2010) and in order to define how sustainable a building is as well as its level of energy used, a major criteria to consider is thermal comfort of indoor occupants (Yao *et al.*, 2009). Recent studies also discussed the importance of thermal comfort within indoor spaces and mentioned that on average, about 90% of people's time is spent indoors in most advanced countries and their productivity level is linked to their indoor environmental conditions (Hoppe, 2002; Chiang & Lai, 2002). The importance of thermal comfort study in dwellings includes understanding a condition at which people will be considered satisfactory and reducing use of energy for improving the thermal conditions of indoor spaces (Nicol, 2008). Hence, the study of thermal comfort in UK timber houses is very important to occupants' health and overall well-being.

Recent literature has mentioned that the history of thermal comfort survey lacks data on dwellings when compared to data gathered on non-residential buildings (Firth & Wright, 2008; Lowe & Oreszczyn, 2008; Djongyang *et al.*, 2010; Peretti *et al.*, 2011; Limbachiya *et al.*, 2012). Past studies on thermal comfort in dwellings have focused more on dwellings built with heavyweight materials such as concrete, bricks with limited studies on thermal comfort in lightweight dwellings (Kendrick *et al.*, 2012). This suggested that more studies are required to understand the thermal environment of various types of dwellings built with different materials. Considering the few thermal comfort surveys carried out on residential buildings across the globe especially in the UK, majority of the studies have been focusing on dwellings built with high thermal mass materials (Firth & Wright, 2008; Lomas & Kane, 2012, 2013; Beizaee *et al.*, 2013); while very few comfort surveys focusing on low thermal mass or lightweight dwellings have been considered (Rijal & Stevenson, 2010; Jowett, 2011). The recent comfort studies carried out in UK residential thermal environments suggest that indoor occupants are likely to experience summertime overheating due to the recent building regulations which did not consider the impact of summertime high temperatures in recent years but considered the use of high insulated fabrics and airtightness in dwellings (CLG, 2007). Therefore, this study examined thermal comfort of indoor occupants in prefabricated timber houses in the UK and the thermal behaviour of the houses in different seasons.

2.3 Approaches to Study of Thermal Comfort

There are two major approaches that have been extensively used in understanding thermal comfort in buildings. They are heat-balance and adaptive comfort approach. The heat-balance approach, also known as rational approach focuses on using data collected from laboratory tests (climate chamber studies) to back up heat-balance theory which was developed by Fanger (Fanger, 1970); while, adaptive comfort approach explores data generated from field surveys of indoor occupants (Nicol, 2008). Heat-balance approach considers that people do not actively accept the thermal environment but rather passively receive it (Cao *et al.,* 2011; Nicol, 2011). Adaptive approach explains people's ability to adjust to different situations within indoor climate (Nicol & Humphreys, 2002). Adaptive comfort principle explained that '*if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*' (Nicol & Humphreys, 2002; Nicol, 2008; Nicol, 2011). This study focuses on the application of adaptive comfort model for defining thermal comfort in dwellings. Climate chamber studies will be discussed using heat-balance approach. While field studies will be explained using adaptive comfort approach.

2.3.1 Climate Chamber Studies

Climate chamber studies propounded by Fanger provided a series of conditions at which occupants find indoor temperatures to be comfortable. The studies considered physiological factors such as sweat secretion can be employed to regulate the human body temperature due to heat gains and heat loss. Climate chamber studies highlighted that a major condition for occupants to be thermally neutral is to maintain heat balance in the human body (Charles, 2003). Also, Fanger's model considered the human body as thermoregulatory structure which is effective, thereby producing required heat balance within a range of environmental factor limits, even when comfort condition seems difficult to achieve (Djongyang *et al.,* 2010). Fanger also developed a 7-point index known as 'Predicted Mean Vote' (PMV) using tests carried out in climate chambers to describe and measure the expected participants' feeling of cold or warm when they are allowed to remain under a steady-state environmental condition (Hong *et al*, 2009). Fanger's work also developed use of 'Predicted Mean Vote' (PMV) index which later included the 'Predicted Percentage Dissatisfied 'PPD' known as PMV-PPD model on thermal comfort has been considered as an innovative development to the study of thermal comfort as well as to the indoor thermal environment of building assessment (Lin & Deng, 2008) and remain a basis for thermal comfort standards. The PMV-PPD model has been generally considered in past investigations for design and thermal comfort field evaluation (Nakano *et al.*, 2002); while many studies have used climate chamber tests to assess thermal comfort of people in buildings (Fanger & Langkilde, 1975; Gonzalez & Berglund, 1979; De Dear & Leow, 1990).

Climate chamber studies provided the opportunity for respondents' feeling to reach and indicate neutral part of the scale by regulating the thermal environment. The studies helped to understand steady-state thermal comfort criteria indicating a strong link between cold discomfort and the average skin temperature; while suggesting a strong link between warm discomfort and the sweat secretion in human's body. The model also helped to understand that dissatisfaction occurs in a human body when feeling too warm or too cold, or when part of the body experiences local discomfort due to unwanted heating or cooling (Hensen, 1991). Climate chamber studies are used to develop indicators for steady-state thermal comfort. The experiment is carried out in a climate chamber that allows for variations of climatic variables. The tasks assigned during the experiment are standardised including personal variables and they are observed under various thermal environments. The studies help to adjust parameters that are not important during the experiment and concurrently achieve a steady-state condition.

However, limitations of climate chamber tests and the comfort conditions cannot be suggested for PMV or PPD without knowing occupants' clothing insulation and level of activity (Nicol, 2008). Other limitations of the model developed by Fanger include: subjective data collected from laboratory tests (climate chamber studies). Also, for the investigators to consider the application of Fanger's model in climate chamber studies, the investigators need to know occupants' clothing insulation. The investigators also need to understand the level of activity and the possibilities that different activities are being carried out concurrently within the thermal environment (Nicol, 2008). Based on the highlighted limitations of climate chamber tests, this study will not focus on the model but will consider adaptive comfort approach through field studies.

2.3.2 Field Studies

Field studies have been extensively used in recent investigations for assessing thermal comfort in dwellings (Wright *et al.,* 2005; Firth & Wright 2008; Rijal & Stevenson, 2010; Lomas & Kane, 2012, 2013; Beizaee *et al.,* 2013) due to actual evidences the studies provided from occupants' actions and understanding of buildings' thermal behaviours. The studies were first considered by Humphreys (1976). Field studies provided the opportunities to examine adaptive thermal comfort in the actual world's settings (Zhang *et al.,* 2010; Taleghani *et al.,* 2013); and provided opportunities for people to interact with the thermal environment as well as considered various adaptive opportunities that could be explored to achieve occupants' comfort (Nicol, 2011). Field studies provided a good indication for people's adaptive actions when considering participants' responses (Nicol & Roaf, 2005); the evidence that cannot be obtained in climate chamber studies. The studies can also be conducted in different seasons which cannot be achieved in climate chamber studies as it can only consider changes relating to climate, living or working situations. They provided the participants the evidence of warm or cold situations in a real way which cannot be achieved in climate chamber studies. The studies provided the opportunity of selecting the thermal conditions while respondents were asked to record their feeling of warm or cold taking into account the ASHRAE 7-point scale of thermal sensation from (-3) to (+3) indicating 'cold' to 'hot'. According to ASHRAE (2004), the 7-point scale of thermal sensation indicates that cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (1), warm (2) and hot (3).

Considering the history of comfort field studies over the last two decades, post-occupancy evaluation and environmental monitoring have been widely used as a reliable methodology for assessing performance of many buildings (Stevenson & Rijal, 2008). The methods are necessary in order to understand indoor occupants' behaviours and perceptions of the thermal environment as they are considered an integral part of the process of evaluating building performance. Field studies' methods provide an understanding of building performance during summertime and wintertime as well as occupants' behaviours and perception of feeling of warm or cold within their indoor environment. Several studies have considered post-occupancy survey (Baird *et al.,* 2008;

Baird & Lechat, 2009; Hendrickson & Wittman, 2010) which is often used by social scientists to collect data with great input from the occupants that took part in the survey; while some studies have considered environmental monitoring (Lomas & Kane, 2012, 2013; Beizaee *et al.,* 2013) commonly used by building scientists which focuses on measurements of environmental parameters such as indoor air temperature and relative humidity with limited input from occupants.

Post-occupancy survey helps to evaluate the building's performance while environmental monitoring shows how the building responds to the outdoor environment. Comfort survey shows how the occupants respond and interact with the surrounding thermal environment (Nicol & Roaf, 2005). Post-occupancy survey relies on the building occupants' memory to measure and evaluate how the building performs in different periods (Cohen *et al*., 2001); while comfort survey focuses on occupants' feeling at a specific time during the field studies by enquiring from them to vote and rate their perception in relation to some questions such as at the moment 'I feel warm'. Post-occupancy survey provides vital information regarding the general assessment of the building and occupants' impression in order to evaluate the building. On the other hand, environmental monitoring focuses on measurements of environmental variables during the field studies as the climate is considered as one of parameters that influences occupants' comfort and it is not static as it changes from one period to another and it is often difficult to forecast (Nicol & Roaf, 2005). Hence, it is important to understand thermal behaviour of dwellings and indoor occupants' comfort as indoor environmental conditions change due to change in external temperature.

Field studies help to collect data on the thermal environment using measurements concurrently with thermal response of occupants with no intention to adjust the thermal environments and environmental variables by the investigators (Nicol & Humphreys, 2002). The studies also take into consideration participants' clothing insulation and level of activity. The building's behaviour plays a major role in field studies (Nicol, 2008).

Physical measurement of environmental parameters helps to assess indoor environmental conditions (Wang *et al.,* 2011; Sakka *et al.,* 2012). It provides a range of internal and external temperature variations at which indoor occupants find comfortable (Akande & Adebamowo, 2010). There are three different heights (0.1m, 0.6m and 1.1m) above floor level at which indoor environmental parameter measurements can be taken during environmental monitoring for sitting activities, while measurements can be taken at 0.6m, 1.1m and 1.7m above floor levels when occupants are carrying out non-sitting activities (ASHRAE, 2004). Some previous investigations have taken measurements of variables at 0.6m height (Wang *et al.*, 2010, Wang *et al.*, 2011), at 1.1m height (Han *et al.*, 2007; Akande & Adebamowo, 2010; Indraganti & Rao, 2010), at 1.7m height (Ghisi & Massignani, 2007) above floor level for sitting and non-sitting activities; while other studies have considered measurements of variables at the three heights above floor level concurrently (Wang, 2006; Honjo *et al*., 2012; Limbachiya *et al*., 2012) for sitting activities. Few studies have also considered measurements of environmental variables at different heights not mentioned by ASHRAE (2004) for sedentary and non-sedentary activities. For example, environmental variables were measured at 0.3m above the floor level considered to be centre of gravity for occupants seated on the floor (Ealiwa *et al.*, 2001), at 1.0m level (Hong *et al.*, 2009; Cao *et al.*, 2011), while measurement of variables at 2.10m above the floor to enable participants carry out their everyday routines undisturbed (Gomez-Amador *et al.*, 2009). All the measurements at various heights are considered to ensure that the sensors are placed in the right position with minimum or no interference during the period of monitoring and the occupants are not limited to carry out their daily tasks within the indoor spaces. For this study, measurements at 1.1m (the average height of the head-region of occupants seated) will be considered as recommended by ASHRAE (2004).

A combination of different methods during field studies provides feedback for professionals in the built environment in order to evaluate and improve on the building's performance (Bordass & Leaman, 2005). Also, evaluation of occupants' thermal comfort, physical measurements of environmental variables in different seasons can be carried out during field studies (Gossaver & Wagner, 2007). The information gathered during field studies is very crucial in order to understand indoor environmental conditions and cannot be collected at the construction stage of the building. The studies also help to gather comments and recommendations for professionals in building industry in order to know how different building design features, materials and technologies affect indoor occupants' comfort, satisfaction and overall well-being. Comfort field studies were considered for this investigation over climate chamber tests in order to understand actual occupants' different behavioural actions and how they adjust to their thermal environment as well as their understanding of the differences in occupants' responses during comfort survey which suggested that expectation and sensation differ from one occupant to another (Raja *et al*., 2001).

Comfort field studies of adaptive comfort, measurement of environmental and personal variables can provide information on differences in human behaviours and link between occupants' reactions to high temperatures within indoor climate. Most of the field studies that have been carried out in UK dwellings investigated wintertime thermal comfort (Hunt & Gidman, 1982; Oreszczyn *et al.,* 2006; Summerfield *et al.,* 2007; Shipworth *et al.,* 2009), while few studies have investigated summer period temperatures in UK dwellings (Lomas & Kane, 2012, 2013; Beizaee *et al.,* 2013). This study considered both summertime and wintertime temperatures in UK timber houses.

Regarding categories of field studies, there are three major classifications (Class I, Class II and Class III) of field studies (Nicol, 2008). Class I and Class II studies include measurements of both environmental and personal parameters as they are considered important (Zhang *et al.,* 2010). Class I and II studies are important and appropriate when conducting field studies for adaption in buildings. Class I focuses on buildings in which measurements of environmental variable in particular, air temperature is taken at a certain height with no subjects vote. Class II involves measurements of both environmental and personal variables concurrently with subject votes and the measurements can be taken at a certain or different height. Class III study is suitable when considering the measurement of all parameters required to analyse the exchange of heat rate between occupants and the thermal environment concurrently with subjects vote (Nicol, 2008). Some examples of Class I and II studies carried out in a single dwelling and various dwellings in the UK and outside the UK are shown below (Table 2.1). This study is a Class II investigation focusing on different housing developments built with prefabricated timber.

Table 2.1: Examples of Class I and II field comfort studies.

Class I and II studies in different houses in the UK	Class I and II studies in a single house in the UK	Class I and II studies outside the UK
Hunt & Gidman, 1982; Wright *et al.*, 2005; Oreszczyn *et al.*, 2006; Firth *et al.*, 2007; Summerfield *et al*, 2007; Firth & Wright, 2008; Shipworth *et al.*, 2009; Yohanis *et al.*, 2010; Limbachiya *et al.*, 2012; Lomas & Kane 2012, 2013; Beizaee *et al.*, 2013	Rijal & Stevenson, 2010; Jowett, 2011	Wagner *et al.*, 2007; Ogbonna & Harris, 2008; Andersen, *et al*., 2009; Mlakar & Strancar, 2010; Alders *et al*., 2011; Wang *et al.*, 2011; Sakka, *et al.*, 2012

Due to difficulties of field studies to cover a long duration, thermal comfort in dwellings using thermal modelling and simulation can also be investigated (Hacker *et al.*, 2008; Peacock *et al*., 2010; Mavrogianni *et al.*, 2012). Dynamic thermal simulation is a valuable technique for evaluating thermal performance of buildings with the ability to save time and costs which are associated with post-occupancy survey, environmental monitoring and comfort survey (Pereira & Ghisi, 2011). It does not only overcome difficulties of carrying out rigorous calculation of huge data that is lengthy and time taking (Ralegaonkar & Gupta, 2010; Pereira & Ghisi, 2011) but also provides designers the means of working with all necessary information required for achieving effective decisions about design (Pereira & Ghisi, 2011). This suggested that the application of dynamic simulation provides a better understanding of how the building performs in different seasons in both current and future situations. It has the ability to capture more data than other methods and a combination of different methods provides different sets of data for analysis and comparison (Lomas & Kane, 2012). For this study, application of comfort field studies and dynamic simulations will be considered.

2.4 Overheating: An Issue with a Growing Concern in UK Dwellings

There has been a growing concern regarding the increase in summer period temperatures in UK dwellings (CIBSE, 2010; DCLG, 2012a), even as the climate is considered to be moderately warm, which is expected to occur regularly as global temperatures increase. Recent research has highlighted the problem with increasing summertime temperatures on the occupants' comfort in the UK (Gupta & Gregg, 2013; Lomas & Kane, 2013), as dwellings are built to meet improved regulations. As a result, they tend to be more likely to overheat and are more sensitive to potential summertime overheating than older houses (Gupta & Gregg, 2012, 2013). Similar issues have been identified in highly insulated passive houses in Europe (Mlakar & Strancar, 2010), where occupants are likely to experience high temperatures when such buildings are located in a climatic region with hot summertime. Various studies have addressed the issue of overheating in dwellings in the UK (Orme, *et al.,* 2003; Wright, *et al.,* 2005; Firth & Wright, 2008; Rijal & Stevenson, 2010; Jowett, 2011; Limbachiya *et al*., 2012; Lomas & Kane, 2012; Gupta & Gregg, 2013; Lomas & Kane, 2013; Beizaee *et al.*, 2013). Thermal mass is considered an important parameter to improve summertime thermal comfort (Holmes & Hacker, 2008) as it determines capability of building fabrics to minimise temperature swing within indoor environments (Kendrick *et al.,* 2012). This has led to increasing concerns about lightweight buildings, which potentially cannot cope with increased summertime temperatures and can lead to overheating. According to CIBSE (2010), overheating occurs when the actual indoor temperature for any given day is hot enough to make the majority of people feel uncomfortable. It can also be experienced when the indoor temperature is exceeded long enough to make occupants feel unacceptably uncomfortable, linking overheating to one of the major reasons for occupants' discomfort and dissatisfaction in buildings.

2.5 Evaluation of Overheating Risk in Dwellings Using Thermal Comfort Criteria

This section discusses various indicators that have been extensively used for assessing overheating in dwellings. These indicators have also been considered for accessing overheating risk in this study. The indicators are the static CIBSE criteria and the dynamic adaptive comfort model.

2.5.1 The Static CIBSE Criteria

According to CIBSE (2006), for overheating not to occur within a dwelling, the temperature threshold (25ºC/28ºC) should not be exceeded for more than a reasonable duration of hours (5%/1%) throughout the year. Furthermore, indoor temperature range of 25°C-28°C during the summer can result in an increasing number of occupants feeling hot and uncomfortable, while the majority of the occupants will feel increasingly dissatisfied when the indoor temperatures stay at or above 25°C for long duration of hours in a day. Hence, the duration of hours at which the temperatures stay at or above

25°C should not be exceeded for more than 5% of the total occupied hours per year (usually 125 hours). For bedrooms, lower temperatures are considered, as thermal comfort and quality of sleep decrease with temperatures increasing over 24ºC, or exceeding 26ºC with ceiling fans (CIBSE, 2006). These static criteria have been used extensively to evaluate overheating risk in dwellings (Eppel & Lomas, 1992; Cohen *et al*., 1993; Wright *et al.*, 2005; Firth & Wright, 2008; Peacock *et al.*, 2010; Lomas & Kane, 2012, 2013; Beizaee *et al.*, 2013). The duration of occupancy for bedrooms as mentioned in previous studies is between 23:00 and 07:00 (Lomas & Kane, 2012, 2013); while occupancy duration for living areas is between 08:00 and 22:00 and will be considered in this study. The occupancy duration for living areas from 08:00-22:00 (day-time period) has been considered in past studies for evaluation of the static thermal comfort model (Beizaee *et al*., 2013; Lomas & Kane, 2013).

2.5.2 The Dynamic Adaptive Comfort Model

As people can adapt to changing temperatures (Nicol *et al.*, 2009), the adaptive comfort criteria are used for free-running buildings (BSEN15251). In the UK, the majority of the dwellings are considered free-running in the summer, i.e. not mechanically heated or cooled. In that case, thermal comfort is considered to drift with the outdoor temperature, rising at about 0.33K per K rate as the moving average of the outdoor temperature (T_{rm})[2] rises within the limit $10<T_{rm}<30$ºC (BSI, 2008). The standard also specifies different categories of comfort envelopes, depending on the temperature limits defining thermal comfort (Figure 2.1).

[2] Running mean temperature (T_{rm}): is described ‘as an exponentially weighted running mean of the daily average external air temperature’ and it is computed using the formula: $T_{rm} = (1-\alpha). \{tod\text{-}1 + \alpha.tod\text{-}2 + \alpha 2tod\text{-}3.....\}$. Where tod-1 is the running mean external temperature for the earlier day, tod-2 is the running mean external temperature for the day before and so on. α is a steady from 0 to 1 (an approved value of 0.8) and it describes the rate at which the running mean reacts to the external temperature (BSI, 2008).

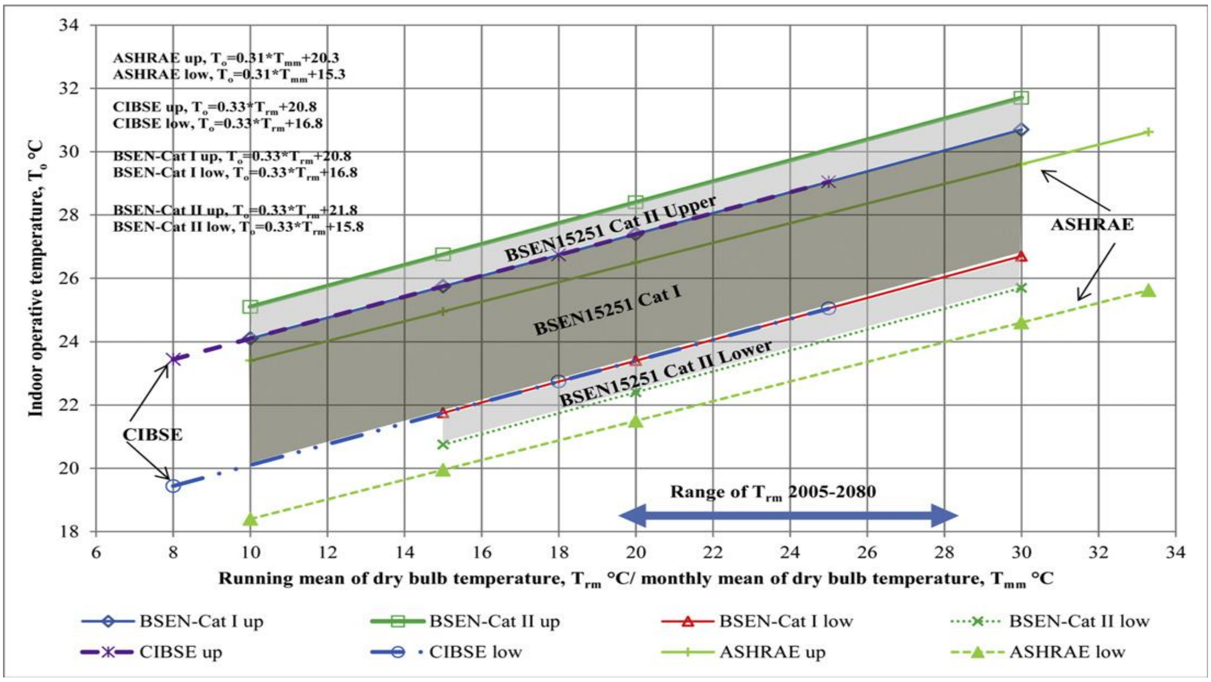

Figure 2.1: Adaptive thermal comfort standard's comparison between different indicators (Lomas & Giridharan, 2012).

According to BSEN15251 (BSI, 2008), the Category I provides comfort for *'high level of expectation and is applicable for spaces occupied by very sensitive and fragile persons with special requirements'* such as elderly occupants, disabled, sick and provides a temperature range of 4K. The Category II provides comfort for *'normal level of expectation'*. The Category III provides comfort for *'an acceptable, moderate level of expectation and may be considered for existing buildings'* and provides a broader temperature range of 8K. The last category (Category IV) is not often used, which provides comfort for *'values outside the criteria for the above categories and should only be accepted for a limited part of the year'*.

For the dynamic thermal comfort criteria, the Category II is employed, which provides comfort for *'normal level of expectation and it is recommended to be used for new buildings and renovations'* with not more than 10% responses indicating dissatisfaction. The Category II applies for evaluating thermal comfort in non-residential and residential buildings and other similar buildings where rigorous tasks are not expected to be carried out and people are allowed to open or close windows and likely to adjust clothing insulation to meet the thermal conditions of their environment (Lomas & Giridharan, 2012). The Category II applies to buildings that are not only naturally ventilated but also mechanically ventilated buildings. In summer, the buildings are likely to use unconditioned air with provision for individual means of regulating the indoor climate with use of night-time ventilation strategy, cooling fans and others that consume low-energy and a major way of adjusting indoor thermal conditions will be through windows (opening and closing). The standard (BSEN15251) shows that the Cat. II applies to all spaces in free-running dwellings that are not occupied by the vulnerable people. The Category II provides a temperature range of 6K. The BSEN15251 standard provides no restriction on the acceptable limits of the category markers and 5% of hours over (warm discomfort) or lower (cold discomfort) the Category II limit will be considered as a benchmark in this study.

2.6 Factors Affecting Thermal Comfort in Dwellings

The relationship between the outdoor environment and the indoor environment influence the building's thermal condition and occupants' comfort. Ventilation is a crucial parameter for improving the thermal conditions of internal spaces in dwellings (Hacker *et al.,* 2008). Solar gains and size of openings can influence occupants' comfort in dwellings (Gupta & Gregg, 2012, 2013; Sakka, *et al.*, 2012). Internal heat gains can contribute to high temperatures (Lomas & Kane, 2012). Thermal mass is an important parameter that could affect occupants' comfort and properties of the building envelope such as U-values influence thermal behaviour of building (Orme *et al*, 2003; Pasupathy *et al*., 2008; Dili *et al.*, 2010; Pereira & Ghisi, 2011; Kendrick *et al.*, 2012; Mavrogianni *et al.*, 2012; Sakka, *et al.,* 2012). The various studies suggest ventilation, solar radiation, size of openings, internal heat gains and thermal properties of dwellings can affect thermal comfort of occupants. However, the highlighted studies only considered evaluation of overheating risk and occupants' comfort in dwellings through modelling; therefore, this study investigates thermal comfort of occupants in timber houses using field studies and dynamic thermal modelling.

2.7 Thermal Comfort in Lightweight Dwellings

The issue of thermal comfort in lightweight dwellings has been ongoing for a while and the possibility of summertime high temperatures within indoor environments of lightweight dwellings as a result of low thermal mass (Szalay, 2004; Kendrick *et al.*, 2012). Thermal mass determines heat capacity of a building (Pasupathy *et al*., 2008; Pereira & Ghisi, 2011). An increase in heat capacity of buildings increases the occupant's comfort and reduces the rate of air temperature change as the temperature tends to remain within the comfort range (Pasupathy *et al.*, 2008; Dili *et al.*, 2010; Pereira & Ghisi, 2011). Through modelling, it was noticed that an improvement in both heat capacity and ventilation rate of a building improve occupants' comfort during summer period (Hacker *et al.*, 2008; Kendrick *et al.*, 2012). By the 2080s, extreme overheating is anticipated in bedrooms of heavyweight dwellings; while as from the 2020s, extreme overheating is expected in lightweight dwellings (Hacker *et al.*, 2008). By the 2030s, overheating will occur in bedrooms of lightweight dwellings in the UK during summertime and the occupants are not likely to be comfortable (Peacock *et al.,* 2010). Well ventilated buildings with exposed thermal mass will minimise high internal temperatures in dwellings (Pereira & Ghisi, 2011; Mavrogianni *et al.*, 2012), thereby enhance occupants' comfort. As a result, this study focuses on thermal comfort of occupants in UK timber houses with low thermal mass.

2.8 Summary

In conclusion, this chapter provided definitions of thermal comfort as mentioned in the literature reviewed. The ASHRAE definition is universally accepted but other definitions also gave a clear understanding of how to describe thermal comfort. Thermal comfort is not a state of condition, but rather a state of mind (Lin & Deng, 2008) and it indicates a state of mind when occupants are relaxed and free from being anxious (Darby & White, 2005). Occupants' comfort and satisfaction in terms of psychological and physiological factors are determined by the thermal environment which influences occupants' health and overall well-being (Nikolopoulou, 2004). Various definitions provided background knowledge on thermal comfort which is occupant's state of mind that expresses satisfaction with the thermal environmental conditions. Since it is widely reported in the literature considered that comfort affects occupants' well-being, it is important to focus on study of occupants' comfort in dwellings especially houses with low thermal mass.

It revealed that occupants' responses in terms of thermal discomfort is subjective while responses regarding thermal sensation is objective and mentioned that thermal comfort of occupants is influenced by environmental, subjective and objective factors. It explained that preference for higher air movement is influenced by occupant's feeling of warm. The chapter also discussed the effect of age, gender and level of control on how occupants' perceive and rate satisfaction within the thermal environment. The literature mentioned that the occupants' rating regarding satisfaction declined when they perceive they have low or no level of controls to regulate their thermal environments. This suggests that the occupants who are likely to be thermally satisfied perceive they have high level of control to adjust the thermal environment. However, this will be discussed in Chapter 6.

Recent studies that have investigated overheating in buildings especially in dwellings were also discussed. From different definitions gathered from various studies, it is clear that overheating is a condition when most of the occupants feel uncomfortable within the thermal environment. This period of time was considered in terms of percentage of total hours occupied by occupants. Major thermal comfort indicators that were used to assess overheating risk in dwellings were discussed. The static CIBSE criteria and the dynamic adaptive comfort model have been widely used in the studies reviewed and will be used as indicators for assessing the risk of overheating at the case studies investigated. This will be discussed in Chapters 6 and 7.

This chapter also mentioned factors affecting occupants' comfort in dwellings such as size of opening and thermal properties of building envelopes and others. Thermal comfort in lightweight dwellings was also discussed. Overall, it considered the important parameters (such as indoor temperature) that will be used for evaluation of thermal comfort supported by the literature.

Chapter 3 Overview of UK Housing: The Recent Historical Period and Space Standards

3.1 Architectural Historic Overview of Housing Development in the UK

'At a time when the Government, the house building industry, economists, homebuyers and renters are concerned about whether we are building enough new homes in the UK, it might seem odd to suggest that the focus should move to thinking about the quality of those homes. And yet this is the very time to do so. In a rush to build quickly and cheaply we risk storing up unnecessary problems for the future. We do not believe that there is any need to see a contradiction between building or refurbishing enough homes and making sure that they are of the highest quality'.

- Harry Rich, Chief Executive, RIBA (2011, RIBA: The case for space, p.3).

This chapter considers the historical development of UK housing in the 1980s and the 1990s with a focus on design, materials, construction methods and environmental sustainability. The arrangement of internal spaces of housing during the period with the consideration of internal floor areas, floor-to-ceiling height, internal conditions and internal partitions will be mentioned.

The minimum space standards used at different times before the 1960s (the decade that saw a great development in UK minimum space standards with the introduction of the Parker Morris standards) till the current time (that is, the whole period under consideration) will be examined. The importance of the Parker Morris minimum space standards as a point of reference over decades and their abolition in the 1980s will be briefly discussed. Other minimum space standards such as the English Partnerships space standards, the Greater London Authority's (GLA) space standards, the Developer standards used for housing developments will be highlighted. Comparison of the various minimum space standards will be provided. The UK minimum space standards will be compared with minimum space standards in other European nations to provide a better understanding of the UK's position and the progress made so far in terms of implementation of minimum space standards across the region.

At the later part of this chapter, prefabricated timber housing development in relation to sustainability in terms of materials will be discussed. The current developments and future prospects in the UK and the world will be presented. Also, the comparison between developments in various leading countries in timber housing stock will be mentioned.

3.2 Review of UK Housing in the 1980s and the 1990s

The late 1980s to the 1990s saw a great development in the use of timber-framed construction for houses. The late 1980s also saw the development of prefabricated timber-framed houses across the UK after rejection of timber-framed construction in the 1970s.[3] Prefabricated timber construction methods were once considered for houses in the UK. Attention was on improvement of cavity wall insulation (50-100mm width) and performance of timber houses during the 1990s with a focus on energy conservation. Also, problems relating to leakage through windows, dampness and use of plasterboards for internal spaces were widely considered. Planning of internal spaces with smaller sizes for energy conservation, reduced size of windows, reduced floor-to-ceiling heights were noticed in modern houses built with timber. Heating was provided in all habitable spaces and the rooms were expected to be naturally ventilated in summer. The gable roofs of the houses were covered with tiles. Most of the houses built were clad with bricks to make the houses look like other conventional houses and different housing typologies were developed. Since majority of the houses built during the period were privately financed houses, they were built to Developer standards. Also in the 1990s, the Conservative government came up with the plan to build an additional 4 million dwellings by 2020 with the use of modern methods of construction. This was done to improve housing conditions but the overall well-being of occupants was not adequately taken into consideration and this study will examine summertime high temperature in modern timber houses in the UK to understand if occupants are comfortable within internal spaces. The houses developed during the period suggest a shift to timber-frame construction which was not accompanied by consideration on the overall environmental effects of internal space, especially volume, orientation etc.

[3] The prefabricated timber-framed houses produced during the period can be assembled on site with a limited number of site workers when compared to traditional timber-framed houses as all the components (walls, floors, roofs) have been processed to the required sizes from the factory.

The late 1990s saw a move from construction of prefabricated timber-framed houses in the UK to construction of houses built with prefabricated structural timber panels such as cross-laminated timber (CLT) panels and structural insulated panels (SIP).[4] Structural timber panels provide internal load-bearing support at every part of the timber panels than timber-framed panels. Structural timber panels also provide vertical, horizontal and angular load-bearing support to different houses. The shapes of many timber panels' houses are rectilinear especially in blocks of apartments. In some cases, the floor plans alternated to provide articulated facades. The internal spaces are not deep with considerable size of openings. The arrangements of spaces were done in open plan designs with limited provision for partitions which reduces occupants' privacy. The floor-to-ceiling height was between 2.1-2.4m depending on the minimum space standards used for construction. The materials used for cladding varied from bricks, timber, and concrete. In some cases a combination of two or more materials was used for construction but conventional cladding materials were preferred over non-traditional materials. Also, the building materials were locally sourced while timber panels were brought to the UK in some cases due to increase in demand for timber panels which suggests additional energy used for production and transport to site. The materials were mass produced in the factory with tendency for necessary adjustments on site and low potential for materials wastage. Structural timber panels have been increasingly used for construction of UK houses since the late 1990s to the present time and various houses built with prefabricated timber panels in the last decade will be presented in Chapter 5.

3.3 Review of Minimum Space Standards in UK Housing

'There has been growing concern that the internal space of new dwellings may be getting smaller. There is evidence that less family size housing is being provided. There is however concern that internal space within both family and non-family homes may also be reducing. This has implications for accessibility, sustainability and quality of life including health'.

- HATC (Housing Space Standards, 2006 p.5).

[4] The period saw a rapid construction of houses built with engineered timber products also known as structural timber panels. The structural timber panels such as CLT, SIP, Glulam (Glued-laminated timber) eliminate use of timber stud and infill panels for construction of dwellings. Houses built with engineered timber panels are structurally sound than prefabricated timber-framed houses. The structural timber panels can be used for construction of high-rise housing developments.

One of the vital parameters to evaluate the conditions of housing quality is the adequate provision of spaces. The size of a dwelling in the UK is assessed by the available number of rooms in the dwellings (Mayor of London, 2009) while the size of houses in other European nations is evaluated by the area of the internal floor space (Eurostat, 2011). Space is a crucial parameter influencing occupants' comfort and level of privacy within the internal environment of a dwelling (Housing Design Standards, 2010). The need for adequate space has become a growing concern for occupants in recent years (HATC, 2006; Roys, 2008; CABE, 2010; RIBA, 2011; Housing Design Standards, 2010) which cannot be substituted with any other parameters (Cope, 2004) as flexibility in terms of space usage enhances occupants adaptation to change in lifestyle due to different conditions such as family size and age (Ozaki, 2002; CABE 2010; RIBA, 2011). Many investigations carried out recently have suggested a decrease in floor area of spaces in dwellings (Evans & Hartwich, 2005; RIBA, 2007; Drury, 2008; Mayor of London, 2009; CABE, 2010; Gallent *et al.*, 2010) with frequent referral to Parker Morris Standards (Mayor of London, 2009; CABE, 2010; Housing Design Standards, 2010). Recent studies have shown that the internal spaces of newly built UK houses are becoming smaller when compared to newly built houses in other European nations such as Germany, Denmark and the Netherlands (Roys, 2008; CABE, 2010; Kelly, 2013); and a more radical approach is required to improve UK housing situations. In order to evaluate the current minimum space standards used for modern UK houses and its impact on indoor occupants' the overall well-being, which will be discussed in Chapters 6 and 7, it is important to understand how UK minimum space standards have evolved over the last few decades.

3.3.1 Pre-1960 Space Standards

From 1666 when there was a fire outbreak in London (that is, the Great Fire of London), the housing quality and minimum space requirements have been given much consideration across the UK. The enactment of the London Building Act in 1667 to the Public Health Act of 1875 had examined various minimum requirements for newly constructed dwellings such as wall thickness, size of rooms, number of storey, floor-to-ceiling height, width of streets, fire place, chimney, drainage, lavatory, private garden and many other important features (Housing Design Standards, 2010). The minimum requirements were constantly reviewed for decades until the latter part of 1910s when a new space standard was introduced. In the early 1910s, private investors such as landlords and developers were major housing providers in the UK with over 80% of total dwellings financed by them with provision for different categories of dwellings to meet the needs of working to middle-class renters (HATC, 2006; Mayor of London, 2009). During the period, social housing was provided by local councils and necessary standards for dwellings regarding accessibility and size of internal spaces were regulated by the authority in charge of public health and bye-law regulations. The private housing built during the period was financed by charities such as the Peabody Trust but most houses were built according to individual design subject to approval by the regulatory body in line with the existing recommendations for provision of spaces in dwellings (The Public Health Act of 1875) which specified at least 14m² private garden space at the back of every dwelling and not less than 2.4m floor-to-ceiling height in all spaces (Woodman & Greeves, 2008; Housing Design Standards, 2010). The Act also indicated proportionality of windows in bedrooms which must relate to size of the bedrooms as well as provision for toilets and drainage in all dwellings. From 1880 to 1910, there was steady growth in the housing sector and over 2.5million terraced housing units were constructed within the period.

The Tudor Walters committee was inaugurated in 1917 to conduct another study on UK housing situations and the outcome of the report led to the approval of the Housing Act (1919) used to develop Homes Fit for Heroes[5] after the World War I (London Councils, 2013). The report also included publicly funded housing for people with approved standards and number of occupants per dwellings. The standards and densities considered in the report were earlier used by Ebenezer Howard[6] for the Garden cities and provided recommendations for renting of publicly funded housing by people (HATC, 2006; CABE, 2010; Housing Design Standards, 2010). Some of the recommendations of the report include: in a 3-bed dwelling, two of the bedrooms must accommodate two beds at a time. Also, in a 2-bed dwelling, one of the bedrooms must accommodate two beds at a time, this was observed in many post-war prefabricated houses such as Arcon house built in the 1940s (Figure 3.1). Also, ground floor dwellings must have a minimum of 3-bed; each

[5] Homes Fit for Heroes are the dwellings constructed for the First World War veterans in the UK. In total, they were about 200,000 dwellings built for the war veterans.

[6] Ebenezer Howard (1850-1928) was a notable British social reformer and inventor who developed the idea of Garden city of how people can live in harmony with nature. He published Garden Cities of To-morrow in 1898 and developed some notable garden city projects such as Lecthworth Garden City and Welwyn Garden City. Parker and Unwin also contributed to the overall development of the Garden City Movement.

dwelling must have bathroom and cool area for storing food items; the density of dwellings per acre must be at least 12 (less than 30 dwellings per hectare) with a minimum floor area of 79.4m² for 3-bed with no living area and 98m² for 3-bed house with a living area (Holmes, 2006; HATC, 2006; Mayor of London, 2009; CABE, 2010); provision of front and rear gardens for cottages and at least 21m between two opposite row housing (HATC, 2006; Mayor of London, 2009; Housing Design Standards, 2010). The green areas provided in front and rear gardens of cottages minimise the impact of summertime high temperatures by absorbing the surrounding heat. Also, the green areas improve the air quality and rate of fresh air that gets into the spaces.

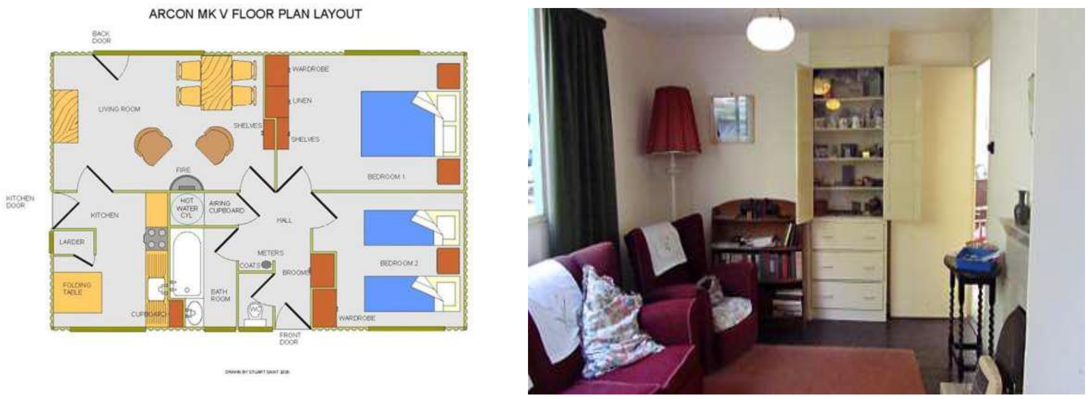

Figure 3.1: Floor plan of post-war prefabricated 2-bed house by Arcon with provision for one of the bedrooms to accommodate 2 beds at a time (left) and view of the living area which indicates change in design of the floor plan and construction of the houses (right) (Gilbert, 2011).

The number of UK houses increased by 52% from the 1920s to 1930s due to rapid development of council housing especially in suburban areas and private developers were involved in development of houses during the period (HATC, 2006; CABE, 2010). Some of the houses provided during the period (from the 1920s to 1930s) were built in line with the recommendations provided in the Tudor Walters report of 1919. At the latter part of 1944, another report on minimum housing space standards known as the Dudley Report was recommended (CABE, 2010; Housing Design Standards, 2010). The report re-examined the standards of UK housing and identified some limitations including non-availability of materials, inadequate housing and trained labour in the sector to build new conventional houses. The report approved the development of detached houses for people that desired to have one and recommended extensive use of non-conventional and prefabrication methods of construction for housing with improved minimum space standards.

From 1944 to 1949, a new set of minimum space requirements published in Housing Manuals was introduced. The report stated recommendations concerning design of houses and estates, site layout, types of dwellings, demography, size of internal spaces, heating and cooling requirements, insulation, methods of construction and new materials for local councils (Milner & Madigan, 2004; Mayor of London, 2006; CABE, 2010). Also, construction of 2-bed and 3-bed houses to provide temporary dwellings for people was included in the report (Mayor of London, 2006; CABE 2010). The report was revised in 1949 and approved a range of 84m² to 88m² as the minimum space requirements for 3-bed house compared to the previous manual released in 1944 that recommended from 74m² to 84m² for 3-bed houses.

In the early 1950s, the existing minimum space standards were changed by the Conservative government that took over and influenced the UK housing policy (Milner & Madigan, 2004; Mayor of London, 2006; CABE, 2010; Gallent *et al.,* 2010). A new set of minimum space requirements (Macmillan's standards) focusing on 'People's House' was recommended with floor area of 83.6m² considered for 3-bed house. The government through the Ministry of Housing and Local Government approved the minimum space standards for apartments and maisonettes but were considerably smaller in terms of internal floor area when compared to minimum space standards stated in 1949 Housing Manuals indicating additional 9.3m² for 3-bed house. Also, Macmillan's standards recommended the use of conventional methods of construction for building UK houses due to availability of traditional materials and stated that non-conventional construction methods will no longer be used for construction of dwellings.[7] The standards also favoured private developers to commence construction of low-cost accommodation with focus on blocks of flats rather than houses.

3.3.2 The Parker Morris Space Standards

The Parker Morris Report commissioned by the Ministry of Housing and Local Government (MHLG) was approved in 1961 as the minimum space standards for new housing design. The report remains a point of reference and the most important minimum

[7] Problems regarding shortages of materials had been resolved due to the improvement in the economy. Also, there was an improvement in the production of locally sourced building materials which favoured construction of houses with conventional materials such as bricks and use of prefabrication methods of construction ceased.

space standards ever used in UK's housing history due to considerations given to various need in housing. The purpose of introducing the standards was to provide minimum space standards for UK housing that would be considered for many years without any future limitations. The standards as stated in the report (Homes of Today and Tomorrow) mentioned limitations of post-war social housing such as smaller sizes of internal spaces (CABE, 2010) and suggested a need for proper assessment of internal spaces and improvement (Campbell, 2008; Roys, 2008; Maliene & Malys, 2009). The report indicated improved production of conventional materials for housing construction with focus on provision of houses that meet future expectations in all spaces and heating requirements for spaces to be habitable in summer and winter. The recommendations highlighted dwellings as a place to carry out various daily tasks and should be well-designed to support occupants' pattern of living and keeping of furniture and appliances.

Also, the standards focused on 'Space in the Home' with a revised report published in 1968 by the MHLG highlighting requirements for various family sizes (Table 3.1). The space standards covered requirements for bedrooms (adult and children) with tendency for children of same gender to share the bedroom with bigger space. The floor area specified by the standards was considerably bigger than earlier used standards in the UK. For instance, 89m² was specified as minimum floor area for a 3-bed house (2-storey) with 5 occupants and 4.5m² for storage area as oppose to 84-88m² specified as the minimum floor area by the Housing Manual of 1949 (Table 3.2). The minimum space standard was intended for development of publicly and privately financed housing but private developers were not mandated to use the standards. The report pointed out the use of open plans in many houses for flexibility of space usage with the possibility of providing additional rooms which may be smaller. It also suggested bigger rooms with reduced number of internal spaces. The minimum space requirements with overall average for various sizes of dwelling type under the Parker Morris standards are provided in Table 3.2.

Table 3.1: The Parker Morris standards of 1961 indicating minimum spaces requirements for different family sizes (Woodman & Greeves, 2008 in Home / Away: Five British Architects Build Housing in Europe)

A home to be built in the future for occupation by:

6 people	5 people	4 people	3 people	2 people	1 person

should be designed with a net floor area of at least:—

Square metre

<table>
<tr><td>3-storey house *</td><td>97.5</td><td>93.8</td><td>—</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>2-storey centre terrace</td><td rowspan="3">91.7</td><td>84.5</td><td>74.3</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>2-storey semi or end</td><td rowspan="2">81.8</td><td rowspan="2">71.5</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>Maisonette</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>Flat</td><td>86.4</td><td>78.9</td><td>69.6†</td><td rowspan="2">56.6</td><td rowspan="2">44.6</td><td rowspan="2">29.7</td></tr>
<tr><td>Single storey house</td><td>83.6</td><td>75.25</td><td>66.8</td></tr>
</table>

* These figures will require modification if a garage is built in † 720 if balcony access

and general storage as follows:

Square metre

<table>
<tr><td>Houses ‡</td><td>4.6</td><td>4.6</td><td>4.6</td><td>4.2</td><td>3.7</td><td>3.3</td></tr>
<tr><td>Flats and Maisonettes
Inside the dwelling
Outside the dwelling</td><td>1.3
1.8</td><td>1.3
1.8</td><td>1.3
1.8</td><td>1.1
1.8</td><td>0.9
1.8</td><td>1.3
1.8</td></tr>
</table>

‡ Some of this may be on an upper floor; but at least 2.3 square metres should be at ground level.

and W.Cs. should be provided as follows:

A. In 1, 2 and 3 person dwellings, 1 W.C. is required, and may be in the bathroom.
B. In 4 person 2 or 3 storey houses and 2 level maisonettes, and in 5 person flats and single storey houses, 1 W.C. is required, in a separate compartment.
C. In 2 or 3 storey houses and 2 level maisonettes at or above the minimum floor area for 5 persons, and in flats and single storey houses at or above the minimum floor area for 6 persons, 2 W.C.'s are required, one of which may be in the bathroom.
D. Where a separate W.C. does not adjoin a bathroom, it must contain a washbasin.

3.3.3 The English Partnerships/ Affordable Homes Space Standards

The standard was set up in the early 2000s by the Housing Corporation and the English Partnerships which were later merged to become the Homes and Communities Agency (HCA). Prior to the 2000s, The UK government had proposed new minimum space standards for publicly financed housing developments (HATC, 2006; Mayor of London, 2009) with various local councils developing individual minimum space standards in line with the HCA standards. In 2007, all newly built houses using the standards were required to meet at least the Code for Sustainable Homes (CSH) Level 3 and non-residential development must be built to meet the lowest threshold of BREEAM (Building Research Establishment Environmental Assessment Method) suggesting a satisfactory level.[8] The standards focus on housing developments with special interest on high-quality material, environment, sustainable material and method of construction. The minimum requirements for internal floor area of spaces in line with adequate number of users were provided in the standards (Table 3.2). Flexibility and adaptability of spaces for various future needs were taken into consideration. Some spaces like study, garden, communal playground were mentioned to promote social cohesion among residents. The standards highlighted a good level of insulation to minimise noise pollution and use of material with good fire rating. Also, the method of construction should be energy efficient to improve performance and quick completion of the project. Emphasis is laid on waste reduction and re-useable materials. Internal spaces should be well-ventilated and spacious to minimise high internal temperature (overheating) in living areas and bedrooms stating the CIBSE thermal comfort standard of 1%/28ºC for living areas and 1%/26ºC for bedrooms (English Partnerships, 2007 p.25). The standards have been discussed in Chapter 2 and the methods used to investigate the potential of overheating at the case studies investigated will be examined in Chapter 4 while analysis and results will be discussed in Chapters 6 and 7. Table 3.2 summarises the minimum space requirements for the standards.

3.3.4 The Greater London Authority's (GLA) Space Standards

The standard was developed as a result of several evidences collected by the Housing Association Training and Consultancy (HATC) Limited regarding sizes of space and its usage in housing. They include in-depth review of literature relating to history, recent developments and implementation of the available minimum space standards in newly built houses across many European nations including the UK. The studies consider the overall well-being of people from various data investigated such as BRE (Building

[8] The Code for Sustainable Homes (CSH) 3 recommends use of materials with a minimum of D-rating as specified by the Building Research Establishment Green Guide for construction of walls, floors, roofs, doors and windows. Newly built houses in the UK are constructed using masonry cavity walls or timber-framed panels classified as A-rating materials. However, concrete walls fall below the minimum threshold (a D-rating) specified by the CSH 3. Overall, the Code specifies that UK houses (newly built and refurbished) must attain at least 57 points across the nine major indicators (energy and carbon emissions, water, materials, surface run-off, waste, pollution, health and well-being, management and ecology) outlined for the standards. The two important indicators that must attain at least 57 points include energy and water.

Research Establishment), NHF (National Housing Federation), CABE (Centre for Architecture and Built Environment) and data generated by the HATC's research group members (HATC, 2006; Mayor of London, 2009; CABE, 2010; Housing Design Standard, 2010). The investigation reviewed various space standards and provided suggestions to be considered for the GLA (HATC, 2006). It also considers current investigations on UK minimum space standards and suggests improvements in UK minimum space requirements (HATC, 2006) which are likely to provide healthier environment and improve the overall well-being of people (Petticrew *et al.*, 2009; CABE 2003, 2009, 2010; The London Housing Strategy, 2013, 2014).

The GLA standards recognise the use of open plan designs in modern UK houses with no privacy for users which has reduced bedrooms to mainly for sleeping rather than for other purposes including study, leisure, recreation and relaxation. This further confirms the assertion made many years ago by the British modernist architects like Maxwell Fry that people do not stay for long in bedrooms therefore bedrooms should not be big. The standards also highlighted the growing need for housing with preference for a greater number of bedrooms which can be used for various purposes instead of providing spaces for specific purposes. Furthermore, the standards mentioned lack of storage space of up to 60% in 1-bed apartment of newly built housing developments in London with an average internal floor area of 46.9m² as opposed to 48m² and 51m² recommended by the Homes and Communities Agency (HCA) and the English Partnerships respectively (CABE, 2010; Housing Design Standards, 2010). The internal floor area of 2-bed apartment was considerably smaller across the housing developments investigated with up to 10m² and more than 91% cases were found to be fallen short of minimum space standards recommended by the HCA and the draft London Plan. Furthermore, the internal floor area of some of the 2-bed apartments studied were found to be 49m² and this led to an anticipation for a radical change to the existing space standards in modern houses by introducing the GLA standards.

For sizes of room, a minimum of 8m² is recommended for a single-bed and at least 12m² for a double-bed. A single bedroom must be able to take a small table, a bed and allowable space for storage and a guest which indicates a single bedroom with internal floor area less than 7m² is considered very small. The standards indicated an increase in internal room height with higher density and provision for lifts which must be positioned at reasonable distance to all apartments for easy circulation. Cross-ventilation is recommended in bedrooms and north facing windows are considered not appropriate in single-ventilated bedrooms. For floor-to-ceiling height, the standard recommends at least 2.5m in all spaces considered as habitable and not less than 2.6m in most commonly occupied spaces such as living areas. It also indicates provision for higher floor-to-ceiling heights in all spaces located at the ground floor. In addition, at least 1.5m depth is recommended for balconies and private outdoor spaces. The internal floor area for balconies and private outdoor spaces should be at least $5m^2$. The standards specify minimum space requirements from floor area for both internal and private outdoor spaces to floor-to-ceiling height. It also recommends the use of floor-to-ceiling height window for adequate ventilation. However, most of the privately financed housing developments recently built in the UK have not considered the standards and this will be discussed further in Chapter 5.

3.3.5 The Developer Standards

The UK Developer standards were developed by the National House Building Council (NHBC) formerly known as the National Housebuilders' Registration Council (NHBRC) set up in 1936. The body came up with the minimum space standards in 1967 for use by UK private developers approved in 1968 with conditions that only members that use the minimum space standards for construction of housing will be supported with additional funding to execute new housing projects. This was done to encourage the members to use the standards and discouraged the use of the Parker Morris report across the UK. The standards initially focused on size of rooms but later revised in 1974 and 1983 to cover workmanship and arrangement of bedroom, kitchen and provision for insulation (thermal and sound), heating requirements, safety and security, space for storage as well as electricity points.[9] The standards did not consider total household size and activities but focused on multiple uses of spaces and size of furniture which were mentioned in the Parker Morris report. The Developer standards considered the UK building regulations (Part L) with a focus on energy conservation in buildings. The regulations recommend an improvement of up to 25% in terms of the performance and conservation of energy to ensure newly built privately financed dwellings meets at least the CSH (Code for

[9] The Developer standards specify a minimum of 100mm thick insulation for walls. The standard before it was revised in the 1980s specified at least 50mm thick insulation for walls. For the electricity points, at least two points were recommended to be installed within a habitable space.

Sustainable Homes) Level 3. The minimum requirements for air permeability, U-values of fabrics, insulation, ventilation and heating were also set by the standards. Also, energy efficiency of up to 75% was set for lighting (NHBC, 2010). However, minimum internal floor areas for spaces are considerably smaller than the minimum floor area set by other standards (Table 3.2). The Developer standards specify minimum floor areas for internal spaces to reduce energy needed for heating and cooling. Also, the internal spaces cannot be used for leisure, recreation but mainly for necessary everyday task such as sleeping and cooking. Modern block of flats in Knightsbridge, London is a good example of privately financed housing development with smaller internal spaces[10] (Figure 3.2)

Figure 3.2: View of a studio apartment in Knightsbridge, London with internal dimension (3.4m by 1.7m) and floor area of 5.78m² which is smaller than area of a snooker board/table of 6.48m² (Kelly, 2013)

3.3.6 Other Minimum Space Standards Available in the UK

Currently, there are other minimum space standards in use for various housing developments by different regulated bodies across the UK. The guidelines and implementations of each standard depend on the organisation in charge of the application of the standards. Examples of other minimum space standards include: the Code for Sustainable Homes (CSH); the Lifetime Homes; Secured by Design; the Wheelchair Housing Design Guide and Building for Life space standards.

The Code for Sustainable Homes was developed in the mid 2000s (DCLG, 2006) and is currently being used as the approved UK indicator for assessing newly constructed dwellings' environmental performance (English Partnerships, 2007) in order to improve

[10] The exact name of the apartment was not indicated.

performance of modern dwellings (McManus *et al.*, 2010; Jowett, 2011). The CSH covers 9 major areas using thresholds for rating the parameters such as energy, pollution, waste management, carbon emission, health and well-being, water, materials, drainage as well as ecology and management.[11] The Code has 6 levels with all new dwellings expected to meet specified requirements for energy and water while other features are used as indicators for meeting higher levels of the Code. For all newly built social housing, at least the Level 3 of the Code must be achieved while privately financed housing developments may be lower than the Level 3 with minimum energy requirements set for all dwellings. The Code indicates all newly built dwellings must meet at least the Level 3 by 2010 and the Level 6 (zero carbon emissions level) by 2016 but did not clearly state how it will be achieved. However, all housing providers are encouraged to provide houses that meet at least the Level 4 (Housing Design Standards, 2010). Most recently developed standards for public housing such as the GLA standards, the English Partnerships have specified application of sustainable design and methods of construction for modern houses. This will also be discussed in line with the case studies investigated in Chapter 5.

Other minimum space standards such as the Lifetime Homes standards will not be considered since the standards are not used for the case studies that will be examined in Chapter 5. Table 3.2 below summarises minimum space requirements for different sizes of dwellings and minimum space standards used by two of the local councils in South and Southeast of England are included for comparison.

[11] The Code for Sustainable Homes does not specify requirements in terms of floor area for internal spaces in dwellings. The Code focuses on energy conservation in dwellings and highlights the requirements for various levels of sustainable houses instead of minimum space requirements for dwellings.

Table 3.2: Comparison between the minimum space requirements for different space standards used in the UK over last few decades[12] (HATC, 2006; Housing Design Summary, 2010; CBD Guide, 2014)

Area of floor (m²) by dwelling type	**1-bed 2P flat**	**2-bed 3P (flat)**	**2-bed 3P (2-storey)**	**2-bed 4P (flat)**	**2-bed 4P (2-storey)**	**3-bed 5P (flat)**	**3-bed 5P (2-storey)**	**3-bed 5P (3-storey)**	**4-bed 6P (flat)**	**4-bed 6P (2-storey)**	**4-bed 6P (3-storey)**	**Floor-to-ceiling height**	**Min. depth of balcony**
Housing Manual (1949)	47	-	-	-	70-74	-	84-88	93-98	84	93-101	102-110	2.4	1.5
Parker Morris (1961)	45	60	70	73	79	82	89	98	89	97	102	2.4	1.5
Borough of Kensington & Chelsea Standards SPG (2002)	44.5	57	-	57	-	70	72-74.5	-	80.5	82-85	94	2.3	1.2
English Partnerships (2007)	51	66	68	71	77	93	93	93	106	106	106	2.5	1.2-1.5
Housing Corporation (2008)	45-50	57-67	57-67	67-75	67-75	75-85	82-85	85-95	85-95	95-100	100-105	2.4	1.2-1.5
NHF Standards (2008)	50	61	-	70	82	86	96	102	-	108	114	2.4	1.5
Developer (NHBC- 2008) standards	43-48	55	-	64	-	98	98	98	101	101	101	2.1	-
Mid-Sussex Council, Space Standards SPD (2009)	51	66	77	66	77	93	93	93	111	111	111	2.4	1.5
GLA standards (2010)	50	61	74	70	83	86	96	102	99	107	113	2.5	1.5
HCA (2010)	48	61	71	70	80	86	96	102	99	108	114	2.4	1.5

*P means person. For instance, 3P indicates 3 persons.

Table 3.2 indicates minimum space standards in the UK have fallen over the last few decades with the Developer standards and the SPG standards specifying the lowest minimum space requirements for different size of dwellings. Looking at the trend from the table suggests there was a steady increase in the minimum space standards in UK housing from 1949 to 1961 while a shortfall in the minimum space requirements was

[12] The Code for Sustainable Homes and the Lifetime Homes standards not included as the two standards did not consider minimum space requirements for internal spaces. The Lifetime Homes only specified the minimum requirements for circulation spaces such as stair halls, access for disabled etc.

observed from 1980 to 2002. From 2002 to 2010, most of the space standards developed except the NHF standards of 2008 specified the same range of minimum space requirements for dwellings. For instance, the English Partnerships of 2007 and the Housing Corporation standards (2008) specified the same range of minimum space requirements for houses. A noticeable change in the trend was observed when the GLA standards and the HCA standards were introduced in 2010 suggesting efforts to improve minimum space requirements in UK housing at the beginning of the current decade.

3.3.7 Comparison between UK Minimum Space Standards and Standards Available in Other Nations

Across Europe, the minimum space standards available in the UK are considered to be considerably below average and considered as one of the nations with the smallest size of houses in the continent (HATC, 2006) as well as the nation with smallest houses in the western part of Europe (Evans & Hartwich, 2005; HATC, 2006). According to Eurostat (2011), newly constructed houses in Ireland are expected to be 15% bigger than new UK houses; while in the Netherlands and Denmark houses are 53% (30.5m²) and 80% (52m²) bigger respectively than UK houses. For a 3-bedroom flat suitable for 5 people, an average of 86m² is considered for publicly financed housing in London but at least 100m² is considered for the same size of dwelling in Dublin and Germany. Many European nations set the minimum internal area of floor for spaces (HATC, 2006; Housing Design Standards, 2010) while the size of UK dwelling is marketed by the number of bedrooms (HATC, 2006; Roys, 2008). Also in the UK, the authorities' recommendations on minimum space standards are based on floor area (m²) while consumer marketing sector focuses on number of bedrooms. Moreover, there is a noticeable difference between the minimum space standards used for publicly and privately financed UK housing while the same minimum space standards are used for both housing developments in other nations. Taking into account population density which could be seen as a potential reason for providing smaller houses, other nations that are providing bigger houses are more densely populated than the UK. For instance, the Netherlands has a population density of 456people/km² while the UK has 243people/km² which is considerably smaller (HATC, 2006). This suggests that the provision of smaller houses is a deliberate action by housing providers especially developers to produce more houses without considering the overall well-being of end users. Chapters 6 and 7 will provide a better understanding of the effect of smaller houses on occupants' comfort.

3.4 Focus on Prefabricated Timber Housing

In recent years, prefabricated timber has been used for contemporary housing developments and it will be examined in line with sustainability in terms of energy needed for production and transport.

3.4.1 Prefabricated Timber Housing, Material and Transport Sustainability

The embodied energy, which is the amount of energy consumed to produce a material, energy used in transportation of a material to the factory and from the factory to site can be used to evaluate sustainability of a material. In addition, a material can also be evaluated by its ability to be recycled and re-used for other purposes. Timber as a building material for housing is best measured in terms of sustainability when it is locally sourced and processed from a nearby location to the construction site where it will be used. Prefabricated timber, considered as one of the most frequently used sustainable materials for modern housing construction in the UK (Sustainable Homes, 2000; TRADA, 2009a; Homebuilding, 2010) requires additional energy for production with use of energy powered machines (especially engineered timber products) when compared to traditional timber. Moreover, prefabricated timber products used for construction of houses in less wooded European nations such as the UK and Hungary are not sourced from nearby locations (Szalay, 2004), which require additional cost of energy needed to bring the materials to site (Sustainable Homes, 2000; Szalay, 2004). However, the amount of energy needed for its production and transportation from factory to construction site has been considered relatively small compared to the amount of carbon locked in timber (Thompson, 2009; TRADA, 2009a) but this is applicable when location where timber is sourced and produced is not far from the construction site. This implies additional cost and carbon emissions to transport timber from other European nations to less wooded nations like the UK and Hungary but the overall amount of carbon locked in timber indicates its positive carbon footprint. Comparing timber with other materials, on average, a timber house consumed 58% of the total energy required to produce similar size of non-heavy block wall house and 35% of energy needed to produce its floor (Sustainable Homes, 2000).

3.5 Current Development and Future Prospects of Prefabricated Timber Housing

Prefabricated timber housing sector has shown steady growth in recent years especially in the USA and the Scandinavian nations where timber has been extensively used for houses (Sustainable Homes, 2000). Modern houses have been constructed using various prefabricated timber products with many proposed projects to be built over the next few years. The market share value of timber housing has been on the increase with more number of timber houses built annually in most nations especially the developed nations. As a result of this trend, current development and future prospects of the housing sector on the international and national levels will be briefly examined under this section.

3.5.1 International Current Development and Future Prospects

It has been observed over the last few years that more than 70% (150 million) houses in the advanced nations across the globe are built with timber (Sustainable Homes, 2000; TRADA, 2009a). Currently, the USA has the largest timber housing stock in the world with over 97.3 million and yearly estimate of over 100,000 new timber houses developed. In Japan, timber houses account for 45% of the housing market share with over 40.5 million timber houses as the nation is accustomed to natural disaster such as earthquake and use of timber is best recommended for housing developments. In addition, modern timber houses in Japan have been modified with provision for earthquake resistant foundation to minimise the effect of earth movement and seismic actions on the houses (Figure 3.3). In Scandinavian nations, prefabricated timber has been used for housing covering up to 90% of total housing market share in Sweden and Norway. In terms of number of houses provided, Sweden and Norway have more than 3.9million and 1.8million timber houses respectively (Sustainable Homes, 2000). Considering Canada and Australia, only 10% of the housing market shares are covered by non-timber houses with more than 10million and 6million timber houses in the respective nation's housing stock. This suggests timber is used for housing developments in many other developed nations than the UK (Sustainable Homes, 2000; NHBC, 2007) with building regulations limiting the height of timber structures in many European nations (Thompson, 2009; TRADA, 2009a) as it will be discussed in Chapter 5. Prefabricated timber has also been used for preservation of houses with historical values in many advanced nations across the world such as Schaustall[13] in Rheinland-Pflaz, Germany (Figure 3.4). Regarding future prospects, improved timber products are used for construction of more structures especially high-rise structures with expanding market share across the world considering the recent growth in global timber housing. For instance, a 49m high-rise timber block of flats is currently undergoing construction in Bergen, Norway and is expected to become the world's tallest prefabricated timber housing when completed in October, 2015 (Figure 3.5). Also, another 34-storey high-rise structure designed by C.F. Moller Architects is currently proposed to be built with prefabricated timber in Stockholm, Sweden (Figure 3.6) and a 20-storey timber tower designed by Michael Green Architects has been approved to be built in Vancouver, Canada.

Figure 3.3: Testing of a prototype earthquake resistant prefabricated timber multi-storey house developed at the Hyogo Earthquake Engineering Research Centre in Japan to reduce the effect of earth movement and frequent seismic actions on houses (Inhabitat, 2014).

Figure 3.4: Installation of volumetric prefabricated timber structure to preserve Schaustall in Rheinland-Pflaz, Germany (left), the historical structure after it has been preserved (middle) and the interior after completion of the project (right) (FNP Architekten, 2010).

[13] Schaustall "house within a house" is a conversion project of an old shed built in the 18th century to showroom located in Rheinland-Pflaz, an urban centre in the southwestern part of Germany. The project is designed by FNP Architekten.

Figure 3.5: View of the 14-storey (49m high) timber tower block of 62 apartments built with CLT and Glued laminated timber (Glulam) materials in Bergen, Norway to be completed in October, 2015 (CIOB, 2014).

Figure 3.6: Typical floor plan and three-dimensional view of proposed 34-storey timber housing in Stockholm indicating articulated facade with provision for roof garden on each floor, that is, the individual balconies to each flat (C.F. Moller Architects, 2014).

3.5.2 UK Current Development and Future Prospects

Currently, most modern timber houses in the UK are constructed with structural timber products and the exterior walls are covered with cladding materials different from structural timber or made from recycled timber. The most frequently used cladding materials in many newly built houses over the last few years are bricks of different kinds for protection against rain and harsh external weather conditions. Structural timber materials are produced outside the UK and brought as off-site products to many sites in the country for assembly. According to figures released by the Office of National Statistics (ONS) and reported in TTF (2014), UK based major timber producers are currently 120 in number with an estimated value of more than £8.5 billion and solid timber market occupies £2.4 billion with overall volume of about 17.1 million/m³. In the last half decade, about 5 to 10 UK based new companies are joining the timber construction sector (Sustainable Homes, 2000). The development has widened the opportunity for the market to grow with many modern publicly and privately financed housing built with prefabricated timber. Some of the prefabricated timber houses built within the last decade in the UK will be considered in Chapter 5. Also, the development has led to improvement in modern methods of construction used for timber houses.

3.6 Summary

This chapter presented an architectural historic overview of UK housing developments in the 20th century (in particular, the 1980s and the 1990s). The design, materials, methods of construction and performance were briefly explained. It appears that the houses are more generous with higher internal floor area, floor-to-ceiling heights and larger size of openings when compared to many newly built houses. In terms of planning, the internal spaces were arranged to avoid having too deep rooms which can possibly enhance natural ventilation of the spaces in summer.

The late 1980s saw a great development of prefabricated timber-framed houses with improvement in the level of insulation to improve the performance of timber-framed houses. The late 1990s saw a move from construction of timber-framed houses to prefabricated structural timber panel houses which have been increasingly built across the UK in the last decade. However, the actual performance of houses built with prefabricated timber panels has not been investigated and it will be discussed in Chapters 6 and 7.

Considering the minimum space standards used over the last few decades in the UK suggest the Parker Morris Standards as a point of reference for other space standards in the UK's housing history due to consideration for various need in housing. From pre-1960s to the current period shows that UK houses are getting smaller with reduced internal floor area of spaces and floor-to-ceiling heights. The consideration of other standards showed that the Developer standards are considerably small and a radical approach needs to be done to improve the size of internal spaces in the UK. Looking at minimum space standards across Europe indicate UK houses as one of the smallest in the continent with lower density per/m² than many nations that build bigger houses.

Finally, the evaluation of current and future developments of prefabricated timber housing on a global scale showed that timber has been widely used for housing developments in many advanced nations with the US as a leading nation in the sector.

Considering the UK, it appears timber housing stock is growing rapidly in recent years with estimated value above £8 billion. The current development suggests there is a potential with huge prospects for prefabricated timber housing sector and every effort must be put in place in terms of policy, market strategy and innovative research to focus more on the sector for future improvement.

Chapter 4 Data Protocol

4.1 Introduction

"The post-occupancy evaluation (POE) of buildings is an increasingly important tool for the improvement of buildings and the evaluation of what makes energy-efficient and sustainable buildings [......]. The science of thermal comfort defines the reproducibility of the human as a thermometer of comfort. The post-occupancy evaluation typically uses this human characteristic as one dimension of its evaluation of a building. Field studies of thermal comfort have shown that the way in which occupants evaluate the indoor thermal environment is context dependent and varies with time".

- Nicol & Roaf (2005, pp.338, 344).

This chapter presents data protocol and techniques used for the analysis of data. The research procedure and strategy used will be discussed which include identification of UK housing developments built with prefabricated timber materials over the last decade, selection of the case studies based on important parameters such as location, sustainability or low energy rating awards, type of building, access and methods of construction. The development of post-occupancy questionnaire, the steps taken to contact the appropriate authorities in charge of the buildings in order to secure approval to investigate and access the case studies as well as administration of the questionnaire will be discussed. The collection of the questionnaires filled by the respondents will be mentioned.

Physical measurements of the variables in order to assess the environmental conditions of the case studies will be presented. Environmental monitoring is considered to be very important in comfort field studies as it provides information and modifications that can be made in predicting the expectation and feeling of the occupants based on data collected from the measurement of environmental variables (Nicol & Roaf, 2005). The experimental plan for the monitoring will be briefly outlined. The collections of outdoor weather data as well as retrieval of the data recorded by the equipment for analysis will be explained.

Comfort surveys which help to understand how indoor occupants interact with the case studies will be examined. The frequency of filling the questionnaire by the participants and minimum hour between administrations of two questionnaires will be mentioned. The collection and collation of the data for analysis will be considered. The comparison between comfort surveys, post-occupancy surveys and environmental monitoring results will be presented in Chapter 6.

The last section of this chapter discusses dynamic thermal modelling and simulation. The software used for dynamic thermal simulation will be mentioned. The sources of outdoor weather data files used for the simulation will be highlighted. The calibration of simulated results and environmental monitoring results will be considered and the details of the results will be discussed in Chapter 7.

4.2 Data Collection Procedure and Strategy

The importance of using appropriate techniques for study of thermal comfort of indoor occupants in dwellings is to gather data that is more consistent under the environment that enables the occupants to carry out their daily routines undisturbed during the period of surveys (Limbachiya *et al.*, 2012). This study developed a plan to gather data required for analysis which had also been considered in past comfort field studies in dwellings (Ealiwa, *et al.*, 2001; Limbachiya *et al.*, 2012). The procedures include:

(a) All prefabricated modern timber houses in the UK built within the last ten years with good potential for research (built with prefabricated timber) and located in the most warming climatic regions (South and South-east of England) were identified. The developments were recipients of different sustainability or low-energy rating awards from reputable organisations.

(b) The buildings identified were studied to gather basic information and understand their immediate environments.

(c) Housing developers and architects were contacted to seek their support and get relevant data required which helped this study to decide on the three case studies investigated.

(d) Development of the questionnaires for review and testing before approval for distribution.

(e) Access to the case studies with permission granted by the various organisations in charge of the buildings was secured. For example, the London Borough of Hackney was contacted for Bridport House and access was granted after careful consideration of the application.

(f) Submission of full ethics application for the research with human participants to the University of Kent Research Ethics Advisory Committee. The application was granted by the Committee through the Faculty of Humanities Research Ethics Advisory Committee in order to seek the participants' consent using the consent form in line with the University's Code of Ethical Practice for Research.

(g) Letters of introduction were sent to all residents of the buildings selected, highlighting the importance of the research, seeking their support and permission to be surveyed as well as enlighten them about the post-occupancy survey and what they were expected to do. The residents' consent was collected using the consent form to express their willingness in participating in the survey and assuring them of confidentiality of the information that would be provided which would be treated anonymously. The occupants were also informed when and how the questionnaires would be administered and collected.

(h) Administration of paper-based post-occupancy questionnaires to all the residents to gather data on how the internal environment is perceived and rated.

(i) The occupants who were willing to participate in comfort surveys were contacted and houses to be monitored at the two case studies (Bridport and Oxley Woods) out of the three case studies considered for the post-occupancy surveys were also selected as access could not be secured at Stadthaus to carry out the indoor monitoring survey.

(j) Indoor measurements of environmental variables (air temperature and relative humidity) using HOBO and Tinytag data loggers that were marked using a code assigned to each space to be monitored and installed at a certain height above floor level were carried out concurrently with the administration of subjective questionnaires to the participants. The accelerators to record windows' open and closed sessions were also installed in three houses at Oxley Woods.

(k) The returned questionnaires were collated and marked using codes for easy identification during analysis. The data loggers and subjective questionnaires were also retrieved.

(l) Analysis of the data collected using different statistical packages (SPSS-Statistical Package for Social Sciences) to determine variance and relationship between different variables and Excel to draw relevant charts.

(m) Relevant architectural drawings including construction details and specification documents collected from the developers and architects were further examined in order to draw plans using Computer Aided Design (CAD) package in preparation for dynamic thermal modelling and simulation. Thermal properties of the case studies' envelopes were also collected and other relevant information required for modelling.

(n) The case study buildings were modelled using DesignBuilder (EnergyPlus) and simulated under the same external conditions as the indoor measurements could only consider data for few days during the monitoring period.

The research procedure and strategy enhanced the quality of data gathered and thus improved the reliability of the results which will be discussed in Chapters 6 and 7. The next section describes each method considered in this study to collect data for analysis.

4.3 Post-occupancy Surveys

Post-occupancy surveys are critical to appreciate the thermal environment in buildings, while it helps to understand and compare the nature and frequency of occupants' complaints of feeling warm or hot that cannot be obtained during surveys such as environmental monitoring (Nicol & Roaf, 2005). In order to compare the nature and frequency of the occupants' complaints of feeling at the case studies, the questionnaire was developed to collect data from the residents and it will be considered along with access to the case studies and administration of the questionnaire in the following sub-sections.

4.3.1 Development of Post-occupancy Questionnaire

In the field of thermal comfort, questionnaires are required to be structured in a very simple format (Nicol, 2008); with a clear focus for better understanding of the respondents. Since subjective responses of occupants are anticipated to provide reliable and good quality data for analysis (Haddad *et al.*, 2012), an effective design of questionnaire must be achieved to meet the research goals. The questions asked were properly structured to remove any form of ambiguity as clarity of the questions improved the data quality collected from the surveys. Scales were employed where required for the occupants to indicate their responses and in most cases the 7-point scale was considered for rating as recommended by ASHRAE (2004). The post-occupancy questionnaire was structured into five sections with 20 questions, requiring 7-10 minutes to complete. The general information about the respondents relevant to the survey such as gender, age and voting time was asked in the first section of the questionnaire. The respondents' perceptions of thermal comfort at the case studies were considered in the second section using ASHRAE 7-point scale. The focus of the section is to understand how respondents describe the thermal conditions and rate overall thermal environment of their dwellings in different seasons. For instance, scale from 1 (cold) to 7 (hot) with 4 indicating neutral for thermal sensation was used. Also, the question to understand how thermally dissatisfied the occupants are with the thermal conditions of the case studies in different seasons was considered in the third section. Since the focus of this study is to investigate summertime overheating at the case study buildings, the questions asked in the second and third sections were very crucial to achieving the research propositions. The fourth section focused on control and questions regarding use of control, level of control, control satisfaction and effect on control were included. The importance of the section is to understand if the occupants' achieve high level of control which could improve internal conditions of the houses as well as link the outcomes with thermal comfort of the occupants. The last section of the questionnaire considered other important questions such as warmest space and rating of the respondents' experience at the case studies to further help the research achieve its aim. Before the questionnaire was administered to the respondents, a testing procedure was carried out to check the questionnaire and some of the words used for rating thermal comfort. The review and testing procedure suggested the participants understand the questionnaire.

4.3.2 Access to the Case Studies

Access to the case studies was granted by various organisations in charge of the housing developments. The organisations were first contacted through mails and followed up with calls and visits. Interviews were conducted in order to examine and understand the purpose of the research before permission was granted to access the case studies. The application period for securing permission to investigate and access the case studies lasted a period of over ten months from August 2011 to June 2012. At Bridport House, permission to access the case study was granted by the London Borough of Hackney after a formal application through correspondence (email) had been made and followed up with calls and visits to the Council Office in London. The security personnel were provided at Bridport House to monitor the progress of the surveys. Permission to access Oxley Woods in Milton Keynes was secured through the support of Rogers Stirk Harbour Architects after conducting an interview to examine the research focus. They thereafter provided the link to meet with the residents. After the interview session, a meeting was arranged by the Architects to discuss with the representative of the residents in order to understand the purpose of the research. They further examined the equipment to be used. At the end of the meeting session, permission to access and investigate the case study was granted by the residents. The Metropolitan Housing Trust in London; one of the joint owners of Stadthaus Housing in Murray Grove, London was contacted and granted authorisation to access the case study. The organisation also conducted an interview before permission was granted to access the case study for post-occupancy survey. However, permission to access Stadthaus Housing was not granted by the housing providers to carry out environmental monitoring and comfort surveys due to the multiple ownership of the development that required the two providers to grant access, frequent change of facility manager in charge of the building and request by the residents not to be considered for the surveys.

4.3.3 Administration of Post-occupancy Questionnaire

Post-occupancy questionnaires were administered to the residents of the three case studies considered for this investigation between June and July, 2012 after permission to access the case studies has been granted by the relevant authorities. Distribution of the questionnaires was based on the number of occupants in each household. The information gathered during the preliminary studies of the case studies provided a good knowledge for distribution. In some cases where the numbers of occupants were not given, the numbers of rooms of the households were considered for distribution. For example, two questionnaires were allocated to one-bed flat and in some instances; the two questionnaires were completed and returned by the occupants. The survey participants were young, adult and elderly occupants and fairly represented in terms of gender (male and female) and age (between 16 and 65) as they are not vulnerable to the thermal environment. Also, the residents have been residing in the UK for not less than 5 years (Limbachiya *et al.*, 2012) and have been living at the buildings for not less than 6 months in order to have acclimatised to the case studies and understand the thermal conditions of the internal spaces. In all, 131 questionnaires were distributed to all residents of the three case studies and 65 completed questionnaires were returned. The analysis of completed post-occupancy questionnaire will be discussed in Chapter 6.

4.3.4 Collection of Post-occupancy Questionnaire

The completed questionnaire was returned and collected on-site. The occupants were asked to drop it at each case study representative's house or flat in sealed envelopes provided when it was distributed. This was done in order to protect the data provided by the respondents. For example at Bridport, the occupants were asked to drop the completed questionnaires at the FL1GFL. At Oxley Woods, the questionnaires were returned to A38ML for collection. The occupants at the case studies were also visited during the last two days of the post-occupancy surveys to check if they had returned the questionnaires. However, no representative was selected at Stadthaus due to bureaucratic procedures and limited access to the building by the housing provider as the post-occupancy questionnaires were collected immediately they had been completed by the residents.

4.4 Environmental Monitoring

The indoor monitoring during the summer survey was carried out at Bridport in the period 29/6/12 - 12/7/12 and Oxley Woods 20/7/12 - 31/7/12. The winter survey was carried out at Oxley Woods between 28/1/13 and 8/2/13.

The spaces monitored at Bridport included three flats on the ground floor (Figure 4.1) with different orientations (FL1GFL- South facing, FL1GFLK- East facing, FL8GFL- North facing), three spaces on the first floor (FL1FFB- Southwest facing, FL7FFB- East facing, FL8FFSB- Northeast facing) shown in (Figures 4.2 and 4.3) and one space at the second floor (FL35SFL- West facing). At Oxley Woods, the houses monitored were also chosen from different orientations (A38ML- South facing, A6ML- South facing, A1WL- East facing, A142HA- West facing and A162HA- North facing) shown in Figure 4.4. In all, 4 flats (7 spaces) were monitored at Bridport and 5 houses (10 spaces) at Oxley Woods. In total, 17 spaces living areas and bedrooms were monitored.

Figure 4.1: The red circles highlighting the three apartments (maisonettes) monitored in the ground and the first floors at Bridport during the summer survey.

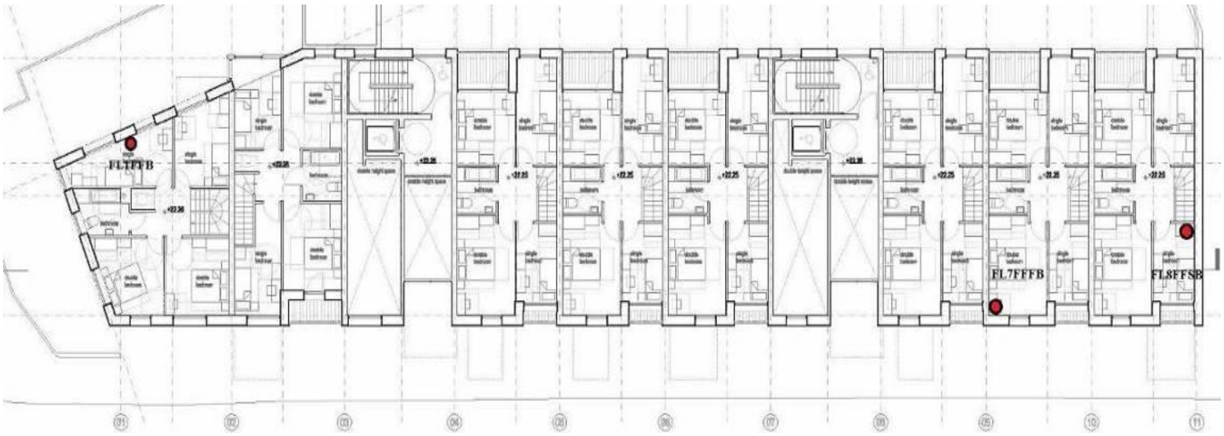

Figure 4.2: The first floor plan of Bridport showing the location of the sensors in red circle placed on the internal wall of the spaces monitored in different apartments during the summer survey.

Figure 4.3: View of FL1GFL at Bridport showing the data logger in red circle mounted on the internal wall at the height of 1.1m above the floor level during the summer survey.

Figure 4.4: Site plan showing location and orientation of the houses monitored at Oxley Woods during the surveys.

At Oxley Woods, the three spaces monitored in the house (A38ML- South facing) were (A38MLGFL- Northeast facing, A38MLFFFB- Southeast facing and A38MLFFBB- Northeast facing) shown in Figure 4.5. In the house (A6ML- South facing) the only space monitored was (A6MLSFBB- Northwest facing) shown in Figure 4.7. Two spaces were monitored in the house (A1WL-East facing) and they were (A1WLGFL- Southwest facing shown in figures 4.6-4.7 and A1WLFFFB- Southeast facing). In the house (A142HA- West facing), the spaces monitored were (A142HAGFL- Southwest facing shown in Figure 4.8 and A142HASFBB- Southeast facing). The spaces monitored at the last house (A162HA- North facing) were (A162HAGFL- North facing and A162HAFFBB- South facing). This shows that the spaces monitored at the two case studies were selected from all orientations. Tables 4.1 and 4.2 below summarise the details of housing types and orientations of the flats monitored at Bridport House and the houses monitored at Oxley Woods.

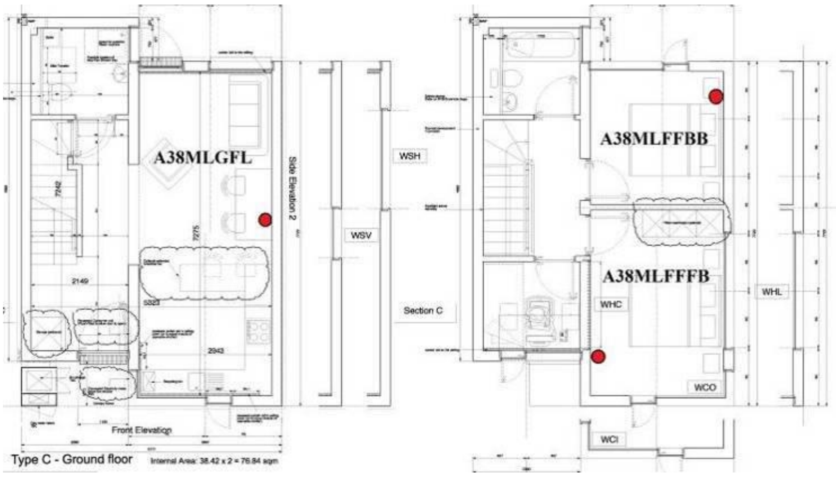

Figure 4.5: Ground floor and first floor plans of A38ML at Oxley Woods showing location of the sensors placed on the internal wall of the spaces monitored in the house during the surveys.

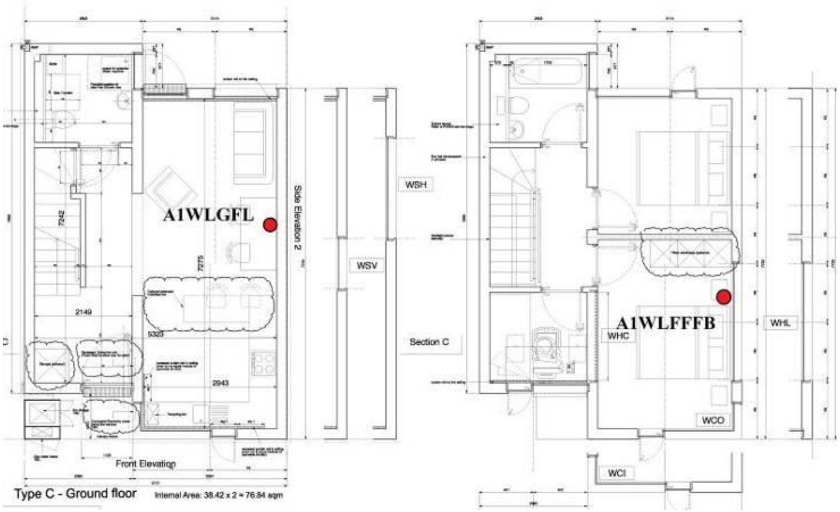

Figure 4.6: Ground floor and first floor plans of A1WL at Oxley Woods showing the position of the sensors placed on the internal wall of the spaces monitored in the house during the surveys.

Figure 4.7: Internal views of A1WLGFL in A1WL (left) and A6MLSFBB in A6ML (right) at Oxley Woods showing the position of the sensors in red circle mounted on the walls during the surveys.

Figure 4.8: Prototype ground floor plan for Type G illustrating A142HA at Oxley Woods with red circles highlighting the location of the sensor (left) and view of the living area (A142HAGFL) monitored during the surveys (right).

Table 4.1: Details of names of the flats and the houses monitored, locations, housing types and orientations.

Name	**Location**	**Dwelling size**	**Housing type**	**Orientation**	**Floor level**
FL1	Bridport House	Maisonnette (4-bed)	End-terraced flat	South facing	Ground and first floors
FL7	Bridport House	Maisonnette (4-bed)	Mid-terraced flat	East facing	Ground and first floor
FL8	Bridport House	Maisonnette (4-bed)	End-terraced flat	Northeast facing	Ground and first floor
FL35	Bridport House	Flat (2bed)	Mid-terraced flat	West facing	Second floor flat
A1WL	Oxley Woods	One-storey house (2-bed)	End-terraced house	East facing	Ground and first floors
A6ML	Oxley Woods	One-storey house (2 bed)	Mid-terraced house	South facing	Ground and first floors
A38ML	Oxley Woods	One-storey house (2-bed with a study room)	End-terraced house	South facing	Ground and first floors
A142HA	Oxley Woods	Two-storey house (3-bed with a study room)	End-terraced house	West facing	Ground, first and second floors
A162HA	Oxley Woods	Two-storey house (3-bed with a study room)	Mid-terrace house	North facing	Ground, first and second floors

Table 4.2: Details of names of the internal spaces monitored at Bridport and Oxley Woods in the summer.

Name	Description of space	Location	Floor area (m^2)	Housing type	Orientation	Floor level
FL1GFL	Flat 1 ground floor living area	Bridport House	29.7	End-terraced flat	South facing	Ground floor
FL1FFB	Flat 1 first floor front bedroom	Bridport House	13.1	Mid-terraced flat	Southwest facing	First floor
FL7FFFB	Flat 7 first floor front bedroom	Bridport House	15.2	Mid-terraced flat	East facing	First floor
FL8FFSB	Flat 8 first floor small bedroom	Bridport House	7.7	End-terraced flat	Northeast facing	First floor
FL35SFL	Flat 35 second floor living area	Bridport House	28.8	Mid-terraced flat	West facing	Second floor
A1WLGFL	A1 Welles ground floor living area	Oxley Woods	20.9	End-terraced house	Southwest	Ground floor
A1WLFFFB	A1 Welles first floor front bedroom	Oxley Woods	12.2	End-terraced house	Southeast facing	First floor
A6MLSFBB	A6 Milland second floor back bedroom	Oxley Woods	8.7	Mid-terraced house	Northwest facing	Second floor
A38MLGFL	A38 Milland ground floor living area	Oxley Woods	20.9	End-terraced house	Northeast facing	Ground floor
A38MLFFFB	A38 Milland first floor front bedroom	Oxley Woods	12.2	End-terraced house	Southeast facing	First floor
A38MLFFBB	A38 Milland first floor back bedroom	Oxley Woods	9.1	End-terraced house	Northeast facing	First floor
A142HAGFL	A142 Holden ground floor living area	Oxley Woods	18.3	End-terraced house	Southwest facing	Ground floor
A142HASFBB	A142 Holden second floor back bedroom	Oxley Woods	9.1	End-terraced house	Southeast facing	Second floor
A162HAGFL	A162 Holden ground floor living area	Oxley Woods	20.9	Mid-terraced house	North facing	Ground floor
A162HAFFBB	A162 Holden first floor back bedroom	Oxley Woods	8.7	Mid-terraced house	Southeast facing	First floor

4.4.1 Environmental Monitoring Plan

This study considered the application of plan for environmental monitoring that has full support of the participants and allowed them to go about their everyday activities without any form of limitations. The plan used for the measurements at the case studies includes:

(a) The occupants that had their households monitored and expressed interest in taking part in the comfort surveys were further visited to fully discuss the focus of the study, the questionnaire to be completed and how many times they will be required to fill the questionnaire per day. The participants' consent was also collected using the consent form provided by the University of Kent Research Ethics Advisory Committee.

(b) The data loggers were mounted on the internal walls in the living areas and the bedrooms of the houses and the flats monitored at above floor level to measure and record indoor temperature and relative humidity at a specific interval (1.1m).

(c) The accelerators were also installed to monitor window open and closed sessions in order to understand how often the occupants use controls like windows to regulate the thermal environment of their indoor spaces.

(d) The loggers installed were checked every three days to know if the loggers were kept at the right positions and to identify any possible mistakes. However, not all the spaces monitored were accessed on a regular basis to check due to limited access to some of the monitored spaces.

(e) The occupants were encouraged to do various activities before they filled the subjective questionnaire for each session.

(f) The data were downloaded using HOBO and Tinytag software and the raw data were processed in Excel.

4.4.2 The Equipment Used

The equipment used for measurement of indoor temperature and relative humidity included the HOBO and TinyTag sensors. They were installed not far from the occupants' sitting position or working area (Indraganti & Rao, 2010; Sakka *et al.*, 2012). Air velocity was considered to be or not more than 0.1m/s while average radiant temperature was considered to be the same as indoor air temperature (Limbachiya *et al.*, 2012) and these two parameters (air velocity and mean radiant temperature) were not considered in this study. The HOBO state data loggers (HOBO U9-001) to monitor open and closed sessions of windows were placed on the windows that were not fixed and regularly used by the occupants to ventilate the indoor spaces. Table 4.3 below summarises detailed specification of the HOBO and Tinytag data loggers used for environmental monitoring.

Table 4.3: Details specification of the HOBO and Tinytag data loggers used for the experiment.

Variables	**HOBO Specifications**	**Tinytag Specifications**
Product name	HOBO U12 Temp/RH logger	Tinytag Ultra 2 (TGU-4500) Temp/RH logger
Range of measurement	-20º to 70ºC (-4º to 158ºF)	-25ºC to 85ºC (-13ºF to 185ºF)
Accuracy	±0.35ºC from 0º to 50ºC (±0.63ºF from 32º to 122ºF)	±0.35ºC from 0º to 50ºC (±0.63ºF from 32º to 122ºF)
Resolution of reading	0.03ºC at 25ºC (0.05ºF at 77ºF)	0.01ºC at 25ºC (0.03ºF at 77ºF)
Drift	0.1ºC per year (0.2ºF per year)	0.1ºC per year (0.2ºF per year)
Time of response in airflow of 1m/s	6 minutes, typical to 90%	20 minutes, typical to 90%
Accuracy of time	±1 minute per month at 25ºC (77ºF)	±1 minute per month at 25ºC (77ºF)
Weight	46g (1.6oz)	55g (1.94oz)
Dimensions	74x58x22mm (2.9x2.3x0.9inches)	72x60x33mm (2.83x2.36x1.3inches)

4.4.3 Calibration of the Equipment Used

Calibration of the data loggers for measurement is a very crucial step and validation procedure that needs to be considered for monitoring of environmental parameters in field studies (BARQA, 2012). This is important to ensure the data loggers are working well in order to avoid errors during measurement of the variables in field surveys. Two major methods have been recommended for calibration of the data loggers and have been extensively used in many studies (BARQA, 2012). The two methods are the static calibration and the dynamic calibration. For this study, the dynamic calibration method was considered. In order to verify that the sensors were working well before the actual measurements were taken during the survey, the data loggers were placed in the habitable spaces similar to the spaces monitored at the case study buildings. The sensors were also placed at the same height (1.1m) in which the measurements will be taken in the spaces monitored at the buildings during the surveys. The variables were recorded at the same set time (that is, 15-minute intervals). The data loggers were installed to record the environmental conditions of the spaces monitored for 3 days to check the consistency of the sensors. The data recorded were downloaded using the appropriate software (HOBO and Tinytag) and graphs were generated. The readings from the data loggers used were compared to check for similarities and differences. Also, the readings obtained from the sensors were compared with the readings from the conventional monitoring equipment and previous studies on thermal comfort in dwellings. The results from the sensors indicate they are within limits recommended in the standard operating procedure for HOBO and Tinytag sensor specifications. The results obtained from the sensors during the calibration indicated that the sensors were working well before they were installed in the spaces monitored at the case study buildings.

4.4.4 Physical Measurements of Environmental Variables

The data loggers were installed using recommended strap to place the sensors. The height of 1.1m was considered as the average height of the head-region of occupants seated and mid-region of participants carrying out standing activities (ASHRAE, 2004). The data loggers were carefully installed in the selected spaces to allow the sensors detect and record parameters. The equipment was mounted on the internal wall that was not close to any source of direct heat from the sun and internal heat gains as well as excess air flow (Sakka *et al.*, 2012). The software for HOBO and Tinytag were installed on the computer in order to launch the data loggers and read the measurements taken. A similar process was used to retrieve the data logged and stopped the sensors from taking unwanted measurements. The date and time were also noted for each data logger installed and marked using codes for easy identification during analysis. The equipment was set to measure and log indoor temperature in degree Celsius (ºC) while the relative humidity was measured in percentage (RH%). The indoor temperature and relative humidity were recorded every 15-minute as considered in some past studies (Mahdavi & Doppelbauer, 2010). The window opening actions were recorded at 15-minute intervals as indicated in previous studies (Rijal & Stevenson, 2010).

4.4.5 Collection of Outdoor Weather Data

The outdoor weather data for the monitoring period (from June to July, 2012) was collected from nearby meteorological stations to the case studies. For Bridport House, the outdoor weather data was collected from London City Airport weather station and from Luton Airport weather station for Oxley Woods. In order to achieve consistency of data collected, mean indoor environmental data on hourly basis was considered for comparative analysis with the outdoor weather data and will be discussed in Chapter 6.

4.5 Comfort Surveys

Comfort survey was carried out concurrently with the physical measurements in order to understand various environmental conditions at which the indoor occupants find comfortable. The questionnaire used to collect data from the residents and administration of the questionnaire will be presented in the following sub-sections.

4.5.1 Development of Comfort Surveys' Questionnaire

The use of questionnaire along with environmental monitoring provide the easiest method of evaluating indoor occupants' comfort by comparing what occupants recorded in terms of their feeling of warm or cold and measured environmental parameters especially indoor air temperature (Darby & White, 2005). The questionnaire was structured into two different sections with three sub-sections under the first section. Overall, it had 14 short questions requiring between 2 and 3 minutes to complete. In the first section, the participants were asked to evaluate their feeling of warm or cold (thermal sensation, from 1- cold to 7- hot), how they would prefer to be (thermal preference, from 1- much cooler to 5- much warmer), thermal acceptability along with different aspects of control used in the last 30-minute to improve the thermal environment. Also questions included clothing insulation checklist in line with ASHRAE standard, clothing preference, drinks consumed in the last 10 minutes, checklist of activities involved in the last 15minutes, preference for higher air movement and overheating experience. In addition, basic background information about the age of participant, gender and space occupied were gathered.

4.5.2 Administration of the Questionnaire

The occupants were asked to fill the subjective questionnaire three times daily (morning, afternoon and evening) between 07:00 and 23:00 and were encouraged to have carried out activities for at least 30-minutes before they filled the questionnaires at any time of the day. They were also asked not to fill two successive questionnaires within a period less than 2 hours in order to have allowed the participants adjust to a broader range of indoor environmental conditions. In total, 141 questionnaires were collected during the summer surveys and 106 during the winter survey. Further analysis of the surveys will be presented in Chapter 6.

4.5.3 Collection of the Subjective Questionnaire

The completed questionnaires were collected during the final day of the surveys when the data loggers were retrieved. The participants were asked to return the questionnaires in the envelopes provided at the beginning of the survey. Some returned questionnaires were not completed during the survey and they were separated and not considered for further analysis. All the questionnaires were checked to confirm if the date and time were correctly entered during the period of voting and numbers were allocated using codes for easy identification during analysis when cross-checked with measured data. The data from the returned questionnaires was entered on the statistical programme SPSS (Statistical Package for Social Sciences) for further analysis.

4.6 Dynamic Thermal Simulation

In order to capture more data for analysis, dynamic thermal simulation was considered for this study and will be briefly discussed below.

4.6.1 Thermal Modelling and Simulation Software

The software (DesignBuilder, 3.2.0 version) was considered for this study in order to carry out dynamic thermal modelling and simulation. The dynamic modelling and simulation software known as DesignBuilder (EnergyPlus) (US DOE, 2005) is created in the United States by the Department of Energy.

4.6.2 The Outdoor Weather Data Considered for Modelling and Simulation

The outdoor weather data files on hourly basis were considered for this study and cover the monitoring periods at the case studies (Bridport and Oxley Woods) and current Test Reference Year (TRY) which is the representative external weather data files for recent climatic conditions. The London Islington TRY (that is, the 2000s) was considered for Bridport House and Stadthaus Housing in Hackney, London due to the two case studies' proximity to London Islington while the St Albans TRY (that is, the 2000s) was used for Oxley Woods in Milton Keynes.

4.7 Summary

This chapter discussed the data protocol and techniques used for data collection that included post-occupancy survey, environmental monitoring, comfort survey and dynamic thermal simulation. The procedure and strategy employed help to conduct the surveys in a way that did not interrupt everyday activities of the occupants. The field studies were more organised and well-planned from selection of the case studies to getting permission to access the case studies to conducting the surveys and gathering of data for analysis. The steps taken enhanced the quality of data gathered and greatly reduced disruption of the equipment used for physical measurements which in turn reduced errors that may occur during the recording and logging of data. This study was conducted in a logical way, thus improving the reliability of the results from the surveys.

The data protocol and collection techniques showed that post-occupancy survey helps to assess the case studies' performance with a great input from the survey participants while environmental monitoring involves physical measurements of environmental parameters to understand the thermal environment with limited or no input from the occupants. Comfort survey helps to understand that the occupants' expectations are not static and change from time to time while dynamic thermal simulation helps to capture more data that cannot be covered by other methods employed. The combination of different methods provided a wider range of data that can be analysed and compared during analysis. It also provided a better understanding to investigate the research propositions using various techniques to see similarities and differences between the results.

This chapter showed explained that a combination of the methods that require limited or no input from the occupants and the methods that required a great input from the participants are important when evaluating the building performance. The results will be discussed in Chapters 6 and 7. The next chapter considers the case studies selected for this study.

Chapter 5 Case Studies

5.1 Introduction

"The unique residential building Bridport House represents green urban architecture of the future. It marks the first time that cross-laminated timber (CLT) has been chosen in the UK for an entire multi-storey structure, including the ground floor, which is traditionally constructed from concrete (like in the case of Stadthaus housing). *[.....]. Using environmental materials* (sustainable materials such as timber)*, we were able to meet the sustainability objectives and in the end real construction costs remained under budget"*

- London Borough of Hackney (2011: In Rethink, Bridport House Factsheet, pp. 1-2).

This chapter describes the three housing developments considered for this study. The case studies are Bridport House, Oxley Woods and Stadthaus housing. All the buildings are modern housing developments built for residential purposes with timber; a lightweight material with low thermal mass. The three case studies are recipients of various low-energy rating or sustainability awards completed within the last decade and built for the working-class to middle-class from high density to low density dwellings. Two of the case studies are modern multi-storey blocks of apartments (Bridport and Stadthaus) and the third one (Oxley Woods) a housing development with ten different prototypes. They are located in South and Southeast of England; the regions considered to be prone to summertime overheating (Orme *et al.*, 2003; Firth & Wright, 2008; Lowe & Oreszczyn, 2008; Rijal & Stevenson, 2010; Porritt, *et al.*, 2012). The description of each housing development will be presented. The design and internal arrangement of the case studies will also be examined and some other features such as the area of the sites will be briefly highlighted.

The floor area of the internal spaces at the developments will be briefly discussed. At a later part of this study (Chapters 6 and 7); the relationship between the internal floor spaces and occupants' comfort will be examined. The materials used for construction of each housing development will be discussed. Sources of the materials, composition and their thermal properties will be examined. The construction methods used, the period of construction, personnel involved and technological innovations adopted for the buildings will be outlined.

The last section under each case study discusses environmental sustainability of the project. This is important as it helps to understand the environmental impact of the materials used, the energy saved for production and the ability of the materials to sequester carbon. Also, sustainability in terms of energy used to transport the materials from the factory to the site will be explained. The differences and similarities between the case studies selected will be briefly highlighted at the later part of this chapter. The next section focuses on the case studies investigated.

5.2 Bridport House, Hackney, East London

"The key objective of the design team of Bridport House was to achieve a practical and economical layout using the flexible cross-laminated timber (CLT) building system, which represents no limitations to the architecture, design or style of a building. The materials (*CLT boards) were prefabricated according to the architect's designs.*

- London Borough of Hackney (2011: In Rethink, Bridport House Factsheet, p.2).

5.2.1 Description of Bridport House

Bridport House is one of the newly-constructed multi-storey social housing in the UK. The construction of the project started in October, 2010 and was completed in September, 2011. The case study is located on a narrow plot of 0.2 hectares with reference (51°53'50N, 0º08'61W) on the national grid. Bridport House is about 100m away from the south of the Regent's Canal with two other nearby privately funded housing developments at the northeast part of the recently renovated Shoreditch Park on the Colville Estate in Hackney (PBA LLP, 2009). The project is regarded as one of the world's tallest residential wooden scheme (Birch, 2011; Rethink, 2011), UK's largest structural timber (CLT) housing project (Willmott Dixon, 2011) and also the first modern social housing development to be built in Hackney in the last four and a half decades (Birch, 2011; Architecture Today, 2012; Wainwright, 2012). It is a £6 million project owned by the London Borough of Hackney and partly funded by the Homes and Communities Agency (HCA) with the sum of £3.4 million (Architecture Today, 2012; Wainwright, 2012). The project is designed by Karakusevic Carson Architects; the main contractor is Willmott Dixon Limited while timber construction and assembly was handled by EURBAN Limited. Bridport has won several awards since it has been completed including the Woods Awards and Mayor's Housing Design Award for Community Consultation in 2011 (Willmott Dixon, 2011). The awards suggest that it is an outstanding modern prefabricated timber housing that has gained wider recognition in the UK and across the world.

The building adds to the overall urban skyline of Hackney town especially at the southern side of the Regent's Canal (Figures 5.1 and 5.2). It is a part of the on-going masterplan development covering 5 hectares of land from the east to the north part of the Canal and one of the first phase schemes to replace 438 dwellings with newly built 925 dwellings in Hackney (PBA LLP, 2009). All the apartments are socially rented and the housing development covers a total floor area of 4,220m² indicating building cost of the project at £1435/m² (Architecture Today, 2012). Bridport House comprises of 8 four-bed family maisonettes located at the ground and the first floor respectively with 8 front doors positioned at the back of low-walled (1.8m high) thresholds. It also has 33 apartments that include one-bed, two-bed and three-bed units with two main entrances located at the ground floor along with other eight entrances to the four-bed family maisonettes to access the apartments at the upper floors and the same number of exit doors for the maisonettes and the apartments at the rear side of the development (Figure 5.3). In total, the case study consists of 41 apartments that stretch across the five storey block and the eight storey block. This shows that it is a well-developed project with good accessibility and exit for the residents.

The project is an inclusive housing development with 3 parking spaces for the disabled and many of the apartments are suitable for different family sizes and easily accessible for the residents using wheelchair. The combination of the maisonettes and the flats in one housing development with variation in total number of floors showcases that Bridport House is built with the materials that weigh just 10% over the weight of the demolished 1950s social housing it replaced (Architecture Today, 2012). The newly built housing development accommodates more residents with additional number of apartments from 21 to 41.

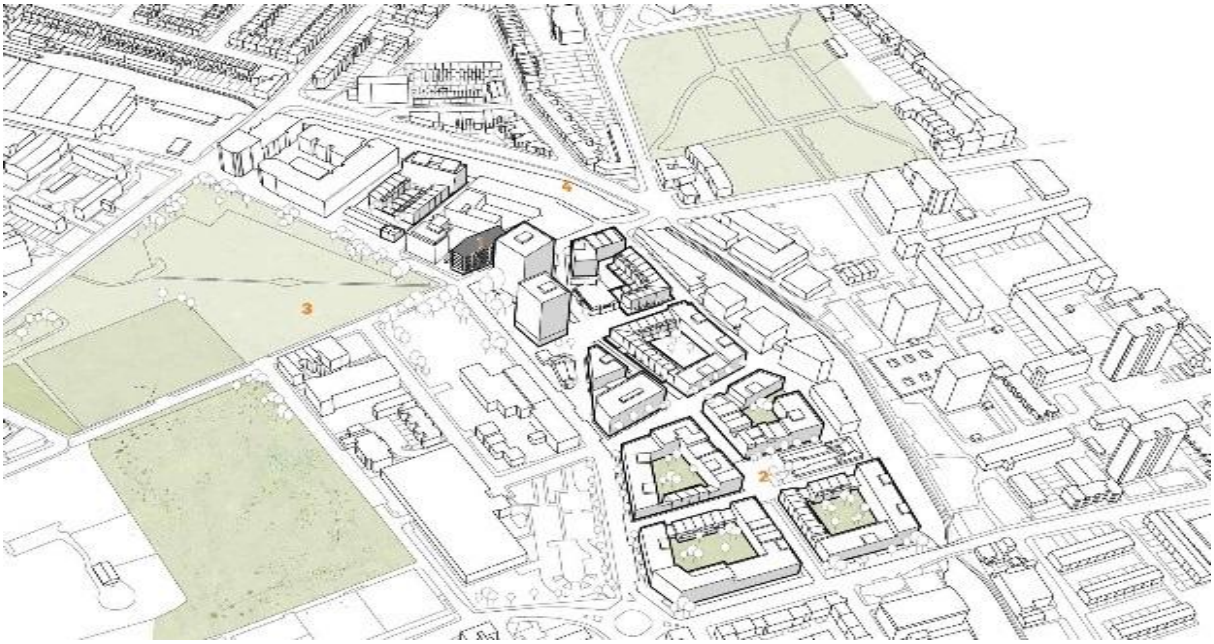

Figure 5.1: An aerial view showing various developments at the south side of the Regent Canal in Hackney town with 1- indicating Bridport House highlighted using dark colour for roof, 2- proposed Colville Estate scheme, 3- the Shoreditch Park suggesting its closeness to the project which is being used by the residents for various outdoor activities and 4- the Regent's Canal. (Wainwright, 2012)

Figure 5.2: An overall skyline at the north part of the Shoreditch Park in Hackney town showing Bridport House at the centre, the Shoreditch Park at the left-hand side and other nearby developments on the Colville Estate. (Karakusevic Carson Architects, 2011)

The internal arrangement of the spaces at Bridport House follows the rectilinear shape of the plan (Figures 5.4 and 5.5) facing the east and west orientations which provide the opportunity for the occupants to enjoy early morning and late evening sun with the use of floor-to-ceiling height windows for adequate ventilation and day lighting. This suggests that the project is well-planned with the ability for good natural ventilation and day lighting which will reduce energy used for running the building in summer.

Figure 5.3: Ground floor plan of Bridport House showing the linear arrangement of the internal spaces of the maisonettes with front entrance doors, exit doors and private outdoor spaces at the rear side of the development including the bicycle sheds for the residents.

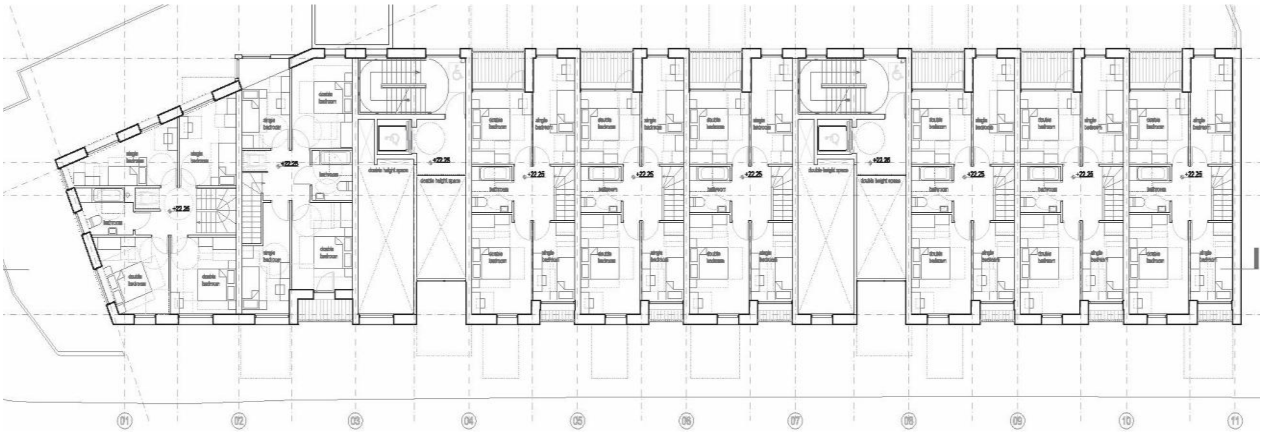

Figure 5.4: First floor plan showing arrangement of the internal spaces of the maisonettes,

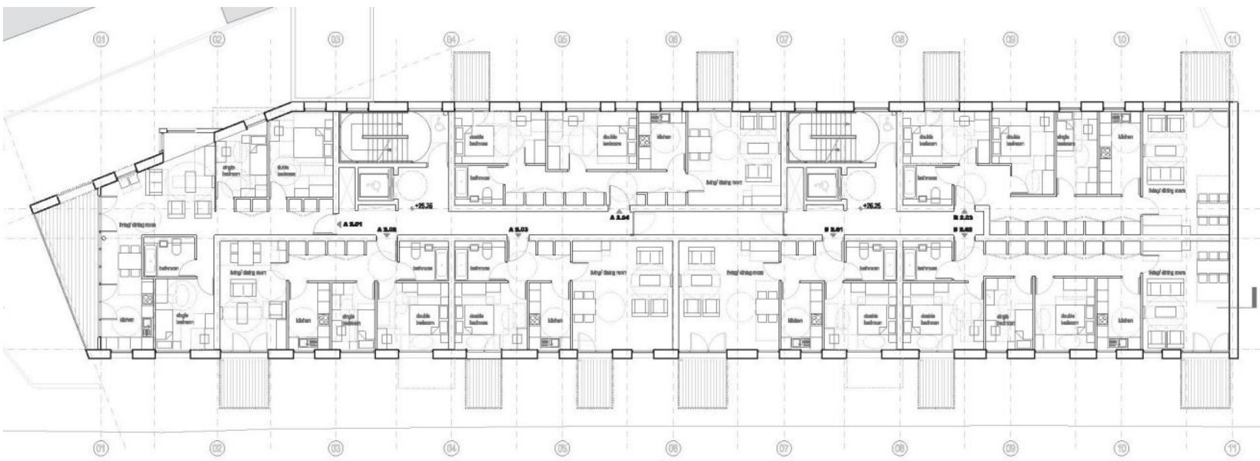

Figure 5.5: Typical upper floor plan showing internal arrangement of one-bed, two-bed and three-bed flats and balconies along the different orientations of the housing development.

Concerning the outdoor spaces, each flat at the upper floors is provided with private outdoor space such as balcony to enjoy nature and for the residents to relax and view the environment. Although the maisonettes at the ground floor are provided with private gardens, the provisions of balconies for the apartments at the upper floors provide alternative outdoor spaces for the residents (Figures 5.6, 5.7 and 5.8).

Figure 5.6: Street elevation (east facing) of Bridport House in Hackney showing eight-storey and five-story block of apartments with floor to ceiling height windows for ventilation and natural lighting and arrangement of balconies for relaxation and other purposes.

Figure 5.7: South facing elevation of Bridport House in Hackney showing the eight-storey and the five-story block of apartments.

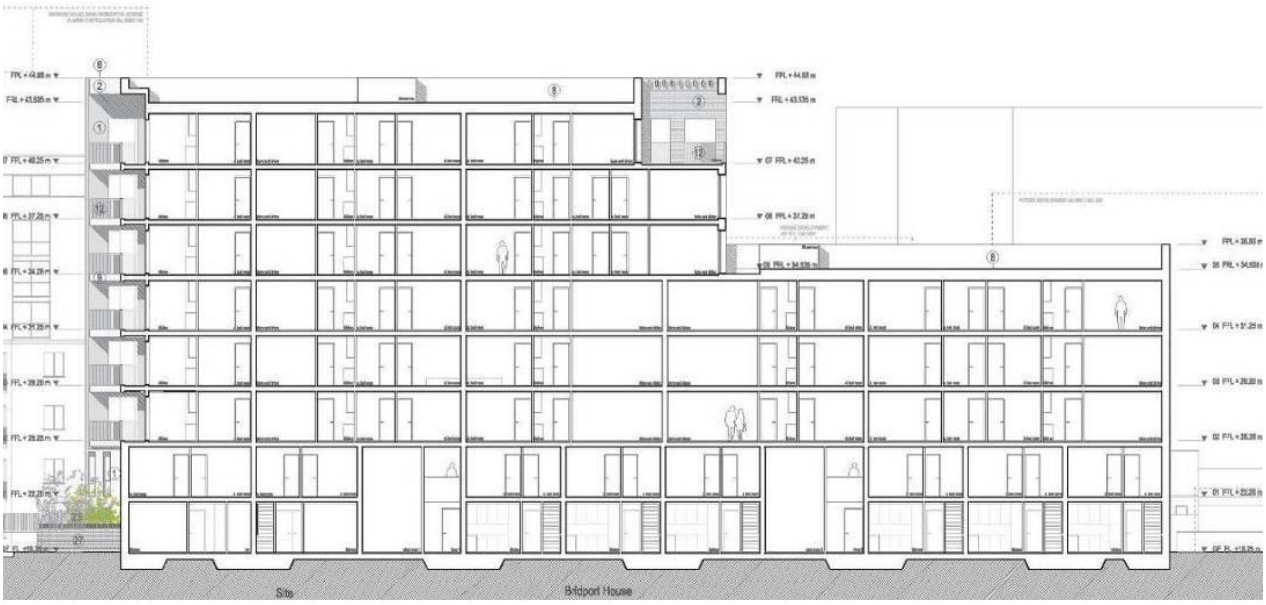

Figure 5.8: Sectional view of Bridport House along the south-north direction (longitudinal) showing the internal arrangement of the spaces at the eight-story block and the five-storey block of apartments.

5.2.2 Space Standards

The project meets and even exceeds the minimum space requirements highlighted by the Greater London Authority (GLA) standards considered in Chapter 3 which specify an additional 10% of the minimum space standards recommended by the Parker Morris Report. The standards were put in place in the late 2000s by the Office of The Mayor of London (Mayor of London, 2010), when there was an increasing concern on the internal floor spaces of newly constructed dwellings in the UK which are becoming smaller (Drury, 2008; Roys, 2008; RIBA, 2011). The internal floor spaces of Bridport house are generous with floor area between 58m² and 125m² for the apartments with total floor area of each flat indicating more than 10% in addition to the Parker Morris space standards. The apartments also have large storage spaces which are not often considered in many of the modern housing developments in the UK (Wainwright, 2012), such as a housing development in Knightsbridge, London as highlighted in chapter 3.[14] Table 5.1 below summarises the features of the apartments, floor area, and number of bedrooms as well as percentage of the bedrooms to floor area.

[14] The name of the housing development (block of apartments) in Knightsbridge, London was not mentioned by Kelly (2013).

Table 5.1: Features of the apartments, total floor area and percentage proportion of bedrooms.

Type of apartments	Numbers provided	Floor level	Area of internal floor spaces (m²)	GLA space standards- m² (Parker Morris plus 10%)	Proportion of bedrooms to floor area (%)
Four-bed maisonettes	8	Ground floor and first floor	125	107-113	50%
One-bed flat	8	Second floor to seventh floor	58	50	38%
Two-bed flat	12	Second floor to seventh floor	80	61-70	53%
Three-bed	13	Second floor to seventh floor	98	86	55%

Concerning the floor-to-ceiling height of the internal spaces, the GLA space standards specify a minimum of 2.6m for spaces at the ground floor with higher ceiling height, while the minimum of 2.5m floor-to-ceiling height is recommended for spaces at the upper floors (Mayor of London, 2006; Housing Design Standards, 2010; RIBA, 2011). At Bridport House, the floor-to-ceiling height is 2.65m which also exceeds the minimum floor-to-ceiling height specified by the GLA space standards for all the internal spaces across all the floors. This indicates that the building is built in line with the required space standards in the UK (Wainwright, 2012).

Regarding the minimum space standards for balconies and private outdoor spaces, all the apartments at the case study are provided with balconies of 2.5m depth projected along the front and the rear elevations and supported at an angle using tensile steel rods (Architecture, 2012; Wainwright, 2012), which also exceeds the GLA space standards of 1.5m minimum depth specified for all balconies and private outdoor spaces in dwellings. The projected balconies can possibly provide shading for the internal spaces in summer and reduce day lighting into the spaces. The floor area of the balconies at the case study also exceeds the GLA minimum area of 5m² required for a 1-bed flat and 6m² required for a 2-bed flat. The width of the 3 parking spaces for disabled residents also suggest that the parking spaces are generous which exceeds the minimum width required by the GLA and the English Partnerships/ Affordable Homes standards that are often used in newly built publicly/ privately funded housing developments in the UK.

5.2.3 Materials and Construction

Cross-laminated timber (CLT) panels were used for the construction of Bridport House and the case study does not give an impression of a social housing which looks more expensive than the other privately financed housing developments in the neighbourhood. The material (CLT) used was approved by the Programme for the Endorsement of Forest Certification (PEFC): a regulated body for sustainably grown forest products in Europe before it was processed at the factory in Austria and transported to site. The material saved time as it was assembled within 12 weeks by four workers and one supervisor compared to 21 weeks for the same size of project built with concrete. Overall, it saved more than 8 weeks of construction period and additional cost of recruiting more site workers and hiring equipment.

Up to 1,100 prefabricated CLT panels with a total volume of 1,576m³ were manufactured in different sizes with the average width of 2.95m and length of 16m and transported to the site in 30 trips (Rethink, 2011; Willmott Dixon, 2011). The panels are fixed on the ground floor slab over concrete pile foundation that has been done on site. Platform construction system was used for the building. The timber panels are inserted into the floor using tongue and groove method (Figure 5.9). The timber panels are properly connected to the floor with screws and metal base at angles. The construction system used at Bridport house is similar to the system used at Stadthaus housing and the details will be discussed under section 5.4.3. The panels used for internal and external walls are produced in three major thicknesses (100mm, 140mm and 160mm) with thickness of 160mm and 220mm for the floor and roof respectively. The rigid insulation of over 100mm thickness and breather membrane are attached to the CLT wall panels and covered with bricks. The timber board has density of 500kg/m³ and specific heat capacity of 1600 J/kg-K. Table 5.2 below summarises the features of the wall, floor and window with U-values for the different components at Bridport House. Comparing the building with the recommendations stated in the Building Regulations Part L at the time of construction[15], it attains at least 72% improvement above 2007 L1A threshold with

[15] The Building Regulations Part L sets out the requirements for attaining energy efficient buildings in the UK.

projected 45% improvement above 2010 L1A (London Borough of Hackney, 2009). Also, the construction was done in line with the objectives of the London Plan 2011.[16]

Figure 5.9: Connection of CLT wall panels to the structural timber floor at Bridport House using tongue and groove method which are properly fixed using metal base positioned at angles and screws. (Willmott Dixon, 2011)

Table 5.2: U-values for the different components at Bridport (Approved Document Part L, 2010; Rethink, 2011; Willmott, Dixon, 2011)

Components	U-values (Wm^2/K)	Part L1A 2010 (Wm^2/K)
Walls (high quality brown bricks for external walls, cavity, polyurethane rigid insulation board, breather membrane, CLT panel, gypsum plasterboard).	0.13 (internal wall) and 0.14 (external wall)	0.20 (internal wall) and 0.30 (external wall)
Roof (brown/green roof substrate for bio-diverse planting, damp proof layer, rigid insulation, CLT panel).	0.12	0.20
Floor (timber finished floor layer, screed, rigid foamboard insulation layer, CLT panel, cavity, insulation, gypsum plasterboard).	0.16	0.25
Windows (low-e double glazed timber/aluminium composite).	1.37	2.00

The internal spaces of Bridport House are provided with high performance windows (powder-coated aluminium window) and door system. The U-value of the external doors is $1.5W/m^2K$ with thermal bridging value of 0.08W/mK (Rethink, 2011; Willmott Dixon, 2011). The core of the building for circulation of people and the lift shaft are also built

[16] The London Plan 2011 focuses on provision of good dwellings for people living in London that meets all their needs with an emphasis on the design of homes, the quality of spaces and the facilities for the occupants to live in good and conducive environments (Mayor of London, 2009).

with CLT panels for good stiffness of the structure which makes the overall stiffness of the lift shaft similar to the ones built with concrete. The external doors are made of steel for safety.

Bridport House is covered with cladding material made of high-quality brown and lighter coloured bricks. The semi-engineered bricks are used to provide a solid and aesthetically appealing structure. The brown brick finishes cover the five-storey block and the north part of the case study. The lower part (about 20%) of the eight-storey block is also covered with the brown bricks while the upper floors of the block are covered with contrasting lighter brick finishes showing recessed joints and colour matched mortar that delineate the height of the maisonettes (Figure 5.10). The brick is produced from the factory in a workable size of 215x103x65mm with thermal conductivity of $0.77W/m^2K$, minimum compressive strength of $75N/mm^2$ and gross density of $1700kg/m^3$ (Willmott Dixon, 2011); which indicates the choice of heavyweight cladding material for the building. For the timber material (spruce), it has minimum compressive strengths of $2.7N/nm^2$ (at right angles to grain of boards), $24\text{-}30N/nm^2$ (parallel to grain of boards), bending strength of $24N/nm^2$ (at right angles to grain of boards), thermal conductivity of $0.13W/m^2K$ (TRADA, 2009a). The building is well planned with great attention paid to construction details (Figure 5.11).

Fig. 5.10: Different views of Bridport House showing high-quality brown bricks outlining the height of the maisonettes from the upper floors at the 8-storey block and demarcating the 5-storey block of apartments.

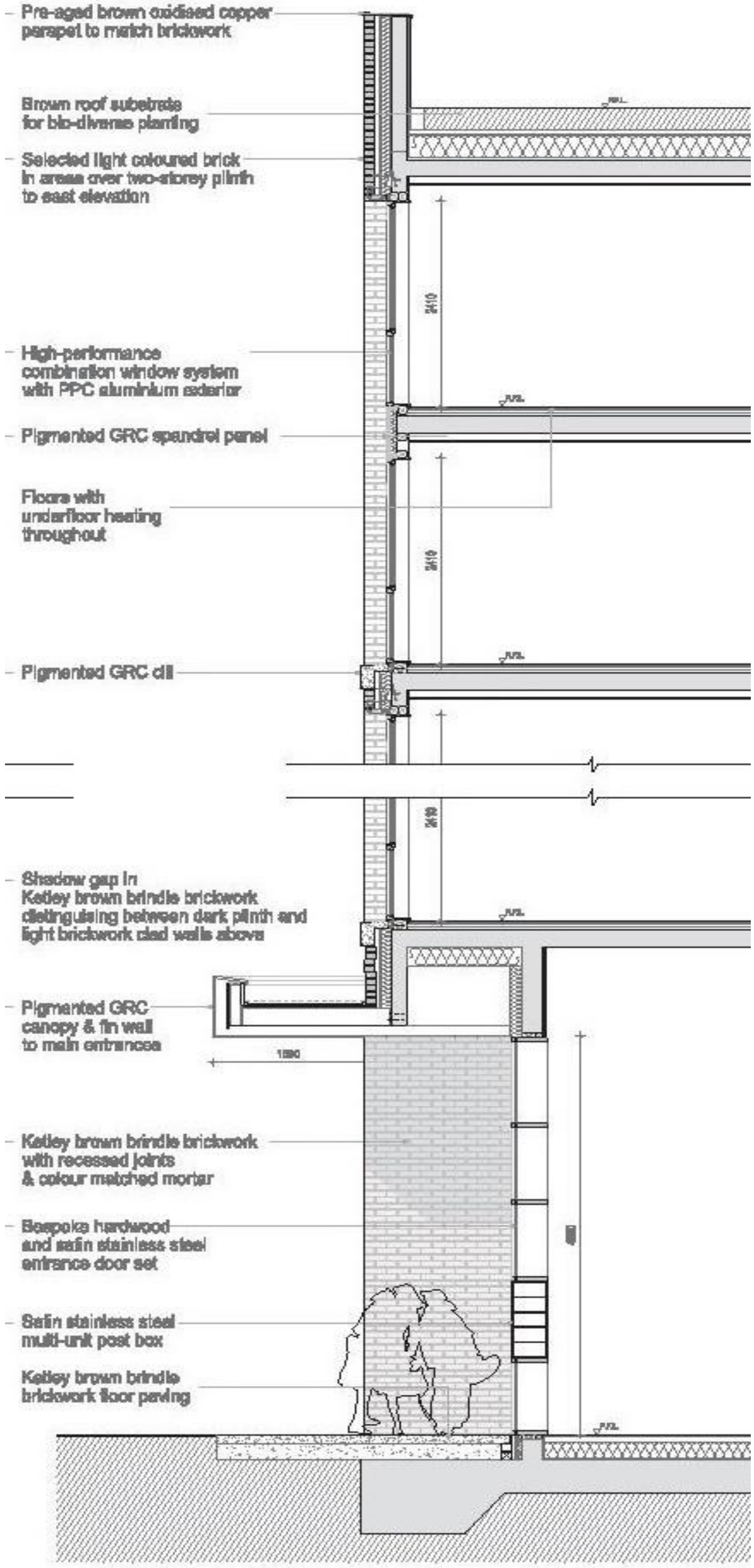

Figure 5.11: Sectional details showing recessed maisonette front area at the ground floor and the upper floor bedroom with the roof and the brick cladding finishes. (Karakusevic Carson Architects, 2011)

5.2.4 Environmental Sustainability

The construction of one flat at Bridport takes between 30m³ and 40m³ volume of CLT panels suggesting a minimum of 30 tonnes of carbon capture per flat with one volume of the timber panel sequesters up to 1.6 tonnes of carbon over its lifetime (Wood Solutions, 2013). The building saves more than 892 tonnes of carbon for using structural prefabricated timber panels to build corresponding to 12 years operational energy for concrete building (Rethink, 2011; Willmott Dixon, 2011). Overall, Bridport House captures over 2,113 tonnes of carbon as long as it stands which equals 29 years operational energy for building of the same size built with heavyweight materials (Willmott Dixon, 2011). The building is constructed with the features exceeding the requirements for the Code for Sustainable Homes (CSH) Level 4 (Rethink, 2011; Birch, 2011), but does not meet Passivhaus standards. The site is easily accessible with good transport networks to encourage the use of public transport as much as possible. Also, the bicycle sheds with galvanised steel doors are provided for the residents to encourage sustainable means of transport.

The internal spaces are naturally ventilated in summertime and are provided with mechanical ventilation and heat recovery (MHVR) systems which are often used during the winter period. Currently, each apartment is provided with a central boiler to heat the spaces and for hot water, while combined heat and power (CHP) system will be provided for the residents at a later stage of the scheme. The case study is provided with photovoltaic (PV) panels which has further improved on-site energy generation for the residents and cut carbon emissions by 10%. The roof system of the building is also done with the aim of achieving good performance with the introduction of brown and green roof that covers the total roof area of the 5-storey block and 50% of the 8-storey block laid over thick layer of rigid insulation and the roof is covered with permeable landscaping for easy flow of water. The ecology of the site was also considered as the only mature tree is retained to be part of the new landscaping.

Regarding airtightness, at $3m^3/m^2/hr$ @50Pa the building performs three times more than the minimum requirements for UK building regulations (Birch, 2011; Willmott Dixon, 2011). The use of glued material for the timber panels also improves performance of the building in terms of acoustics and fire resistance making the timber panels water tight. Concerning fire resistance, the building has up to 90 minutes for fire to spread from one apartment to another within the same floor. The acoustic resistance exceeds the requirements for the building regulations (55db) by 5 decibels (Wood Solutions, 2013) which suggests the case study performs well. The timber panels used also minimised site pollution such as noise, dust, water contamination, and limited the number of deliveries to site as it would have taken up to 7.5 times the number of deliveries if concrete had been used for Bridport House which further reduced carbon emissions on site.

5.3 Oxley Woods Housing Development in Milton Keynes

"Rogers Stirk Harbour & Partners' (RSHP) response to Oxley Woods Housing was to develop a generic house type that can be adapted to suit any location and site constraint using modern method of construction. An emphasis is placed on the potential of adapting houses to suit their occupants' lifestyle changes and family sizes. This mix of tenure and adaptability will create an accessible and adaptable community that can reflect and accommodate change over time".

- Rogers Stirk Harbour & Partners (2008: In Publications on Oxley Woods, p.2)

5.3.1 Description of Oxley Woods

Oxley Woods is a housing development built with prefabricated structural insulated panel (SIP) and consists of 145-unit 'innovative and imaginative' dwellings of 10 different prototypes. The case study is located in Milton Keynes, Buckinghamshire (52°0′36N, 0°48′5W) and bounded by western woodland fringe of the town (Edwards, 2008; LZ Carbon Profile, 2009). The first phase of the project started in April, 2005 with the introduction of the Design for Manufacture competition organised by the English Partnerships: an agency established with the sole aim of national regeneration of housing developments in England which was later merged in 2008 to be part of the newly established Homes and Communities Agency and the first phase was completed in August, 2007. Oxley Woods is built to be a high-quality housing development with average cost of construction per dwelling not above £60,000 approximately £784/m² for 56 (38%) of the houses (CEC, 2009; CIOB, 2009; Design for Manufacture 2009). While the actual construction costs of the remaining houses were projected above the threshold. The housing development occupies a 3.26 hectare area of land and comprises of 42-unit affordable or social housing and 103-unit privately owned dwellings of 2-storey and 3-storey built around a properly planned accessible road network (Figure 5.12) with an average density of 40 dwellings per hectare (dph) (LZ Carbon Profile, 2009; Design for Manufacture, 2009). The houses have a range of bedrooms from 2 to 5 and the total internal floor area from 61.7m² to 136m². The project is designed by Rogers Stirk Harbour and Partners (RSHP) Architects; the client is English Partnerships and has George Wimpey South Midlands as the developer. The project is regarded as George Wimpey's first consignment of multiple award winning eco-homes (Edwards 2008; RSHP, 2008), which include the Royal Institution of Chartered Surveyors (RICS) Sustainability Award, the Building for Life Gold Standard Award, the Royal Institute of British Architects (RIBA) Manser Medal for Housing and the RIBA Southeast Award, all won in 2008 (RSHP, 2008; Edwards, 2008). The estimated cost of the project at the time it commenced was £13 million but the actual cost of the project is still unknown as 116 houses have been completed with 29 dwellings yet to be built.

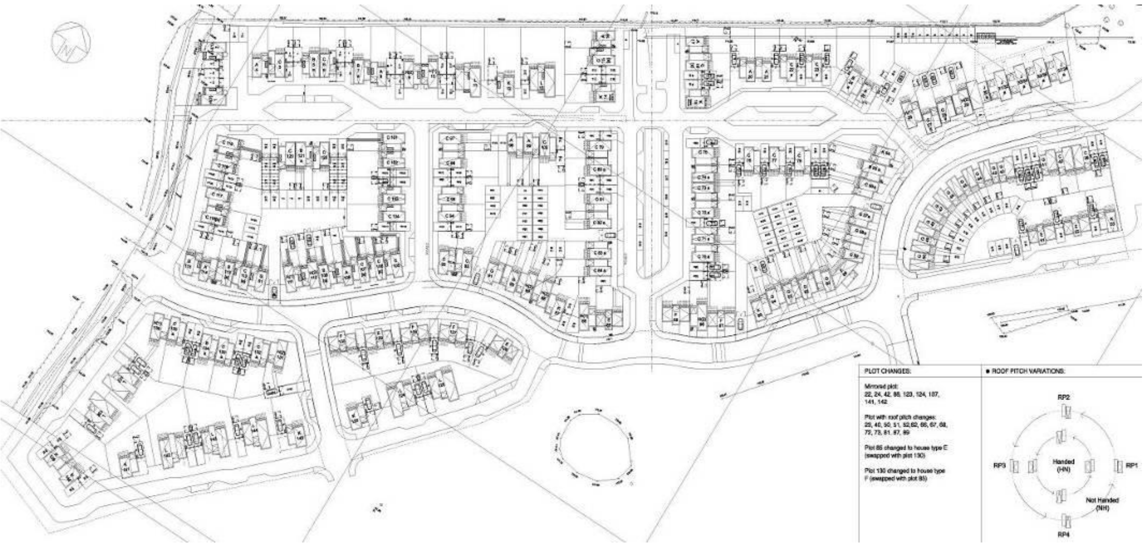

Figure 5.12: Site plan of Oxley Woods showing overall layout of the prototypes positioned at different orientations with private outdoor spaces at the back of the houses and good road networks to access the development (Richard Stirk Harbour & Partners- RSHP).

The design of the project is done to promote the construction of affordable, high-quality, sustainable and low-emissions dwellings as well as reduce shortage of housing supply in one of the suburban areas of England that is not far from London. As the total cost of newly built dwellings over the last two decades in the UK has increased by more than 50%; the project was constructed to encourage first time buyers under the initiative promoted by the client. The need to provide high-quality affordable houses at Oxley Woods was a result of the findings provided by the Centre for Architecture and the Built

Environment (CABE) that showed that just 18% out of the newly built dwellings investigated across the UK were considered to be high-quality while 29% and 53% were rated to be of poor quality and average quality respectively (CEC, 2009; CIOB, 2009). This suggests that approximately only 2 out of 10 newly built houses in the UK are of good quality in terms of construction, affordability, space quality, storage facility, sustainability and Oxley Woods was built to meet the English Partnerships/ Affordable Homes standards.

The houses at Oxley Woods are built to flexible terms in respect of size and space usage to meet the increasing needs of the occupants due to change in family size and lifestyle. The designer's aim was to build different generic prototypes of dwellings using prefabricated construction technique that can be changed or modified over the years when they are built in any region of the UK (RSHP, 2008; Edwards, 2008) while the core remains the same but the spaces such as living areas may change (Design for Manufacture, 2009; LZ Carbon Profile, 2009). The designers also aim to overcome site limitations such as adjacencies and lack of adequate space for in-situ construction by recommending prefabricated method of construction using SIP. The designs of the houses were done by creating small and dynamic standardised units which have been properly tested and adapted for human habitation by the designers (RSHP, 2008). The houses are provided with open space plan for lounge and dining, bedrooms, study area and service areas such as kitchens, bathrooms as well as heating/lighting spaces (Figures 5.13 and 5.14). Each house is supplied with 'Eco-Hat' (Figure 5.15): an innovative and custom-made energy-efficient ventilation steel lantern system produced by Nuaire to improve energy efficiency of the houses (RSHP, 2008; Design for Manufacture, 2009; LZ Carbon Profile, 2009) which has added a striking character to the overall skyline of Oxley Park. The 'Eco-Hat' is placed on the roof which can be regulated and adjusted to different orientations as it allows and cleanses all the incoming fresh air into the indoor spaces. It also removes and re-filters the used air that pass through the stack and re-distributes the air. This helps to improve the internal conditions within the houses. The system supplements the natural way of ventilating the indoor spaces.

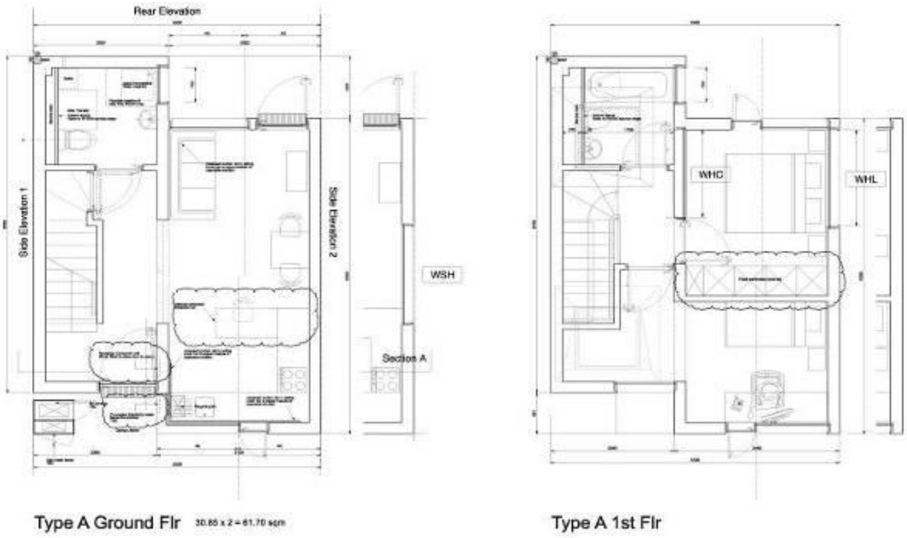

Figure 5.13: Ground floor and upper floor plans of Type A (one of the prototypes) at Oxley Woods showing internal arrangement of the spaces with the overall planning that allows for flexibility and change in the future.

Figure 5.14: Views showing arrangement of the prototypes- Types A, B and G (left) and social housing-Types I-J adding a striking feature to the overall skyline of urban scene at Oxley Park.

Figure 5.15: Different views of the overall skyline of urban scene at Oxley Park with the Eco-Hat placed on the roof of each house to improve energy efficiency of the development (RSHP, 2008).

The main idea of developing Oxley Woods was to ‘challenge orthodox building practices’ of using conventional building materials to construct houses (Edwards, 2008) which are common in the UK with a view to promote the use of new, improved, re-usable and sustainable materials with low-carbon footprint. The houses are well planned with an interesting external view and provision of private gardens for the occupants which are not commonly found in modern UK housing developments. The project is an example of suburban housing development as suburban houses are likely to have more spacious private outdoor spaces than houses in city-centres.

5.3.2 Space Standards

In terms of space arrangement of the houses at Oxley Woods, the floor plans provide for great flexibility of space usage and future extension. The arrangement of the internal spaces are similar to the 20th century houses in the UK but have different minimum space standards, such as the total floor area, the proportion of bedrooms to other spaces in the house, size of windows and floor-to-ceiling height. The interior of the houses are zoned into two different areas with a service area accommodating utility, boilers and bathrooms while a living area indicating dining, living rooms and bedrooms. The total floor areas of the prototypes at Oxley Woods range from 61.7m² to 135.8m². Table 5.3 below summarises the features of each prototype, floor area and proportion of the bedroom to the total floor area of the house. The English Partnerships/ Affordable Homes minimum space standards recommend 76-77m² total floor area for newly built two-bed houses while total floor area for a three-bed house and four-bed house should be at least 93m² and 106m² respectively (Housing Design Standards, 2010). Considering the floor area of the houses at Oxley Woods, the space standards conform to the minimum of the English Partnerships/ Affordable Home space standards.

Table 5.3: Features of the prototypes at Oxley Woods indicating total floor area and percentage of proportion of the bedrooms to floor area.

Prototype/Type of house	Number of bedrooms	Number of floors	Total floor area (m²)	Minimum space standards for type of house	Type of minimum space standards		Proportion of bedrooms to floor area (%)
					AH	EP	
A- detached	1-bedroom plus convertible study to bedroom	2	61.70	61	✓	66	33%
B- semi-detached	2-bedroom	2	76.82	77	70	✓	30%
C- terraced	2-bedroom with study	2	76.84	77	70	✓	28%
D- terraced	3-bedroom	3	94.50	96	✓	93	35%
E- detached	4-bedroom	3	106.20	106	108	✓	43%
F- detached	5-bedroom	3	135.82	135	-	✓	49%
G- terraced	3-bedroom with study	3	100.50	102	✓	93	37%
H- terraced	4-bedroom with study	3	110.50	114	✓	106	45%
I-J terraced	1-bed, 2-bed	3	61.70-76.80	61-70	✓	66-71	30-38%
K-L semi-detached	3-bedroom plus study-convertible	3	109.62	108	✓	106	50%

*AH- Affordable Homes, EP- English Partnerships.

The average floor-to-ceiling height in most of the internal spaces is 2.35m (Figure 5.16) conforming to the Affordable Home space standards. The Affordable Home standards specify a minimum of 2.4m floor-to-ceiling height for all habitable spaces.[17] Since the development is a joint-partnership between public and private organisations located outside London, the minimum space standards adopted were set to meet the English Partnerships/ Affordable Homes standards and not the Greater London Authority (GLA)

[17] The English Partnerships' standards developed by the Homes and Communities Agency (HCA) specify a minimum of 2.5m floor-to-ceiling height for dwellings.

standards which were used in recently developed social housing but exceeded the Developer standards promoted by the National House Building Council (NHBC).[18] Three of the ten prototypes are provided with balconies with depth of 1.48m and floor area of 5m² for two-bed houses and 6m² for three-bed houses suggesting that the houses at Oxley Woods are built in accordance with the English Partnerships/ Affordable Homes standards. All the houses are provided with private gardens with minimum depth meeting the requirements highlighted by the space standards.

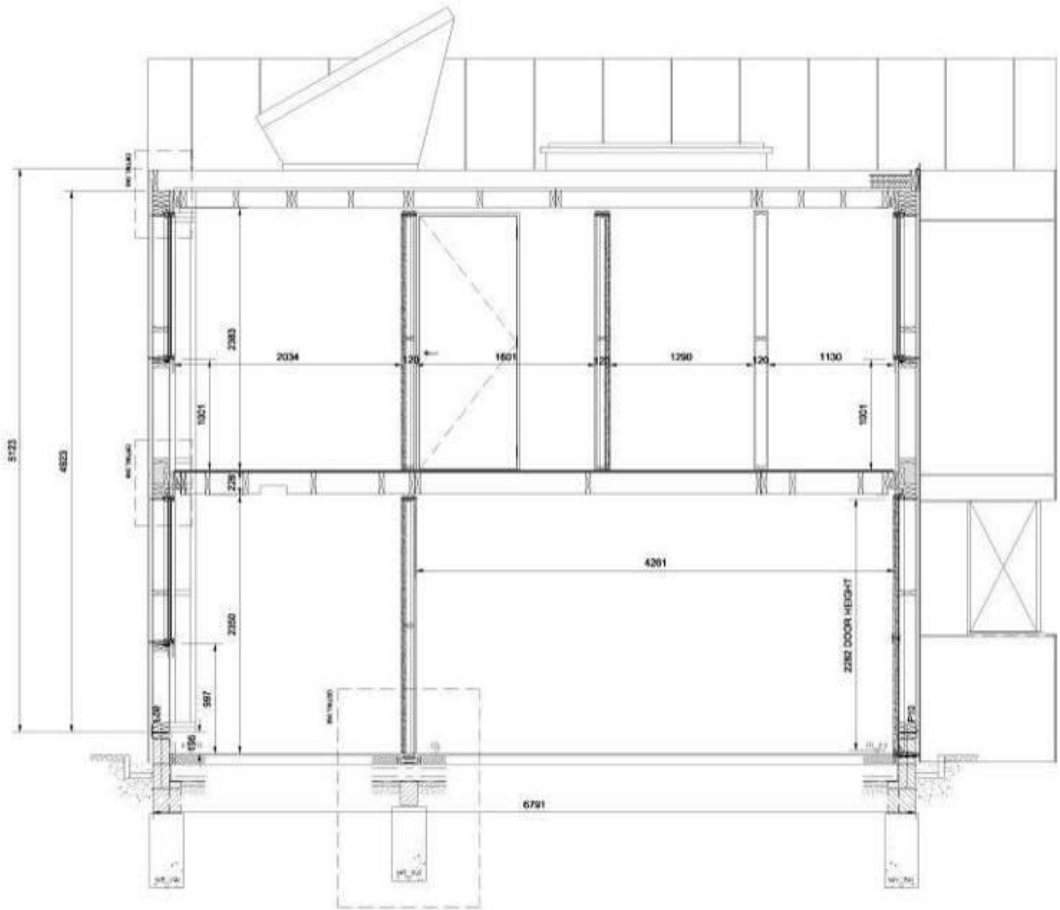

Figure 5.16: Section through Type A showing the internal spaces with floor to ceiling height and 'Eco-Hat' placed above the stair hall at the left-hand side to improve the internal condition of the house.

5.3.3 Materials and Construction

Structural insulated panels used for load bearing wall and roof have a life span up to six decades (60 years) or more (BBA-09/4658, 2010). The insulated panels are manufactured off-site by Wood Newton Limited, a UK based specialist joinery contractor with a good

[18] The Developer standards are used for modern privately funded housing developments which specify a minimum of 2.1m floor-to-ceiling height.

reputation for the production of the materials over the last few years. The materials are made in different sizes ranging from the highest height of 16m (about three-storey high) and width of 3.6m (about one-storey high) to more considerable sizes according to the design and specifications. The timber-framed method of construction provides the opportunity for the timber-framed system to reach the highest part of the houses, thereby limiting the potential for thermal bridging that can lead to heat loss and continuous air flow between various floor and wall connections. The materials were properly cut using the similar concept of 'inside-out' employed for the construction of the popular Lloyd's of London building and the Centre Pompidou in France designed by Richard Rogers to externally express some striking features such as Eco-Hat. In addition, articulation of the external cladding manufactured in different colours makes the houses easily fit in to the vernacular nature of other housing developments at Oxley Park (Figure 5.17).

Figure 5.17: Arrangement of the cladding material (Trespan) made in different colours to provide visual expression with striking features (left) and an aerial view of the houses at Oxley Woods. (Fig 5.17b by RSHP Architects)

The structural timber panels are mounted on the floating concrete ground floor properly laid over concrete strip foundation that has been done on-site (Figure 5.18). The building envelope is made of timber panel board with layers of organic insulation produced from non-toxic recycled newspaper which makes the fabric of the houses at Oxley Woods non-hazardous and eco-friendly. The organic insulation is installed between the timber panels by spraying or inserting the material to properly insulate the panels. The left-over spaces are filled with the insulation material to reduce thermal bridging, enhance airtightness and improve thermal performance of the envelopes. The insulation for the wall panel is 145mm thick solid polyurethane which permits free flow of air and reduces tendency of timber decay. The timber panel has density of 450kg/m³ and specific heat capacity of

1600J/kg-K (ISO 10456, 2007 p.11). Table 5.4 below summarises the features and U-values of the different components at Oxley Woods.

Figure 5.18: Arrangement of the panels using light equipment on the concrete ground floor constructed over strip foundation at Oxley Woods (RSHP Architects).

Table 5.4: U-values for the different components at Oxley Woods (CEC, 2009; LZ Carbon Profile, 2009; UKSIPS, 2013 p.3)

Components	U-values (Wm²/K)	Airtightness test
Walls (Trespan cladding, structural insulated panels, 145mm cavity, non-toxic Warmcel insulation produced from recycled newspaper, gypsum plasterboard)	0.12	2.5m³/m²/hr @ 50Pa
Roof (Roof panel over 100mm thick solid polyurethane insulation, timber cassettes)	0.17	2m³/m²/hr @ 50Pa
Floor (timber finished floor layer, screed, rigid polyurethane insulation layer, timber cassette)	0.10	2m³/m²/hr @ 50Pa
Windows (Timber framed with low-e double glazing)	1.70	-

The prefabricated method of construction and the materials used for Oxley Woods provide the opportunity to complete a three-storey house ready for the residents to occupy in less than two months. Also, the period of manufacturing the prefabricated timber panels from the factory ready to be mounted on site takes no more than a month and the houses are built within a week with duration of a day (24 hours) to complete a watertight house. This suggests that the construction method used for the houses are fast, cost-effective and save time. The construction timeline also suggests that three 2-bedroom houses were completed per day, 15 houses were completed within a week. Up to 780 houses can be built within a year using the same materials if the timber panels are produced from one factory and 7,800 houses if the panels are produced by 10 different manufacturers at the same capacity (RSHP, 2008; Design for Manufacture, 2009). The weight of the material also enhances easy movement from the factory to the site as a lorry can take a 3-storey house. This shows that SIP used for Oxley Woods and prefabricated method of construction adopted is suitable for the project and ultimately cut carbon emissions.

5.3.4 Environmental Sustainability

The materials are more eco-friendly and sustainable in terms of energy used for production and transportation than conventional materials such as brick, block or concrete. They are anticipated to be non-toxic and non-hazardous due to the bonding material (formaldehyde glued) used.[19] However, further investigation on indoor air quality of the houses built with the materials will be required. The wall cavity and roof cavity are filled with the insulation material (Warmcel) made from recycled newspaper and the use of structural panel timber provides ability for the material to capture carbon over its lifetime. Also, the timber panel has a better performance in terms of reliance on synthetic carbon based insulation when compared to other heavyweight materials (RSHP, 2008). The building fabrics such as wall, roof, and window have low U-values and they are airtight. The custom-made large fixed windows and doors are installed to minimise the dependency on artificial lighting due to the need for adequate daylighting and ventilation within the interior spaces as well as enhance the occupants to view the surrounding environment.

The houses at Oxley Woods are predicted to save at least 20% carbon emissions of energy used for heating and cooling when compared to conventional buildings of the same size (RSHP, 2008). The introduction of bespoke ‘Eco-Hat’ placed over the service areas of the houses with the control located in the stair hall area at 1200mm height for easy access is anticipated to save up to 40% carbon emissions (CEC, 2009; LZ Carbon Profile, 2009). ‘Eco-Hat’ is expected to save up to 50% carbon emissions when it is further used for water heating (Edwards, 2008). Also, a dry solar panel system and a 100

[19] Formaldehyde glued is a bonding material used in production of structural timber materials with the ability to join wood particles together.

Watts fan incorporated in the 'Eco-Hat' for effective solar heating and ventilation improve performance of the case study.

Each of the houses at Oxley Woods is provided with a central heating and hot water system for space and water heating purposes using natural gas. The building fabric is well-insulated with airtightness of $2.5m^3/m^2/hr$ @ 50Pa. The houses at Oxley Woods are built with 80% sustainable timber products and attain acoustic value of 65 decibels (db) which also suggest that it meets the minimum requirements in terms of acoustics for UK dwellings. The use of water-saving dual flush system at the toilets also reduces water wastage and overall annual cost of water used at the case study. Concerning fire rating, between 30 and 60 minutes fire resistance must be provided for SIP walls of up to six stories (UKSIPS, 2011). For Oxley Woods, 60 minutes fire resistance was considered for the party walls due to the number of floors (3-storey) as specified by the UKSIP.

Oxley Woods is developed with the aim of achieving easy access for the residents as well as promoting sustainable mode of transport. The houses are well-planned as the residents are not expected to walk more than 400m to the nearest bus stop. This is done in accordance with section 106 of the Town and Country Planning Act 1990 that promotes the use of public and sustainable transport for people which will reduce carbon emissions across the UK (CEC, 2009). The houses are also provided with sustainable drainage systems that make the development to be at low risk for flooding. The use of sustainable transport and drainage system at Oxley Woods minimise overall carbon emissions by the residents.

5.4 Stadthaus Housing, Murray Grove, East London

"The architects and engineers had prior experience of CLT, gained through a variety of low rise housing, commercial, educational and industrial projects. Their interest in using CLT for Stadthaus *arose from an 'environmental' position and a desire to make timber more readily accepted in the UK especially for tall structures that have hitherto been feasible only with inorganic building materials such as concrete, masonry and steel".*

- TRADA (2009, p.1)

5.4.1 Description of Stadthaus

Stadthaus is a nine-storey residential high-rise block of flats, built with prefabricated cross-laminated timber (CLT) panels that commenced in 2007 and was completed in January, 2009. It is located in Murray Grove: a highly urbanized area of Hackney in north-east London (51°53'50N, 0°05'32W). Stadthaus is a German word that stands for 'townhouse' (TRADA, 2009a). It is regarded as a monumental development in the history of timber structures across the globe due to the building's landmark achievements in recent years which defines it as a modern and innovative project that will shape people's behaviours and perceptions towards timber construction in our modern world (Thompson, 2009; TRADA, 2009a). It is a multi-award winning timber tower including the Judges Special Award by British Construction Industry, Building for Life Gold Standard by the Commission for Architecture and the Built Environment (CABE), Innovation Award by Daily Mail Newspaper, all won in 2009 and Winner of Structural Wood Award in 2008 among others. The building is jointly owned by the Telford Homes Plc and the Metropolitan Housing Trust, UK. The clients' interest in environmental view and passion to make timber gain wider acceptance in the UK housing sector contributed to the choice of CLT timber panel as a material to build. The architect for the project is Waugh Thistleton Architects while the structural engineer is Techniker Consulting Structural Engineers. The main contractor is Telford Homes and the timber panel was supplied and erected by KLH UK, Limited. It is built to be a route to carbon neutral and even carbon-positive structure (Lowenstein, 2008; Thompson, 2009; TRADA, 2009a), and it is regarded as 'the tallest modern timber residential building in the world' (Alter, 2007, 2010; Thompson, 2009; TRADA, 2009a; AIA, 2010; Fortmeyer, 2010; Waugh *et al.*, 2010). It showcases a great development in the history of timber construction using structural timber panels for construction of modern and tall urban block of flats to reduce the problem of housing facing major urban centres across the globe especially in the UK.

The building is a £3.8 million project built on a 17m by 17m piece of land initially owned by Event Investments, UK with a supplementary modern play area for children of the community with total site area of 305m² (Thompson, 2009; CMA Planning, 2009) located near 1930s and 1940s social housing built with bricks (Thompson, 2009; TRADA, 2009a; Waugh *et al.,* 2010). The ground floor of Stadthaus serves as an office space (89m²) for the Murray Grove local residents' association with two separate entrances from the two sides of the local streets to access the privately owned and socially rented apartments which are located at the upper floors (Figures 5.19 and 5.20). The socially rented flats owned by the Metropolitan Housing Trust are located on the first three levels above the ground floor (first floor, second floor and third floor) while privately owned flats are located on the last five upper floors (fourth floor to eighth floor) and they are managed by the Telford Homes. The fourth floor indicates a modification in the arrangement of spaces within the floor plan and the building facades (TRADA, 2009a; Waugh *et al.*, 2010). The building comprises of 29 flats at a recorded density of 2993 habitable room per hectare (CMA Planning, 2009). The apartments include: 19 privately owned, 9 socially rented and 1 shared ownership flats consisting of one-bed, two-bed, three-bed and four-bed apartments with each flat having its own balcony located at the corners of the building (Lowenstein, 2008; Thompson, 2009) with provision for outdoor spaces for leisure and relaxation.

In terms of the design, the concept was developed on a honeycomb pattern around a central core (Thompson, 2009; Waugh *et al.*, 2010), with an overall internal floor area of 2,750m² at approximately £1,382/m² cost of construction for the project. The design of Stadthaus expresses integration of technology with sustainable material without sacrificing the design principles (Alter, 2007, 2010) and it has a strong connection with the immediate environment (Figure 5.22). The building was originally designed as twenty-storey but was later reviewed and reduced to a nine-storey due to the cost, time to build and need to minimize risks from defects[20] (Yates, *et al* 2008; Thompson, 2009; Waugh *et al.*, 2010). Recent findings suggest that the timber panels can be used to build tall structures of up to thirty-storey (Thompson, 2009; TRADA, 2009a) but it was restricted to nine-storey for Stadthaus after due consultations with the regulatory bodies in the UK such as the National House Building Council (NHBC) and the Building Research Establishment (BRE) stating the minimum lifespan of 60 years for the housing development (Thompson, 2009; TRADA, 2009a; Alter, 2010, Waugh *et al.*, 2010). The development of Stadthaus has also shown that engineered timber products can be used for tall structures in any part of the world.

[20] Examples of defects identified include structural defects which can occur due to poor details, fire attack and natural disasters.

Figure 5.19: Site/ground floor plan of Stadthaus showing internal arrangement of spaces used by the local residents' association with entrances from two local streets and outdoor space for relaxation and leisure (Waugh Thistleton Architects, 2009).

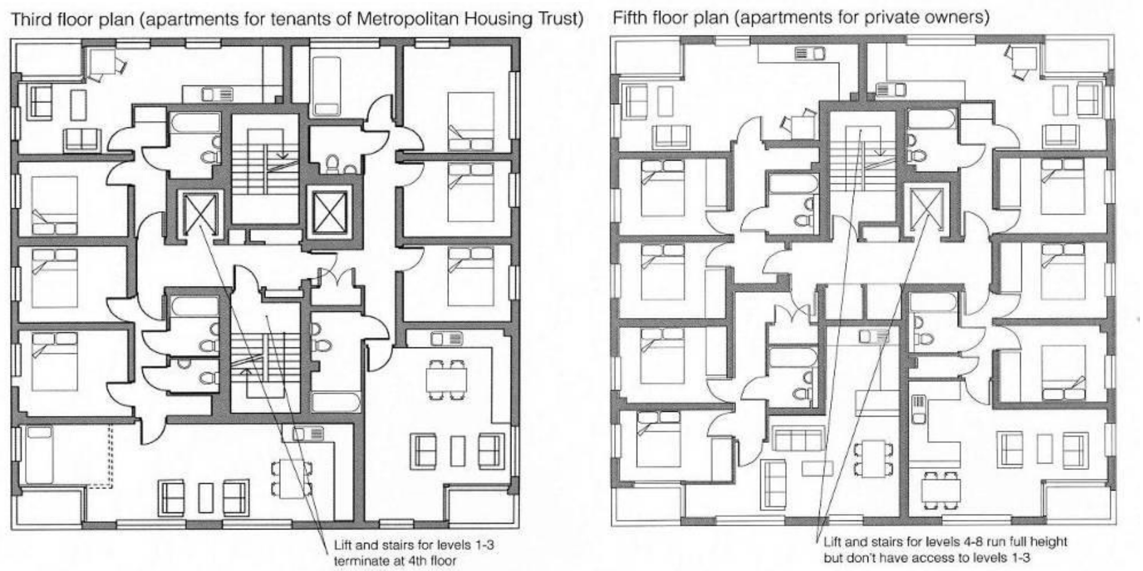

Figure 5.20: Third floor and fifth floor plans showing internal space arrangement of the socially rented apartments (left) and privately rented apartments (right) with different floor layout and access to the apartments.

Figure 5.21: Street views of Stadthaus in Murray Grove, London showing a strong connection with the environment (Thompson, 2009).

5.4.2 Space Standards

Concerning the minimum space standards, the developers and the architects did not provide any information regarding the space standard considered for the construction of Stadthaus but the internal floor area of the flats, size of the bedrooms and floor-to-ceiling heights indicate that the standards conform to the UK Developer standards developed by the National House Building Council (NHBC) as discussed in Chapter 3. The space standards used are below the minimum space requirements considered for the English Partnerships/ Affordable Homes standards as well as the Parker Morris standards because the housing development is solely financed by the two developers[21] as they will be more concerned about the number of apartments than any other criteria. The internal floor area of one bed-flat at Stadthaus indicates approximately 48m² which is within the range (43-48m²) set by the UK Developer standards for one-bed flat while the English Partnerships/Affordable Homes and the Parker Morris standards specify at least 51m² and 49m² respectively for one-bed flat. Also, the floor area of two-bed flat is about 65m² showing the building is built in accordance with the UK Developer standards that specify 64m² for two-bed flat (4 persons). The evaluation of a proportion of the bedrooms to the total internal floor area of the apartments suggests a range from 35-65%. This also suggests that the internal floor area especially the sleeping areas are smaller than the bedrooms at Bridport and Oxley Woods.

[21] The two developers are the Metropolitan Housing Trust, UK and the Telford Homes Plc.

The floor-to-ceiling heights of the internal spaces at Stadthaus housing is 2.35m which do not meet the requirement for the GLA standards but conform to the Developer standards. All the apartments at Stadthaus are provided with balconies with depth of 1.35m indicating shortfall in the minimum depth recommended for balconies by the GLA and the English Partnerships/ Affordable Home standards. This further suggests the use of Developer standard for Stadthaus. The area of communal outdoor space provided by the developers for use of the residents also falls below minimum area of 20m² per apartment recommended by the GLA and the English Partnerships standards and shows that Stadthaus housing is built using the Developer standards. Table 5.5 below summarises the features of the apartments, floor area, and number of bedrooms as well as percentage of the bedrooms to floor area.

Table 5.5: Features of the apartments, total floor area and percentage proportion of bedrooms.

Type of apartments	Numbers provided	Floor level	Area of internal floor spaces (m²)	UK Developer minimum space standards (m²)	Proportion of bedrooms to floor area (%)
One-bed apartment (socially rented)	3	First floor to third floor	48.2	43-48	35%
One-bed apartment (privately owned)	5	Fourth floor to seventh floor	48.6	43-48	35%
Two-bed apartment for four persons (privately owned)	15	Fourth floor to seventh floor	65.8	64	50%
Three-bed apartment (socially rented)	3	First floor to third floor	96.4	98	60%
Four-bed apartment (socially rented)	3	First floor to third floor	100.5	101	65%

5.4.3 Materials and Construction

The construction of Stadthaus was done using 'the proprietary system' of solid timber panelling: an innovative method of construction developed in Austria by KLH Limited with an office based in London (Lowenstein, 2008; TRADA, 2009a; Waugh *et al.*, 2010). The choice of KLH cross laminated timber panels from Austria to construct Stadthaus is influenced by the availability of material, location of the manufacturer, cost of production, technological innovation required, type and size of building, handling techniques as well as ecological consideration. Austria is known as one of the European nations with the largest area of forests and unspoiled nature and the people in Austria grow more trees than they are taken out of the forests (Lowenstein, 2008; Thompson, 2009). The timber panels are manufactured using softwood such as spruce which is taken from environmentally sustained forests grown by KLH under factory-regulated environmental conditions. The softwood boards are industrially harvested, dried, stacked at the right angles and joined together with glue over their entire surface under high pressure of 60tonnes/sqm to produce large-format solid timber elements. The timber board layers which are usually in 3, 5 or 7 are available in different sizes such as 2400mm (length) by 1200mm (width) and the size are influenced by purpose of use and static requirements of the structure (Thompson, 2009; Waugh *et al*, 2010). Most KLH timber panels have maximum length of 16.5m but the manufacturer recommends a maximum length of 13.5m, a width of 2.95m and a thickness of 0.5m at maximum depending on both external and internal requirements. The flexibility in the use of KLH timber panel to build the building is influenced by the ability to produce large formats of the panels, the cross lamination, the structural capacity and tendency of using timber panel with other materials such steel and glass (KLH, 2009; Thompson, 2009). The material (CLT) is also known as 'Cross-lam' or 'X-lam'. It was first developed in Switzerland in the mid 1970s but had been recently modified using modern technology.

The construction of Stadthaus was done within 49 weeks while the same size of the building built with concrete takes a minimum of 72 weeks to be completed (Thompson 2009; TRADA 2009a). The construction method and the material used for Stadthaus save 23 weeks of the construction period. The building took only 9 weeks by 4 workers sent from the factory in Austria and 1 supervisor to assemble the CLT panels with each of the workers working 3 days per week, 27 days in total and each floor was completed in three days (Tall Order for Timber, 2007; Lowenstein, 2008; Thompson, 2009; TRADA, 2009a). All the timber panels were manufactured according to the designer's specification. The construction of Stadthaus shows that the CLT boards are flexible to use for construction and save time.

The foundation of Stadthaus is made of concrete piles dimensioned to receive the entire load frame of the building. The ground floor of Stadthaus is built with in-situ concrete to provide additional open accommodation for the building. The upper eight floors are built with the timber panels. The building lift and stairs are prefabricated separately and fixed to the building. Both stairs and lift are isolated from the immediate core walls perimeter and they are load-bearing. Stair flights are produced from prefabricated hollow steel forms filled with concrete. The two lift shafts and stairwells are made of laminated plywood. This shows that timber is used for 90% of the project.

According to the post-completion test on airtightness carried out in some selected indoor spaces at Stadthaus in accordance with the Code for Sustainable Homes (CSH) in the UK suggest values between 2.02 and 3.82 $m^3/m^2/hr$ @ 50Pa (Jowett, 2011); while the UK Approved Document L1A (2006, p.19) indicates an acceptable air permeability limit up to $10m^3/m^2/hr$ @ 50Pa for structures that have the tendency for heat conservation. Concerning the exterior and interior walls of Stadthaus, the structural material (CLT panel) has a lower U-value than a typical timber stud structure. It has a lower density of $500kg/m^3$ than other building materials such as concrete ($2400kg/m^3$), brick ($1920kg/m^3$), aluminium ($2740kg/m^3$) and stone ($1600kg/m^3$). The heat conductance of the 128mm thick of 3 layers CLT wall panels with over 70mm thick layer of insulation used for construction of internal walls at Stadthaus is $0.13W/m^2K$ (TRADA, 2009a), while the specific heat capacity of the timber panel is 1600J/kg-K compared to concrete with 880J/kg-K. The external wall of the case study has a higher U-value than the internal wall (Figure 5.22). The timber panels manufactured from Austria (a nation known for extreme weather conditions in winter) are properly insulated for airtightness and retention of heat to enable timber structure withstands the harsh external weather conditions (Thompson, 2009; TRADA, 2009a). Table 5.6 summarises the U-values of various components used for construction of Stadthaus.

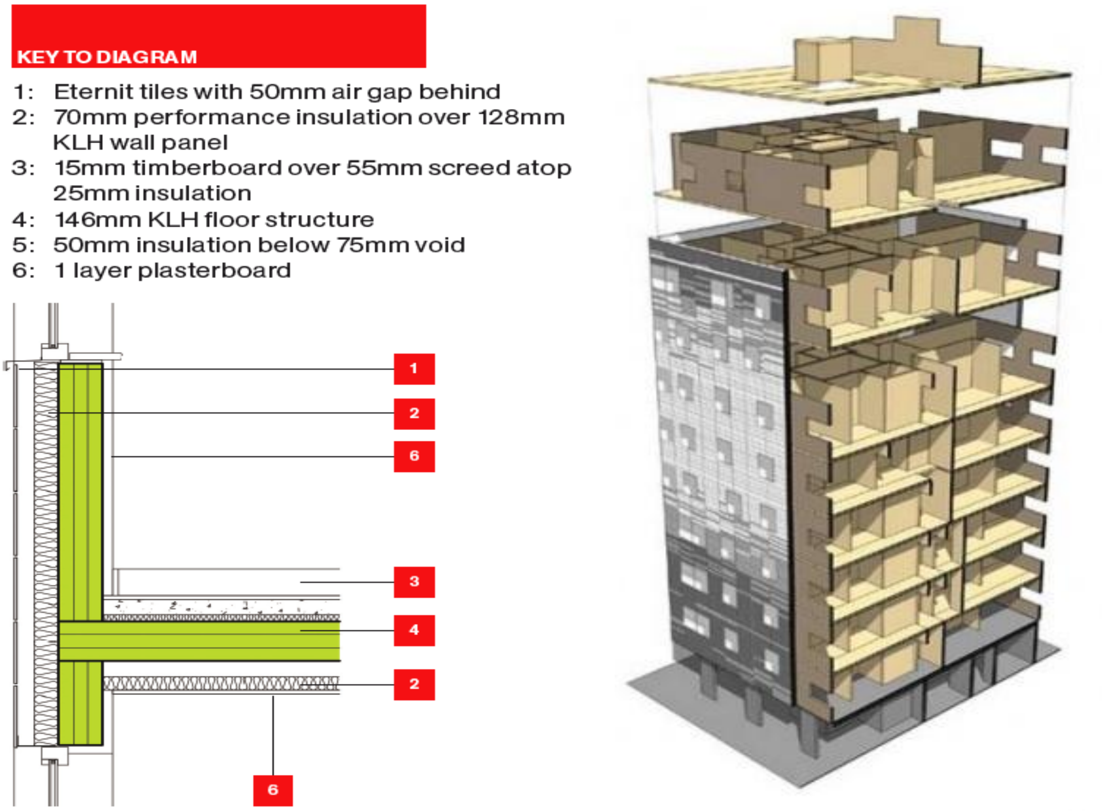

Figure 5.22: Construction details showing the wall to floor connection with finishes (left) and sectional view of the structure showing massive walling system of the timber panels used for Stadthaus (RIBA, 2010; Lowenstein, 2008).

Table 5.6: U-values for the different components at Stadthaus

Components	U-values (Wm²/K)
External wall (wood fibre cement tile, cavity, polyurethane rigid insulation board, CLT panel, gypsum plasterboard)	0.16
Internal wall (gypsum plasterboard, polyurethane board, CLT panel)	0.13
Floor (timber finished floor layer, Glyvon screed, compressed EPS rigid insulation layer, CLT panel, cavity, EPS insulation, gypsum plasterboard)	0.14
Low-e double glazing window (2001 building regulations)	1.98

All the walls, floors and cores are load bearing. The timber panels also insulate heat, support both dead and live loads without any deformation as well as resist fire and also absorb sound (Thompson, 2009, TRADA, 2009a; Waugh *et al*., 2010). The CLT panel is usually made up of about 99.5% of timber and 0.5% of glue. The material is considered as a monolithic building material due to its process of production and each of the timber panel is prefabricated including cut-outs for windows and doors which reduced time spent on site. The method of construction considered for Stadthaus and Bridport is known as ‘platform construction’ using interconnected timber panel walls positioned vertically next to each other to provide support on which the next floor is constructed (Figure 5.22). Each floor is mounted on the walls below and another storey of walls is raised. The wall panels are connected to the floor with the use of screws and angle platters (Figure 5.23). The connection minimises stress to low level both on the structure and at points. Reinforced screws are used to connect the joints where cross-grain is high. KLH timber panel’s density is higher than that of unmodified timber-framed building and it enhances its acoustic performance. The presence of solid structural core arranged on different layers helps to overcome acoustic problem.

Figure 5.23: The interior of Stadthaus showing the connection between wall and floor timber panels (left) (Thompson, 2009); using angle platters and screws for connection (right) (Wood Solutions, 2013).

Stadthaus was built without any precedent. This was possible in the UK as there is no part of the building regulations that limit the height of timber buildings. It was after the completion of the case study that the UK building regulations’ authorities included the guidelines under the appendix based on the information gathered from the project (Thompson, 2009; TRADA, 2009a; Waugh *et al.,* 2010). Stadthaus stands at 29.75m high and a timber volume of 926m³ (DETAIL Green, 2009; Thompson, 2009). Across Europe, the building regulations do not clearly define or restrict the height of timber structures in any country but most nations like Germany, France, Austria restrict high-rise timber building construction from five floors to six floors at the maximum in order to limit risks (Tall Timber Buildings, 2009; Thompson, 2009). In Austria where KLH timber panel is produced, any building that is going above 22m high must be built with non-combustible materials such as brick, concrete and steel as timber does not meet the requirements outlined for non-combustible materials (Thompson 2009; Fortmeyer, 2010). In Scandinavian countries like Finland, timber construction is restricted to 3 floors to minimize risks and enhance its durability (DETAIL Green, 2009). However, construction of Stadthaus has shown that timber can be used for structures above 22m without any structural defects and limited risks.

The internal walls of Stadthaus are covered with plasterboards (15mm thick) and make the internal environment more appealing (Figure 5.24). The timber floor of Stadthaus is laid with a compacted 25mm thick rigid insulation and covered with a 55mm thick Glyvon screed that accommodates the underfloor heating pipes (Figure 5.22). The screed layer is then covered with a 15mm thick timber floor finishes to provide acoustic insulation of 55 decibels (db) between the apartments and 53db between the floors that do not only meet the UK requirements but also exceed the requirements. This suggests that all the necessary requirements in terms of acoustic insulation are met for Stadthaus.

Figure 5.24: Interior walls of Stadthaus covered with plasterboards to give the indoor environment a false impression of apartments built with conventional building materials (Thompson, 2009).

Stadthaus façades are covered with 5,000 individual wood fibre cement cladding panels that formed pixilated images in shades. The panels are produced in three different colours: black, grey and white. Each of the cladding material is measured 1200mm by 230mm and produced from 70% reused timber and 30% of other components such as cement by Marley Eternit, UK (Baseline, 2008; Thompson 2009; TRADA, 2009a). The pixilated images create façades that have changing lights and shadows generated on the void site by the surrounding buildings; trees and a captured sun-path animation are used to wrap the building. The building façades have series of 'missing pieces' for the creation of internal balcony and windows for each apartment across the 8 upper floors (Figure 5.22). The design of building façade with pixilated images of different colours was inspired by the pixilated images developed by artist Gerhard Richter (Tall order for timber, 2009; Thompson, 2009; TRADA, 2009a). Stadthaus facades show a great development in using timber products for cladding as the panels protect the structure from harsh external weather conditions and improves its aesthetic value.

5.4.5 Environmental Sustainability

The use of KLH timber panels for Stadthaus construction is considered to promote the use of timber for modern housing development. Moreover, timber is eco-friendly, sustainable, biodegradable and sequesters carbon. Although the materials are produced and brought from the factory in Austria to the site in the UK which created 'a long eco-haul', the carbon generated was offset when compared to the amount of the carbon locked within the timber panels (Lowenstein, 2008; TRADA, 2009a). The building saves up to 306,150kg of carbon when compared to other structures of the same size built with steel and concrete (Lowenstein, 2008; Thompson 2009); while the timber panels used for Stadthaus store a supplementary 181,360kg of carbon over its lifetime (Thompson, 2009; DETAIL Green, 2009; Fortmeyer, 2010). This suggests that Stadthaus stored up to 16,810kg of carbon per flat. During the period of construction, equipment such as cranes was also minimised on-site to reduce carbon emissions. The method of construction employed takes into consideration safe delivery of the materials to the site with the support of various appointed consultants that worked closely with the site workers and the building team.

In terms of energy used for production, the timber panels used for Stadthaus consumed low amount of energy. According to Thompson (2009), a tonne of brick requires 4 times the amount of energy needed to produce the same size of CLT boards, while a tonne of concrete and glass require 5 and 6 times the amount of energy to produce the similar size of CLT panels respectively. Likewise, a tonne of steel will consume 24 times the amount of energy needed to produce the same size of softwood and a tonne of aluminium will require 126 times the amount of energy needed. This suggests that the material consumes a lower amount of energy for production when compared to other conventional materials. Each of the flats has a condensing boiler and radiator for heating of the internal spaces and hot water. The timber panels are properly cut from the factory to create ducts for service runs such as ventilation ducts, electrical wires, boiler flues and ventilation. This shows that CLT panels can be used for construction of tall structures to accommodate all the service runs if they are well designed and prefabricated from the factory according to the designers' specifications. The heat recovery system install in the case study for mechanical ventilation is expected to retain up to 70% of the heat during winter (Thompson, 2009).

KLH timber panels are considered to have conveniently attained the expected fire resistance (TRADA, 2009a; Waugh *et al.*, 2010). In the event of fire disaster, the char that forms on the outer layer of the timber panel acts as an insulator which improves its fire resistance. The use of retardants creates chars at the back of the timber panels during fire outbreak and help to improve its capacity to resist fire. Considering the thickness of the fabric, it also helps to achieve 60 minutes fire rating while the use of dry wall (made of plasterboard) in combination with the timber panels increases the fire rating by an additional 30 minutes (Thompson, 2009; TRADA 2009a; Waugh *et al*, 2010). It will take up to 90 minutes for fire to spread from one apartment to another within the same floor and up to 150 minutes from one floor to another (DETAIL Green, 2009; Thompson, 2009).

The seismic resistance of timber structure is relatively high provided the quality of the material and the construction are done to meet the satisfactory requirements (World Housing, 2010). Timber, a lightweight material helps to minimize earthquake forces in the building when compared to heavyweight materials such as brick, concrete or stone. As a result of its lightweight, timber structures have the tendency to perform better in resisting seismic forces in the event of earthquake than any other conventional building material.

5.5 Summary

Bridport House is a publicly funded housing project; Oxley Woods is a public/ private partnership housing development while Stadthaus is solely funded by the two private developers. All the three case studies are located in the South and Southeast of England; the regions in the UK where the residents are likely to experience summertime high temperatures (Orme *et al.*, 2003; Firth & Wright, 2008; Lowe & Oreszczyn, 2008; Rijal & Stevenson, 2010; Porritt, *et al.*, 2012). They have all won various sustainability and low energy rating awards from reputable organisations. Bridport House and Stadthaus are built with cross-laminated timber (CLT) with use of heavyweight cladding materials (brown and lighter coloured bricks) for Bridport and lightweight cladding materials (wood fibre cement tiles) for Stadthaus while Oxley Woods is built with structural insulated panels (SIP) clad with Trespan (also made from recycled timber). The buildings are built within the last decade. Bridport and Stadthaus are high-rise structures and located in urban areas while all the prototypes at Oxley Woods are low-rise dwellings with a maximum height of three-storey located in a suburban area. Construction of the case studies suggest that timber is a good material to build due to low energy required for production, more appealing in terms of appearance with the application of new technology pushing the use of materials beyond its initial boundary and promoting its wider acceptance in the UK. The case studies are built for the working-class to middle-class people to reduce shortage in the supply of housing in the UK and to make sustainable housing accessible to people. The description of the case studies also suggests that they are well-planned with different size of dwellings and provision for flexibility as well as change in the future use of the internal spaces.

The minimum space standards used for the buildings were discussed. Bridport House is the most recently completed development out of the three housing developments. It is solely built for social housing by the London Borough of Hackney. The floor-to-ceiling height of the spaces at Bridport is at least 300mm higher than the floor-to-ceiling height of the spaces at Oxley Woods and Stadthaus. The review of the space standards showed that publicly financed housing developments are designed to meet the minimum space standards set by the UK building regulations' authorities while privately funded housing projects are built using the Developer standards which are below the Parker Morris standards of 1961 which was abolished in the 1980s. This suggests that the internal space and floor-to-ceiling height of the UK houses built by the developers are likely becoming smaller with no or lack of adequate provision for storage and private outdoor spaces. In some cases where the spaces are provided, the floor areas are smaller than floor areas of publicly financed housing. Of all the three standards considered for the case studies, the GLA standards used for Bridport are more generous followed by the English Partnerships/ Affordable Homes standards used for Oxley Woods while the Developer standards used for Stadthaus are contributing to construction of dwellings with reduced internal floor spaces and floor-to-ceiling height in the UK.

The construction of Bridport is entirely built with the timber panels from the ground floor to the upper floors while the ground floor of Stadthaus is built with concrete for commercial activities and the upper floors are built with CLT panels. Oxley Woods is built with SIP from the ground floor to the upper floors. All the walls, floor and core areas for circulation at the case studies are load bearing to provide structural support for dead and live loads. Consideration of thermal properties of the materials suggest that all the case studies are built with fabrics that have low U-values and well insulated which will improve the ability for heat retention and minimise heat loss. The thermal properties for the components as well as similarities and differences between the case studies are summarised in Tables 5.7 and 5.8 below.

Table 5.7: Comparison of U-values (W/m^2K) for the three case studies. (Approved Document Part L 2010: special edition, p.4).

	U-values for the different components (W/m^2K)			
Case study	Walls	Windows	Roof	Floor
Bridport House	0.14	1.37	0.12	0.16
Oxley Woods	0.12	1.7	0.17	0.10
Stadthaus	0.16	1.98	0.20	0.14
Part L1A 2006	0.35	2.20	0.25	0.25
Part L1A 2010	0.30	2.00	0.20	0.25

Table 5.8: Similarities and differences between the three case studies (ISO 10456, 2007, p.11; TRADA, 2009a; UKSIPS, 2011)

	Similarities						Differences		
Case study	Structural material for walls and floors	Internal wall finishes	Max. fire rating (minutes)	Density (kg/m³)	Specific heat capacity (J/kg-K)	Thermal conductivity (Wm-K)	Space standards	Floor-to-ceiling height	External cladding
Bridport House	Timber (CLT)	Gypsum plasterboard	90	500	1600	0.13	GLA	2.65	Brick
Oxley Woods	Timber (SIP)	Gypsum plasterboard	60	450	1600	0.12	English Partnerships/ Affordable Homes	2.35	Trespan
Stadthaus	Timber (CLT)	Gypsum plasterboard	90	500	1600	0.13	Developer standards (NHBC)	2.35	Wood fibre tiles

Considering prefabrication method of construction used for the case studies saved up to 8 weeks of construction period at Bridport; a 3-storey house was completed within 3 weeks at Oxley Woods and the method saved up to 23 weeks at Stadthaus when compared to the same size of building built with heavyweight materials. It provides quick returns on investment and can be used for construction in different seasons. Moreover, the method saved construction cost as it reduced number of site workers and equipment used. At Bridport and Stadthaus, four workers and one supervisor were required for each of the buildings throughout the construction period. Few workers and equipment were needed for construction at Oxley Woods. The method of construction used also enhances safety of the site workers and improve the carbon footprint of the projects.

The internal spaces of the case study buildings are naturally ventilated with adequate openings for daylighting to reduce dependency on artificial lighting and thus reduce the overall cost of energy required for the buildings. All the case studies exceed minimum requirements recommended by UK building regulations for airtightness and perform well in terms of acoustics. The timber panels used are easy to insulate and finishes used for the timber panels also improve its fire resistance in the event of fire outbreak. In addition, timber has a natural ability to resist seismic attacks which improve its overall performance. However, the performance of the case studies in different seasons will be examined in Chapters 6 and 7.

Chapter 6 Analysis of Collected Data and Findings on Post-occupancy, Environmental Monitoring and Comfort Surveys

6.1 Introduction

This chapter describes the results of the post-occupancy surveys as well as the outcomes from environmental monitoring, the comfort surveys carried out in the summer, and the winter at the case studies considered in Chapter 5. The findings from the post-occupancy surveys requiring information on the general background of the survey participants will be outlined. The discussion on the outcomes of the occupants' feeling of hot or cold, thermal satisfaction and overall thermal comfort in the summer and the winter will be examined. In addition, the results of occupants' use of control, level of control, satisfaction for control, frequency of control and effect of control on the activity carried out at the case studies will be discussed. The section also discusses the space the occupants spent most of their time, the warmest space, as well as the occupants' pleasant experience at the case studies and the variables highlighted above will be linked to thermal comfort of the occupants. Additional comments on several aspects of the indoor environment at the case studies will be considered in relation to the results from the surveys. The relationship between the variables considered in this study will also be discussed using Pearson tests across this chapter with significance level ($p<0.05$) to find out the level of association between the variables.

Concerning the comfort surveys, the findings from the respondents on thermal sensation, thermal preference, acceptability, controls used, clothing insulation, clothing preference, as well as overheating experience will be presented. The results will be linked to the findings from the post-occupancy surveys. Similarities and differences between the outcomes of the comfort surveys and post-occupancy surveys will be highlighted. Statistical tests showing level of significance and correlation between the variables at the case studies will be mentioned. Additional comments provided by the participants in relation to the findings from the surveys will be discussed.

The outcomes of environmental monitoring carried out at Bridport and Oxley Woods in the summer and the winter will be presented. The variables measured during the surveys will be discussed in order to understand the environmental conditions of the case studies.

The findings of the accelerators used to monitor window opening behaviours will be highlighted. The charts showing relationship between the temperatures (internal and external) and window opening and closing sessions at the case studies will be considered and overall results will be presented.

The analysis to assess the risk of overheating at the case studies will be considered using the CIBSE 'static' criteria and the dynamic adaptive comfort (BSEN15251) model. The 5%/25ºC and 1%/28ºC thresholds between 08:00-22:00 and 18:00-22:00 for the living areas as well as 5%/24ºC and 1%/26ºC thresholds between 23:00-07:00 for the bedrooms will be used to evaluate the summertime temperatures measured at the case studies. The outcomes of the static and the dynamic thermal comfort criteria analysis will be outlined. The charts showing the percentage of hours within the different thermal comfort categories in the approved BSEN15251 thermal comfort standard will be used to know the spaces that exceed 5% of hours above the Category II (normal level of expectation) upper marker. In addition, the charts will be used to evaluate the internal spaces that exceed 5% of hours below the Category II lower marker.

The final part of this chapter focuses on linking all the results from the post-occupancy surveys, environmental monitoring, and the comfort surveys together as well as findings from overheating analysis to understand thermal performance of the houses and thermal comfort of the occupants. Possible link between the performance of the two case studies monitored and the minimum space standards used for construction will be examined while further link between the three case studies and the space standards will be considered in Chapter 7. The results from this investigation will be compared with previous studies focusing on overheating in UK dwellings. The comparison between the results will help to provide a clear picture of summertime temperatures at the case studies and observe if the results suggest the occurrence of high temperatures within the internal spaces of the buildings. In addition, the findings from the surveys will provide a better understanding of how the occupants adjust the thermal environments of the houses in order to be comfortable especially during summertime high temperatures, which could affect the overall well-being and productivity level of the occupants.

6.2 Post-occupancy Surveys

A breakdown of post-occupancy questionnaires distributed at the three case studies indicates that 41 questionnaires were distributed at Bridport House, 70 and 20 questionnaires were distributed at Oxley Woods and Stadthaus respectively. A further breakdown of questionnaires administered showed that 26 questionnaires were returned from Bridport House, 26 from Oxley Woods and 13 from Stadthaus. There were 25 male (38.5%) and 40 female (61.5%) responses. Table 6.1 below shows frequency and percentage of gender distribution of questionnaires returned from the three case studies during the post-occupancy surveys.

Table 6.1: Gender distribution of post-occupancy questionnaires returned from the three case studies.

	Gender (frequency distribution)		Gender (percentage distribution)	
Case Study	Male	Female	Male (%)	Female (%)
Bridport House	9	17	35	65
Oxley Woods	13	13	50	50
Stadthaus	3	10	23	77

6.2.1 Analysis of Post-occupancy Surveys

Analysis of age distribution votes across the case studies suggest that over 73% of the respondents are above 30 years of age (Figure 6.1). The analysis suggests the respondents have the ability to understand the thermal environment of the case study buildings and vote accordingly. Table 6.2 below highlights the frequency and percentage of age distribution of questionnaires returned from the three case studies during the post-occupancy surveys.

Table 6.2: Age distribution of post-occupancy questionnaires returned from the three case studies.

	Age (frequency distribution)					Age (percentage distribution)				
Case Study	Under 18	18-30	31-45	46-55	56 and above	Under 18 (%)	18-30 (%)	31-45 (%)	46-55 (%)	56 and above (%)
Bridport House	-	-	7	8	11	-	-	26.9	30.8	42.3
Oxley Woods	2	5	15	1	3	7.7	19.2	57.7	3.8	11.5
Stadthaus	-	1	8	2	2	-	7.7	61.5	15.4	15.4

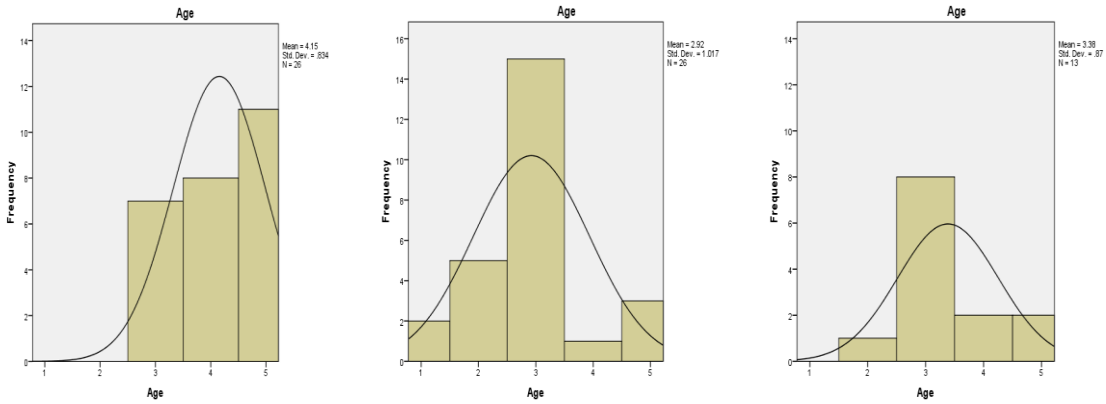

Figure 6.1: Distribution of age during the post-occupancy surveys at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) (where 1= Under 18, 2=18-30, 3=31-45, 4=46-55 and 5=56 and above).

Distribution of occupancy type and responses at Bridport and Stadthaus indicate 92% non-ownership status. However, 96% responses at Oxley Woods indicate ownership status which may influence the occupants' perception of the thermal environment. Occupancy duration of the residents at the case studies suggest 85% have been living at Oxley Woods and Stadthaus for more than 18 months while majority of the residents at Bridport House have been living at the case study for about 6 months as at the time of the survey. The responses also suggest that Stadthaus has higher density of occupants per household than Bridport and Oxley Woods. This may be as a result of the location of Stadthaus and different tenancy status available at the case study as most of the residents are either private housing renters/owners or social housing renters.

Regarding factors influencing the participants' choice of living at the case studies, the responses across the case studies show that 80% are influenced by the 'building type' while 70% are influenced by 'location' (Figure 6.2). Some of the residents also mentioned proximity of the case studies to local shops, place of work, school and communal facilities such as playground for kids when asked to make additional comments. The residents at Oxley Woods also indicate preference for private gardens. The younger occupants are influenced to live at Oxley Woods due to location ($r=-0.461$, $p<0.05$). The sizes of households influence the occupants' decision to live at Stadthaus ($r=-0.662$, $p<0.05$) as the respondents with smaller households' size consider living at the building than occupants with bigger household size. The male occupants are mainly influenced by cost to live at Stadthaus than the female occupants ($r=-0.778$, $p<0.05$).[22]

[22] Correlation is significant at the 0.05 level (2-tailed).

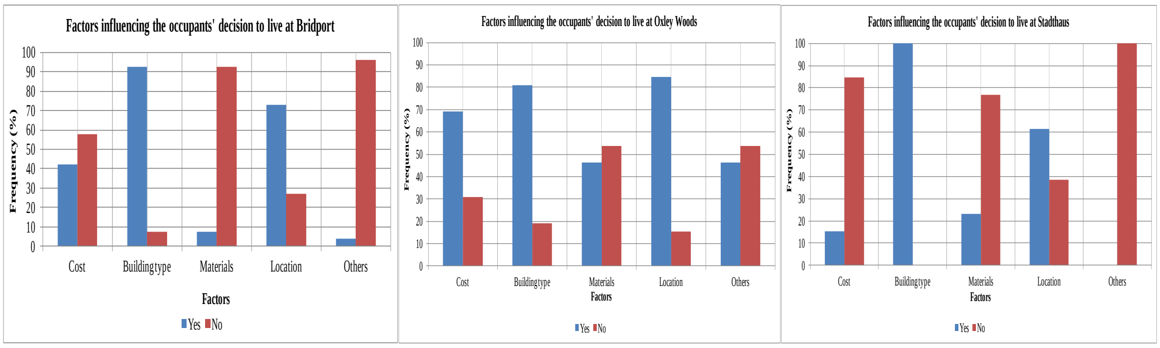

Figure 6.2: Distribution of factors influencing the occupants' choice of living at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) during the post-occupancy surveys.

6.2.2 Thermal Comfort Votes

As far as thermal conditions are concerned, there is an overwhelming response for thermal sensation in the summer period across the case studies, with 81% of the occupants feeling 'warm' or 'hot' at Bridport and Oxley and 70% at Stadthaus (Figure 6.3). However, in the winter, there is a noticeable shift of thermal sensation with more than half of the responses at either 'neutral' or 'slightly warm' part of the scale (Figure 6.4), with the mean thermal sensation focusing around neutrality (Table 6.3). A strong correlation exists between gender and thermal sensation in the summer as male occupants feel much warmer than female respondents in the summer at Stadthaus ($r=-0.551$, $p<0.05$). Also, female occupants feel cooler than male occupants at Bridport ($r=-0.529$, $p<0.05$) in the winter but no significance exists at Oxley Woods and Stadthaus. Significance is noticed between occupancy duration and thermal sensation in the winter at Stadthaus ($r=0.813$, $p<0.05$) as the occupants with a longer occupancy duration feel much warmer in the winter than the occupants with a shorter period of occupancy.

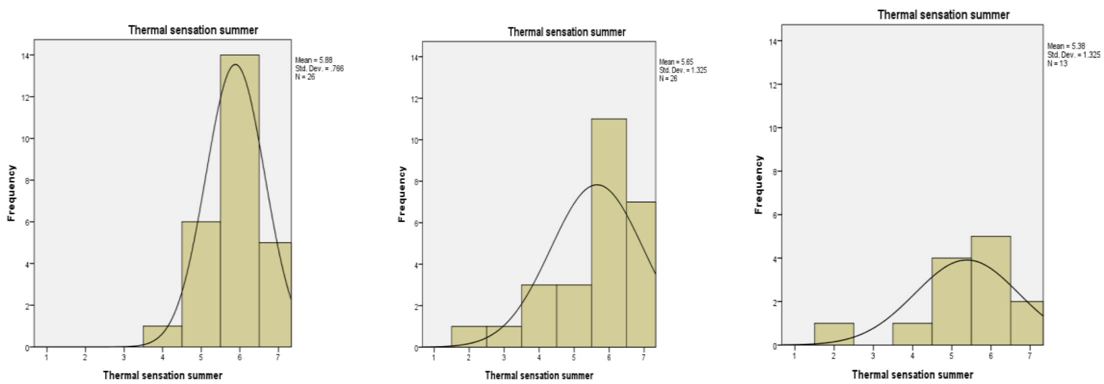

Figure 6.3: Distribution of thermal sensation votes during the summer at Bridport House (left), Oxley Woods (middle) and Stadthaus (right).

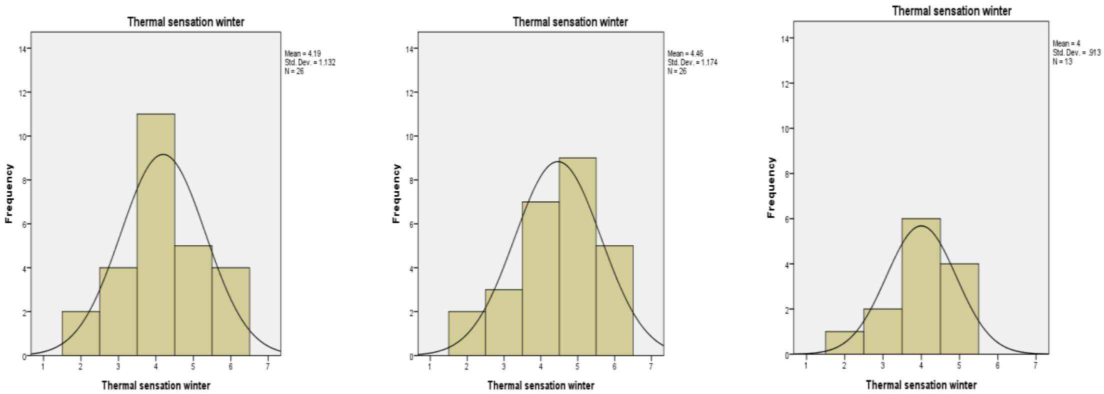

Figure 6.4: Distribution of thermal sensation votes during the winter at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) (where 1= cold, and 7 = hot).

Table 6.3: Mean responses for thermal sensations and overall thermal comfort in the summer and the winter from the post-occupancy surveys.

	Thermal sensation		Overall thermal comfort	
	Summer	Winter	Summer	Winter
Bridport House	5.58	4.19	3.35	6.04
Oxley Woods	5.65	4.46	3.85	4.58
Stadthaus	5.38	4.00	4.54	5.69

A 7-point scale (from 1 very dissatisfied to 7 very satisfied) was used for thermal satisfaction. Overall, occupants are satisfied with their thermal environment during the summer, with the lowest levels of satisfaction at Bridport (Figure 6.5). Also, the mean distribution of votes suggested that occupants are well satisfied with their thermal environment during the winter with over 80% of responses indicating levels of satisfaction across the case studies. However, the lowest level of satisfaction during the winter was observed at Oxley Woods (Figure 6.6). There is a correlation between occupancy duration and thermal satisfaction in the summer at Stadthaus ($r=0.460$, $p<0.05$) as the occupants with a longer occupancy duration indicate high levels of satisfaction in the summer than the occupants with a shorter occupancy duration. The occupants that feel warm in the summer are dissatisfied with the thermal environment of the houses at Bridport ($r=-0.806$, $p<0.05$) and Oxley Woods ($r=-0.418$, $p<0.05$) in the summer.

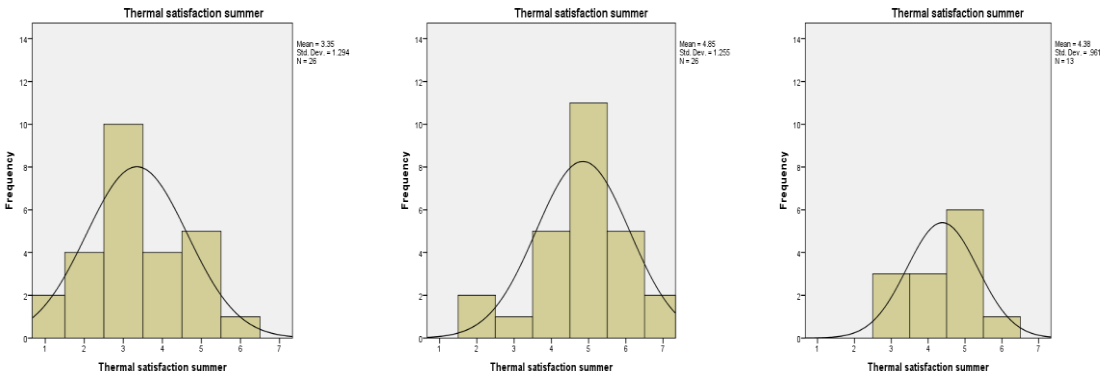

Figure 6.5: Distribution of thermal satisfaction votes during the summer at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) (from 1=very dissatisfied to 7=very satisfied).

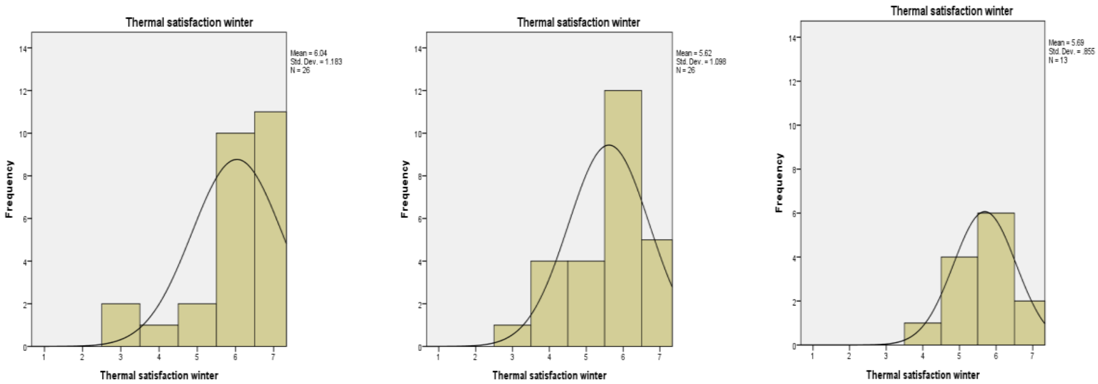

Figure 6.6: Distribution of thermal satisfaction votes during the winter at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) (from 1=very dissatisfied to 7=very satisfied).

Similarly, Bridport has the lowest evaluation for overall thermal comfort in the summer (Figure 6.7). On the contrary, in the winter, there is a noticeable shift in overall thermal comfort vote, with more than half of the responses at either ‘comfortable’ or ‘very comfortable’, and 65% of the occupants satisfied with the overall thermal comfort (Figure 6.8). Significance is found between gender and overall thermal comfort in the summer at Bridport ($r=0.446$, $p<0.05$) with male occupants having a higher mean value than female occupants. A strong correlation is noticed between occupancy duration and overall thermal comfort in the summer at Stadthaus ($r=0.845$, $p<0.05$) indicating the occupants with longer occupancy duration are more ‘comfortable’ than the occupants with shorter occupancy duration. Significance is noticed between overall thermal comfort in summer and thermal sensation in summer at Bridport ($r=-0.447$, $p<0.05$) as well as thermal satisfaction in summer at Bridport ($r=0.662$, $p<0.05$) and Stadthaus ($r=0.705$, $p<0.05$). Comparing overall thermal comfort in the winter with arrangement of the houses, significance is recorded between the variables at Oxley Woods ($r=-0.500$, $p<0.05$) as the occupants in the mid-terraced houses are more 'comfortable' within the internal spaces in the winter than the occupants living in the end-terraced houses.

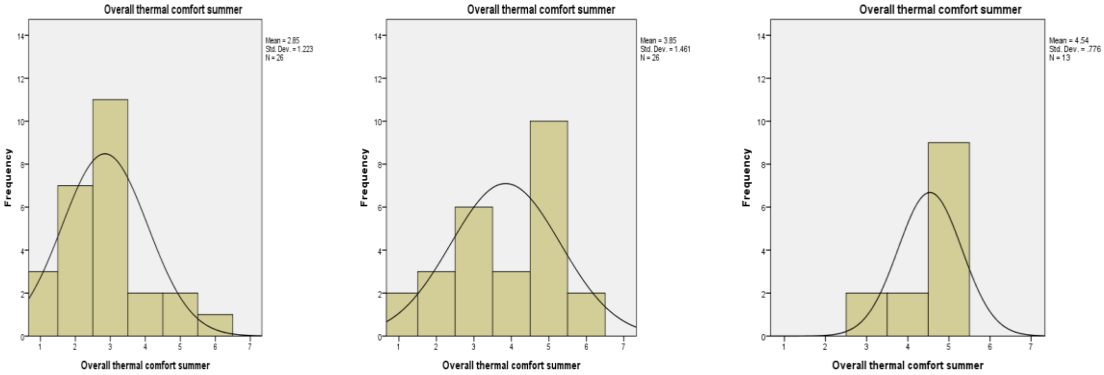

Figure 6.7: Distribution of overall thermal comfort votes during the summer at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) (Scale: 1= very uncomfortable, 7= very comfortable).

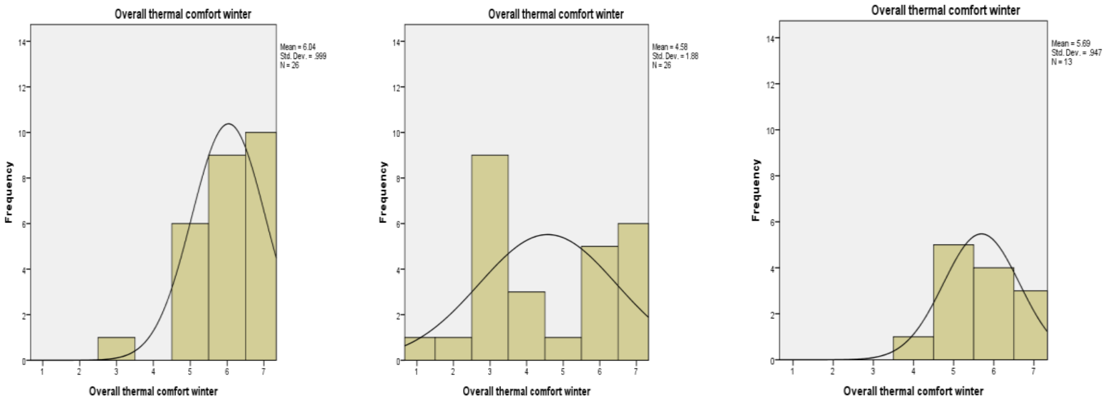

Figure 6.8: Distribution of overall thermal comfort votes during the winter at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) (Scale: 1= very uncomfortable, 7= very comfortable).

6.2.3 Control Votes

Concerning responses relating to use of control, 92% of the respondents indicate use of control to improve the thermal environment of the case studies. Likewise, 88% of the responses across the case studies mention use of window to regulate the thermal environment (Figure 6.9). However, at Bridport and Stadthaus, the results indicate low responses in use of door as control for security reasons as mentioned by the respondents during the survey while over 95% use door at Oxley Woods which is located outside London. The responses also indicate that 73% across the case studies use shading device to minimise direct heat from the sun into the indoor spaces. Significance is noticed between the use of control and thermal sensation in the summer at Bridport (r=-0.532, p<0.05) and Stadthaus (r=-0.767, p<0.05) as the occupants that did not use control to improve thermal conditions of the internal spaces feel much warmer than the occupants that use control at the two case studies in the summer. The participants were satisfied with the thermal environment at Bridport (r=0.490, p<0.05) in the summer when they use control. The occupants that use shading device were satisfied with the thermal environment at Oxley Woods (r=0.486, p<0.05) and Stadthaus (r=0.563, p<0.05) in the summer.

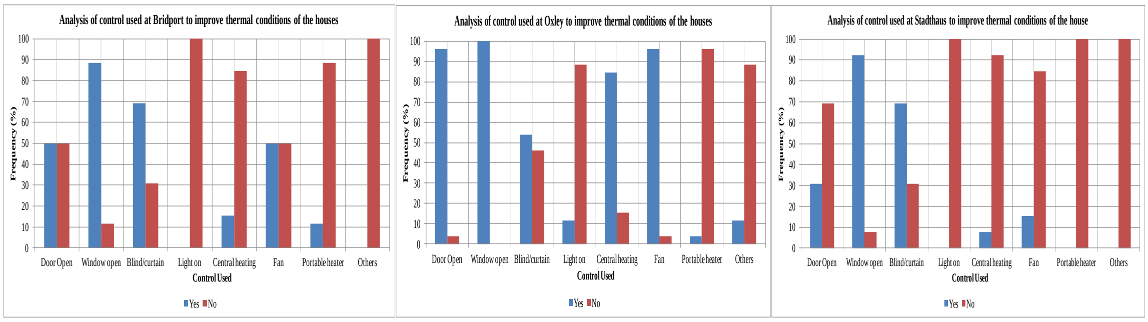

Figure 6.9: Distribution of control used at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) during the post-occupancy surveys.

Like thermal sensation scale, a 7-point scale (from 1 no control to 7 high control) was also considered for level of control. The results across the case studies show 57% responses on high level part of the scale with highest levels of control at Stadthaus, suggesting that more than half of the respondents have high levels of control to regulate the thermal environment (Figure 6.10). Significance is found between gender and level of control at Stadthaus (r=0.681, p<0.05). A strong correlation is indicated between level of control and thermal sensation in the winter at Bridport (r=-0.532, p<0.05) as the occupants that perceive high level of control feel much warmer than the occupants that indicate low level of control. The occupants that have low level of control were significantly less satisfied with the thermal condition of the indoor spaces in the summer at Bridport (r=0.555, p<0.05).

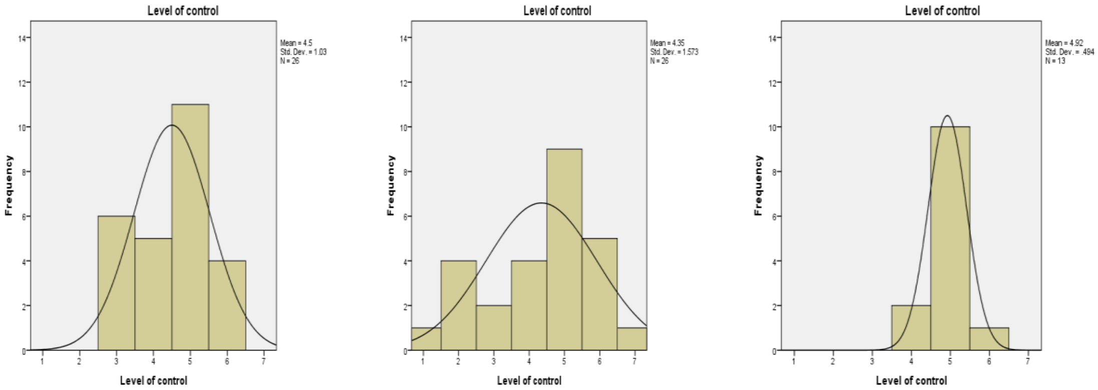

Figure 6.10: Distribution of level of control votes at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) during the post-occupancy surveys (Scale: 1= no control, 7= high control).

In addition, Stadthaus has the highest level of satisfaction for control across the case studies as more than 70% of the responses indicate control satisfaction at Bridport and Stadthaus while only 53% of the respondents are satisfied with the level of control at Oxley Woods (Figure 6.11). The occupants that use control significantly indicate satisfaction for control at Stadthaus ($r=0.801$, $p<0.05$) but no significance at Bridport and Oxley Woods. The residents that use shading device signify satisfaction for control at Oxley Woods ($r=0.387$, $p<0.05$). The occupants that indicate satisfaction for control have high levels of control at Oxley Woods ($r=0.896$, $p<0.05$) and Bridport ($r=0.321$, $p<0.05$). The respondents that indicate satisfaction for control were also satisfied with the thermal environment at Oxley Woods ($r=0.538$, $p<0.05$) in the summer. The indoor occupants that were uncomfortable with the thermal condition of the spaces in the winter were less satisfied with the level of control provided at Stadthaus ($r=0.739$, $p<0.05$). Category of the occupants that indicate satisfaction for control were less warm in the summer at Stadthaus ($r=0.669$, $p<0.05$). However, the respondents that feel much warmer in the summer indicate dissatisfaction for control at Oxley Woods ($r=-0.483$, $p<0.05$) and signify low level of control at Bridport ($r=-0.482$, $p<0.05$) and Oxley Woods ($r=-0.401$, $p<0.05$). The results suggest the occupants that feel much warmer in the summer also indicate low level of control and are dissatisfied with the level of control provided.

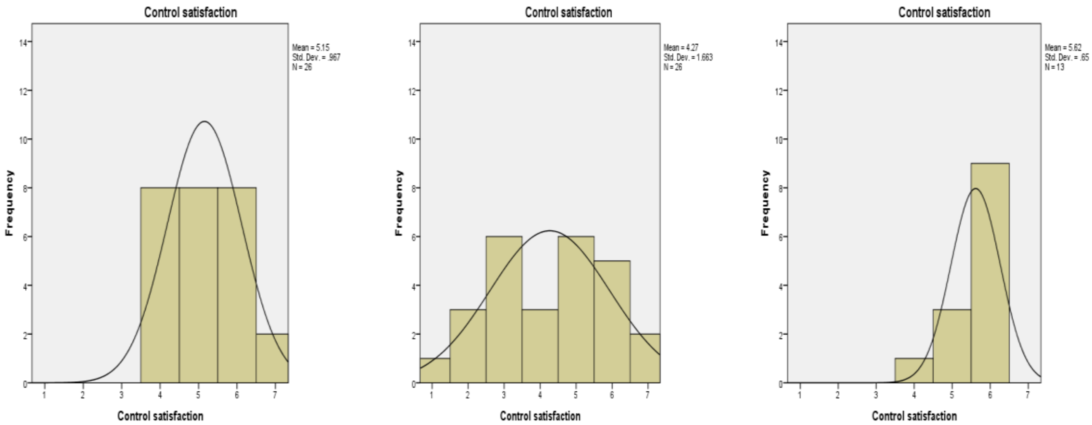

Figure 6.11: Distribution of control satisfaction votes at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) during the post-occupancy surveys (from 1= very dissatisfied, 7= very satisfied).

A 7-point scale (from 1= never to 7= regularly) was also used for frequency of control. The responses from the participants across the case studies indicate that 65% use control frequently to adjust the thermal environment (Figure 6.12). Considering the occupancy duration of the residents at Bridport, over 90% have been living at the case study for not more than 6 months at the time of the survey, suggesting they may have a limited understanding of the control provided. While majority (85%) of the residents at Oxley Woods and Stadthaus have been living at the case studies for more than 24 months suggesting a better understanding of the control provided. The occupants with a high level of control use control more often at Bridport ($r=0.288$, $p<0.05$) and Stadthaus ($r=0.619$, $p<0.05$). The respondents that use control more frequently also indicate satisfaction for control at Bridport ($r=0.563$, $p<0.05$). The occupants indicate a neutral or warm part of thermal sensation scale when they use control frequently at Bridport in the winter ($r=0.402$, $p<0.05$). The residents feel more comfortable with the thermal environment when they use control regularly at Oxley Woods ($r=0.409$, $p<0.05$) in the summer and at Bridport ($r=0.394$, $p<0.05$) in the winter. The participants that use control more often were satisfied with the thermal environment at Bridport ($r=0.469$, $p<0.05$) in the winter.

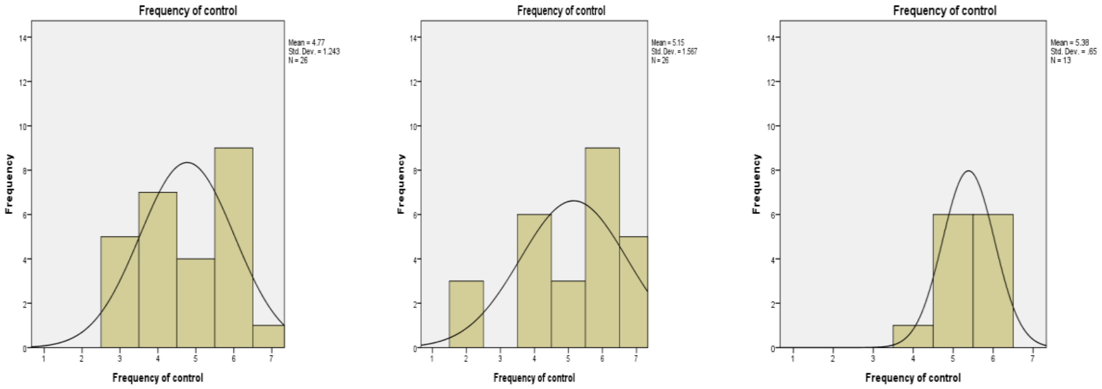

Figure 6.12: Distribution of frequency of control votes at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) during the post-occupancy surveys (from 1= never, 7= regularly).

The participants were also asked to indicate the effect of control on activity on a 7-point scale (from 1= no effect to 7= high effect). The responses across the three case studies indicate 53% at the high end of the scale with lowest levels of effect of control on activity observed at Bridport (Figure 6.13). Significance is noticed between gender and effect of control on activity at Bridport ($r=0.550$, $p<0.05$) and Stadthaus ($r=0.873$, $p<0.05$) as female occupants use control significantly to enhance their ability to carry out various activities within the indoor spaces. Correlation exists between average hours spent within the indoor spaces and effect of control on activity at Oxley Woods ($r=0.203$, $p<0.05$). The occupants with high levels of control were significantly enhanced to carry out various tasks at Oxley Woods ($r=0.607$, $p<0.05$) and Stadthaus ($r=0.801$, $p<0.05$). The residents that indicate satisfaction for control were considerably enhanced with the control provided at Oxley Woods ($r=0.573$, $p<0.05$). The occupants that feel less warm in the summer were more enhanced with the control provided at Oxley Woods ($r=0.421$, $p<0.05$). Significance is noticed between thermal satisfaction and effect of control on the occupants at Bridport ($r=0.394$, $p<0.05$), Oxley Woods ($r=0.550$, $p<0.05$) in the summer and Oxley Woods ($r=0.441$, $p<0.05$) in the winter.

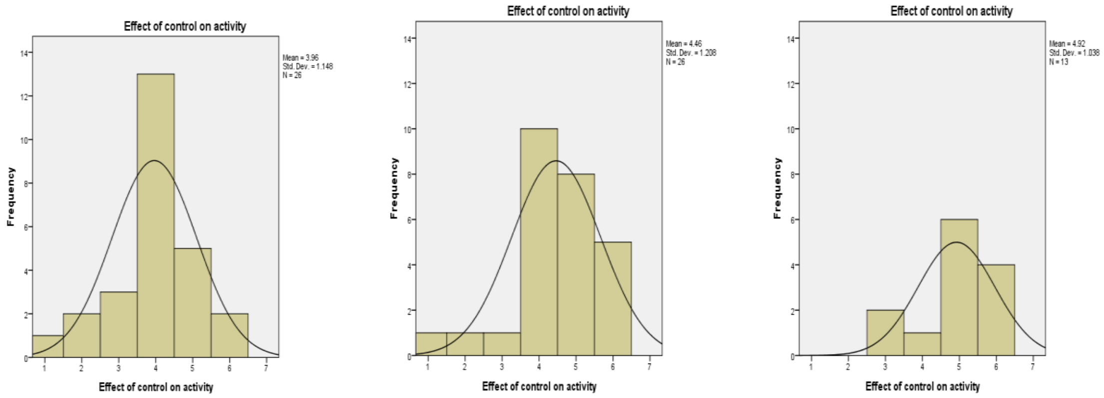

Figure 6.13: Distribution of effect of control on activity votes at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) during the post-occupancy surveys (from 1= no effect, 7= high effect).

6.2.4 Votes on Warmest Space

Occupants are likely to spend most of their time in spaces that provide the best environmental living condition (Nicol, 2008). At the three case studies, 62% of responses indicate they spent most of their time in the living areas (Figure 6.14), while 69% indicate the bedroom as the warmest space across the case studies with highest level of responses (that is, 92%) at Oxley Woods (Figure 6.15). The respondents feel much warmer in the bedrooms than the living areas at Oxley Woods ($r=0.590$, $p<0.05$) and less warm at Stadthaus ($r=-0.631$, $p<0.05$) in the summer. This may be due to difference in the floor level as the bedrooms at Oxley Woods are located in the upper floors while the bedrooms at Stadthaus are located on the same floor within the apartments. A strong correlation is found between warmest space and overall thermal comfort in the winter at Bridport ($r=-0.556$, $p<0.05$). The occupants that indicate living areas as the warmest space were significantly more satisfied with the thermal environments at Oxley Woods ($r=0.505$, $p<0.05$) and Stadthaus ($r=0.631$, $p<0.05$) in the summer as well as in the winter at Bridport ($r=-0.577$, $p<0.05$). Significance is noticed between gender and the warmest space at Bridport ($r=0.425$, $p<0.05$) as female occupants consider the bedroom as the warmest space but no significance is found between the variables at Oxley Woods and Stadthaus. Correlation also exists between the use of shading device and warmest space at Oxley Woods ($r=-0.677$, $p<0.05$) and Stadthaus ($r=-0.567$, $p<0.05$) as the occupants use shading device more often in the warmest space. The occupants that spent longer hours within the house per day stayed longer in the bedrooms at Stadthaus ($r=0.640$, $p<0.05$) and spent fewer hours in the living areas. Considering the design of Stadthaus as shown in Figures 5.19 and 5.20, the findings showed that the bedrooms are located along the northwest and the northeast orientations. While most of the bedrooms at Bridport and Oxley Woods are located in different orientations such as south, southeast, east, and southwest orientations. The design implication suggests that orientation may likely influence the occupants to spend more hours in the bedrooms at Stadthaus. Also, the overall urban built form may likely influence the occupants at Stadthaus to spend more hours in the bedrooms as the adjacent buildings (such as blocks of flats) are located at different orientations (east, south and west orientations) around the building. The arrangement of the adjacent buildings may contribute to overshadowing at the lower floors at Stadthaus and likely influence the occupants to spend more hours in the bedrooms. The respondents indicate less satisfaction for control in the warmest space at Bridport (r=-0.407, p<0.05).

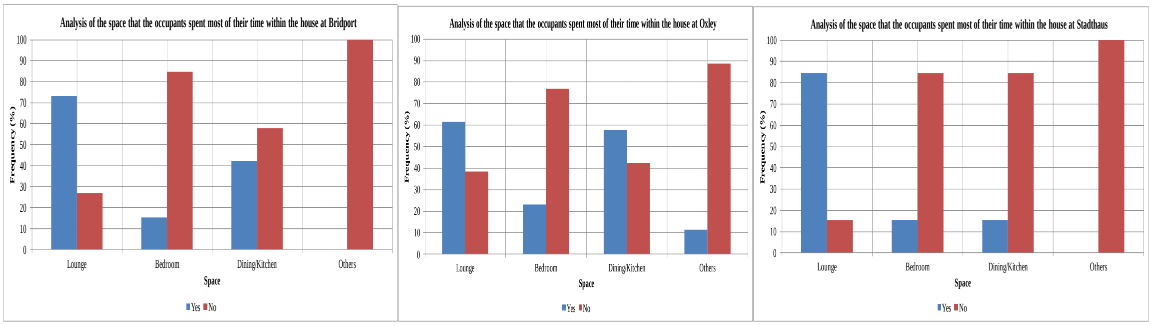

Figure 6.14: Distribution of space with highest time spent votes at Bridport (left), Oxley Woods (middle) and Stadthaus (right) during the post-occupancy surveys.

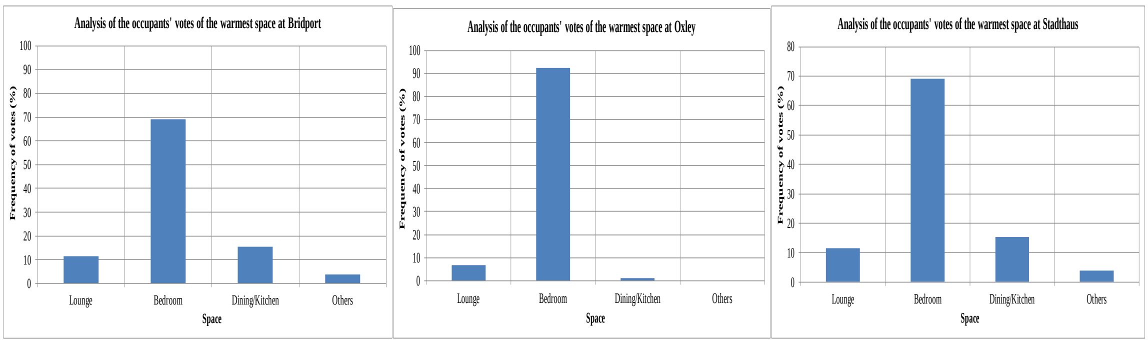

Figure 6.15: Distribution of the warmest space votes at Bridport (left), Oxley Woods (middle) and Stadthaus (right) during the post-occupancy surveys.

6.2.5 Pleasant Experience Votes

The respondents were asked to rate their experience (from 1= very unpleasant to 7= very pleasant) at the case studies. The results suggest 57% are pleased with their experience at Bridport while there is a noticeable shift from ‘neutral’ part of the scale to ‘pleasant’ part of the scale at Oxley Woods and Stadthaus suggesting over 77% are pleased with their experience as the occupants of the two case studies (Figure 6.16). The respondents with high level of control were significantly pleased with their experience at Bridport (r=0.637, p<0.05). The respondents that indicate satisfaction for control were considerably pleased with the experience at Bridport (r=0.598, p<0.05). At Bridport, the residents that use control more often were pleased with their experience as occupants of the building (r=0.454, p<0.05). Significance is noticed between average hours spent within the indoor spaces per day and pleasant experience at Bridport (r=-0.446, p<0.05). There is a correlation between pleasant experience and thermal sensation in the summer at Bridport (r=-0.488, p<0.05) as well as at Bridport (r=-0.443, p<0.05) and Oxley Woods (r=-0.442, p<0.05) in the winter. The occupants that were satisfied with the thermal environment in the summer at Bridport (r=0.638, p<0.05) and Oxley Woods (r=-0.413, p<0.05) are pleased with their experience at the buildings. There are possibilities that shorter occupancy duration of the respondents, type of occupancy and level of control at Bridport are contributing to less satisfaction due to limited understanding of the building and how to improve the thermal environment. The findings suggest significance is noticed between occupancy type and overall thermal comfort in the summer at Stadthaus (r=0.845, p<0.05); occupancy type and level of control at Stadthaus (r=0.656, p<0.05); occupancy type and effect of control on activity at Oxley Woods (r=0.416, p<0.05). Significance is also recorded between occupancy duration and overall thermal comfort in winter at Oxley Woods (r=-0.454, p<0.05); and occupancy duration and thermal sensation in winter at Stadthaus (r=0.813, p<0.05).

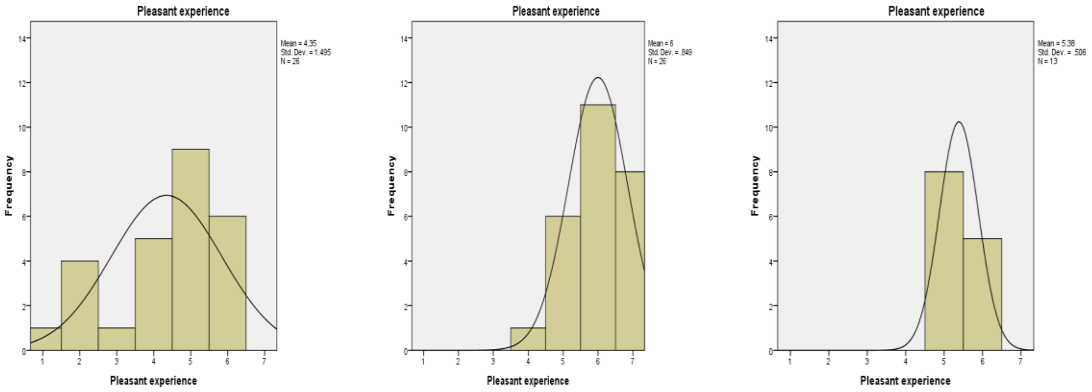

Figure 6.16: Distribution of pleasant experience at Bridport House (left), Oxley Woods (middle) and Stadthaus (right) (from 1= very unpleasant, 7= very pleasant).

Additional information on performance of a building helps to understand if the building meets the need of its occupants and allows for necessary improvement that can be made on the future design which can be gathered during post-occupancy survey (Riley *et al.*, 2007). The participants were asked to provide additional comments on any aspect of the indoor environment to further understand performance of the case studies. The findings suggest that majority of the occupants at Oxley Woods feel much warmer in the upper floors during the summer while they feel warm and nice in the ground floors. At Bridport and Stadthaus, the respondents feel warmer in the upper floors than the lower floors. Also, the occupants at Oxley Woods and Stadthaus indicate preference for more windows that can be manually operated for natural ventilation while at Oxley Woods, the residents mention change of wooden frame windows to reduce noise when windows are left open or closed. Across the case studies, the residents suggest need for retractable external shading to reduce direct sunlight in the summer. The residents at Oxley Woods prefer installation of the control regulator in the ground floors while at Bridport and Stadthaus, the thermostats are located on the same floor. At Bridport, the residents mention cross-ventilation for the bedrooms while most of the bedrooms at Oxley Woods and Stadthaus are cross-ventilated. However, the higher floor-to-ceiling height of the bedrooms and large windows are likely to improve internal condition of the indoor spaces at Bridport. The results from environmental monitoring and dynamic thermal simulations will help to understand if the parameters improve the internal conditions of the spaces at Bridport when compared to the indoor spaces at Oxley Woods and Stadthaus.

6.3 Environmental Monitoring Surveys

A breakdown of the surveys in the summer and the winter indicates four living rooms and six bedrooms monitored at Oxley Woods. At Bridport, physical measurements were carried out only in the summer and the internal spaces monitored are analysed below. The external weather data collected from London City Airport for Bridport and from Luton Airport for Oxley Woods will be discussed in this section. The monitoring period in the summer at Oxley Woods was warmer than the survey period at Bridport. The maximum and minimum internal and external temperatures measured during the summer and the winter surveys will be analysed.

6.3.1 Analysis of Environmental Monitoring Surveys

Throughout the monitoring period in the summer, the external temperature at Bridport varied from 11ºC (the minimum temperature) on the 12th July, 2012 to a peak of 23.5ºC (the maximum temperature) on the 5th of July, 2102 (Figure 6.17); while the external temperature at Oxley Woods varied from 8ºC (the minimum temperature) on the 30th of July, 2012 to a peak of 27.5ºC (the maximum temperature) on the 24th of July, 2012 (Figure 6.18). The beginning of the monitoring period at the case studies (Bridport and Oxley Woods) was considered to be wet and mild. Starting from the 4th of July, 2012 the average daily temperature rose above 19.2ºC for two consecutive days at Bridport while beginning from the 23rd of July, 2012 the average daily temperature exceeded 19.2ºC for four successive days reaching 21.2ºC on the 25th of July, 2012 at Oxley Woods but reducing back to 18.3ºC on the 27th of July, 2012. This is considered along with the findings from epidemiology, with the external temperature rising above 19ºC providing a critical threshold, for increased mortality (Hajat *et al.*, 2002). The average daily temperature for the remaining days during the monitoring period was below 19ºC at both locations of the case studies. The external temperature during the two days at Bridport did not rise above 25ºC; while the external temperature during the four successive days at Oxley Woods rose above 25ºC for 25 hours, with the 24th and the 25th of July, 2012 having 8 hours each over 25ºC.

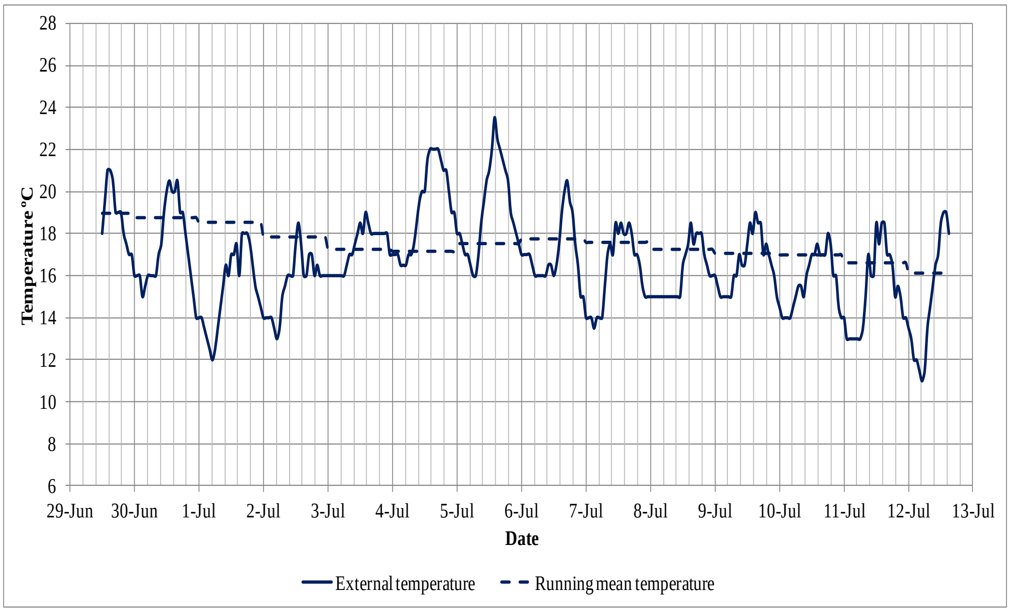

Figure 6.17: External temperature and running mean of daily average temperature during the monitoring period in the summer at Bridport House.

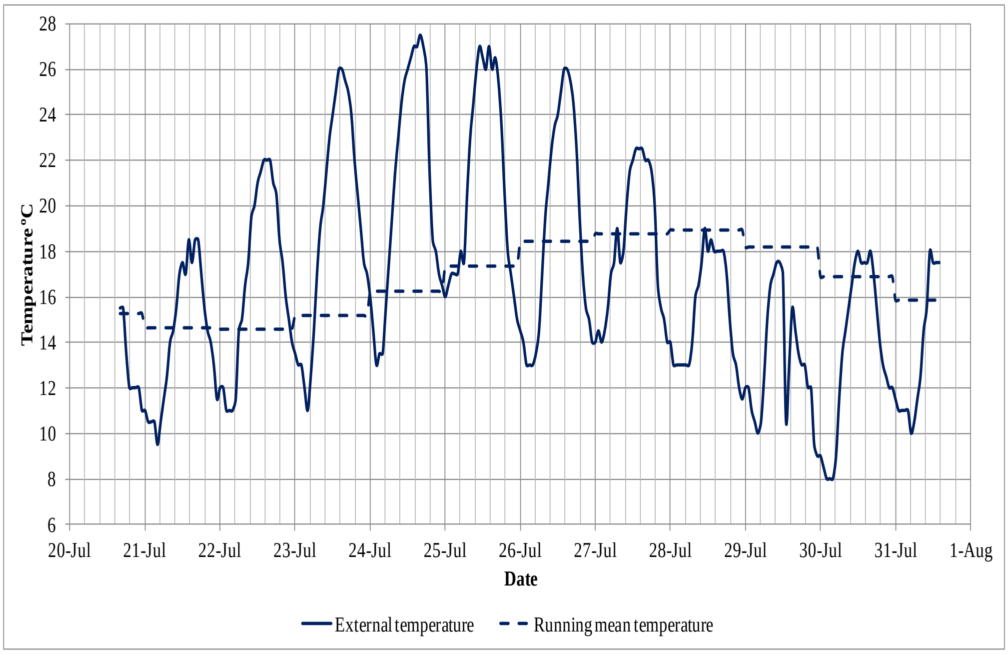

Figure 6.18: External temperature and running mean of daily average temperature during the monitoring period in the summer at Oxley Woods.

The running mean temperature of the measured external temperature, T_{rm}[23], (Figure 6.17 and Figure 6.18) as defined in BSEN15251 (BSI, 2008) reached 19ºC on the 29th of June, 2012 at Bridport and 19ºC on the 28th of July, 2012 at Oxley Woods. The average running mean temperature during the monitoring period was 17.5ºC at Bridport and 16.8 at Oxley Woods. The results suggest that the overall monitored period was greatly cooler than normal for the time of the year when compared to the hottest month (August) in 2012 with the average monthly temperatures of 23ºC and 22.5ºC recorded in London and Luton respectively. The running mean temperatures, T_{rm}, throughout the monitoring period rose above 16ºC for 100% of the time and 18ºC for 19% of the time at Bridport compared with the T_{rm} value at Oxley Woods which exceeded 16ºC for 64% and 18ºC for 37% respectively.

The average indoor temperature in all the spaces monitored at Bridport during the summer was between 21.3ºC and 23.7ºC (a difference of 2.4ºC) while the average indoor temperature in all the spaces measured at Oxley Woods varied from 22.4ºC to 25.7ºC (a difference of 3.3ºC). The overall average of the spaces monitored at Bridport and Oxley

[23] Running mean temperature (Trm): is described 'as an exponentially weighted running mean of the daily average external air temperature' and it is computed using the formula: Trm = (1-α).{tod-1 + α.tod-2 + α2tod-3…..}.

Woods were 22.6ºC and 23.9ºC respectively. In all the living areas monitored at Bridport, the average temperature between 08:00-22:00 was 22ºC, with the hottest living room (FL35SFL)[24] having a mean of 23.8ºC and a maximum of 25.4ºC. The coolest living area (FL1GFL) indicated a mean temperature of 23.2ºC and a peak temperature of 24.6ºC (Figure 6.19). At Oxley Woods, the average temperature between 08:00-22:00 in all the living areas monitored was 23.7ºC, with a mean temperature of 24.2ºC recorded in the hottest living room (A1WLGFL)[25] and a maximum of 30ºC (Figure 6.20) while the average temperature of 22.8ºC and a peak of 28ºC was recorded in A142HAGFL (Figure 6.21).

Taking into consideration the period between 18:00-22:00, the average temperature in all the living areas monitored at Bridport was 23.5ºC. At Oxley Woods, the mean temperature in all the living rooms measured between 18:00-22:00 was 24ºC. The mean temperatures between 18:00-22:00 at the hottest living room monitored at Bridport and Oxley Woods were 23.8ºC and 24.5ºC respectively. The hottest living area (FL35SFL) at Bridport indicated a peak of 24.5ºC while a maximum temperature of 29.6ºC was measured in the hottest living room (A1WLGFL) at Oxley Woods. The analysis suggests that the mean temperature in the living rooms monitored at Oxley Woods is moderately higher than the average temperature in the living rooms measured at Bridport for the period between 08:00-22:00 and 18:00-22:00 during the summer surveys.

For the period between 23:00-07:00, the average indoor temperature in all the bedrooms monitored at Bridport during the summer was 21.8ºC while the average indoor temperature of 23.1ºC was recorded at Oxley Woods in all the bedrooms monitored. The mean temperature in the hottest bedroom (FL1FFB) at Bridport was 22.3ºC and a peak temperature of 24.7ºC. At Oxley Woods, the average temperature for the hottest bedroom (A162HAFFBB) was 25.7ºC and a maximum temperature of 30.5ºC. Also, high temperatures were recorded in all the bedrooms monitored at Oxley Woods between 23:00-07:00 (Figure 6.21). The analysis suggests that the mean temperature of the

[24] FL35SFL (Flat 35 second floor living area- the sensor was placed at the west facing), FL1GFL (Flat 1 ground floor living area- the sensor was located at the south facing), FL1FFB (Flat 1 first floor bedroom- the sensor was placed at the southwest facing).

[25]A1WLGFL (A1 Welles ground floor living area- the data logger was located at the southwest facing), A142HAGFL (A142 Holden ground floor living area- the sensor was placed at the southwest facing), A162HAFFBB (A162 Holden first floor back bedroom- the data logger was placed at the southeast facing).

bedrooms monitored between 23:00-07:00 at Oxley Woods during the summer is higher than the mean temperature of the bedrooms measured at Bridport. Moreover, the apartments monitored at Bridport are located at the lower floors (the ground floor, the first floor and the second floor) while the houses monitored at Oxley Woods are 2-storey and 3-storey with a tendency for higher solar radiation into the internal spaces at Oxley Woods than Bridport. Furthermore, the internal spaces at Bridport are bigger in terms of floor area and floor-to-ceiling height than the internal spaces at Oxley Woods and the parameters may influence overall temperature of the spaces. However, further analysis will be carried out and will be discussed in Chapter 7.

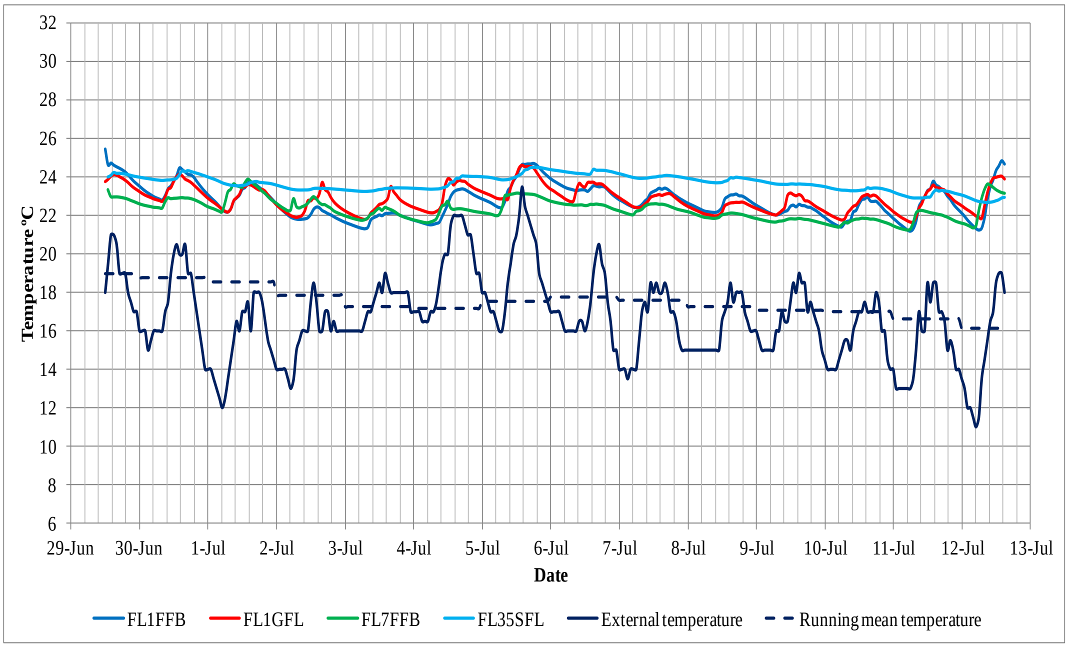

Figure 6.19: The living rooms and the bedrooms monitored in different flats at Bridport in the summer.[26]

[26] The data loggers were placed in the spaces monitored at Bridport as follow: FL1FFB- southwest facing, FL1GFL- south facing, FL7FFB- east facing, FL35SFL- west facing.

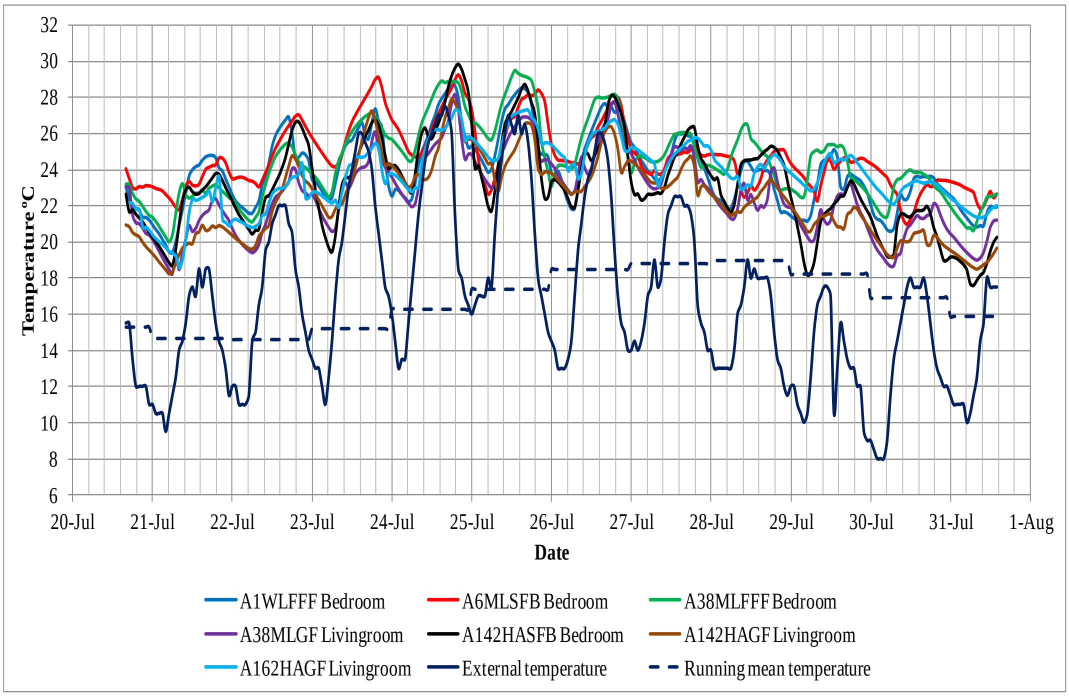

Figure 6.20: The living rooms and the bedrooms monitored in the five houses at Oxley Woods in the summer.[27]

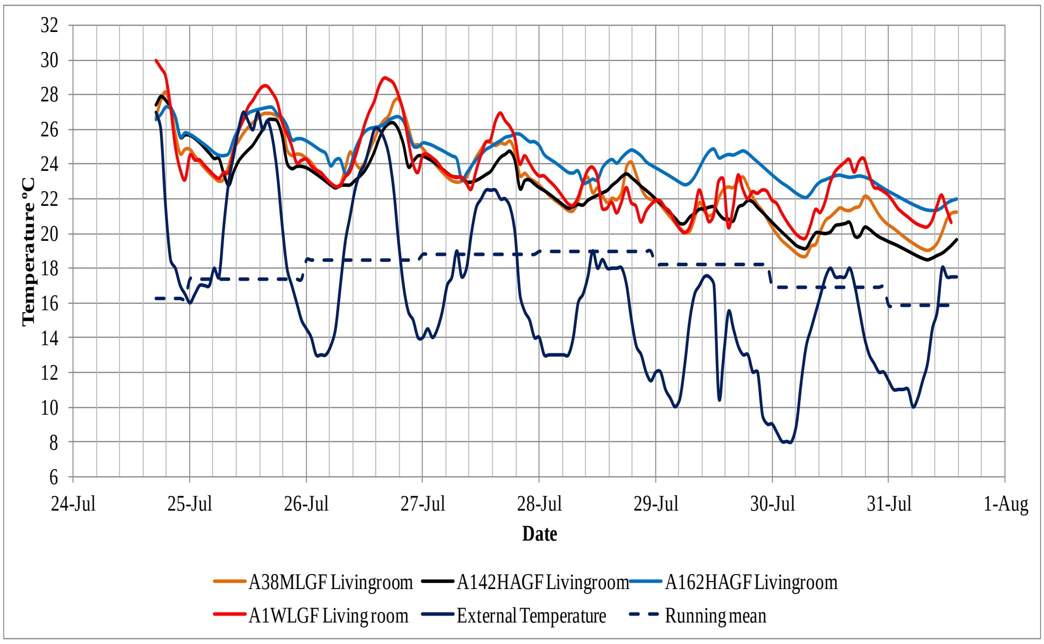

Figure 6.21: Living rooms monitored in different houses at Oxley Woods between 24th and 31st July, 2012.[28]

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[27] The sensors were placed in the spaces monitored at Oxley Woods as follow: A1WLFFF Bedroom- southeast facing, A6MLSFB Bedroom- northwest facing, A38MLFFF Bedroom- southeast facing, A38MLGF Living room- northeast facing, A142HASFB Bedroom- southeast facing, A142HAGF Living room- southwest facing, A162HAGF Living room- north facing.

The winter survey carried out at Oxley Woods suggests the external temperature varied from -1ºC on the 2nd of February, 2013 for six hours and on the 7th of Februrary, 2013 for three hours to a peak of 13ºC on the 29th of January, 2013 for five hours. The average external temperature throughout the monitoring period was 5.1ºC. The running mean temperature of the observed external temperature, T_{rm}, as stated in the thermal comfort standards (BSEN15251) recorded a minimum of 1.7ºC on the 8th of February, 2013 and reached a peak of 8.7ºC on the 30th of January, 2013 for 12 hours (Figure 6.22). The average running mean temperature during the winter survey was 5.5ºC. The analysis suggests that the overall monitored period in the winter was much warmer than the coldest month (March) in 2013 with the average monthly temperature of 2.2ºC observed in London and 2ºC recorded in Luton. The findings also show that the period of the winter survey was significantly cooler when compared to the period of the summer survey at the case study. The running mean temperatures, T_{rm}, during the monitoring period did not rise above 16ºC at anytime. The analysis also suggests the period of the winter survey at Oxley Woods did not experience high external temperatures which can significantly increase the internal temperatures of the spaces monitored.

Regarding the internal spaces monitored during the winter survey, the average indoor temperature varied from 17ºC to 19.6ºC (Figure 6.22). For all the living areas monitored, the mean temperature between 08:00-22:00 varied from 18.5ºC to 20.2ºC. The warmest living area (A142HAGFL) indicated a maximum temperature of 22.7ºC between 08:00-22:00 at A142HAGFL and a minimum temperature of 12.7ºC. The results suggest that the internal temperature in the living areas monitored during the winter survey did not rise above 25ºC at anytime. Likewise, for all the bedrooms monitored, the average temperature between 23:00-07:00 indicate a range from 16.5ºC to 19.3ºC. In the warmest bedroom (A1WLFFFB), a peak temperature of 22.8ºC was recorded and a minimum of 17.7ºC. The internal temperature of the bedrooms monitored in the winter did not rise more than 24ºC throughout the period of the survey.

[28] The data loggers were positioned in the spaces monitored at Oxley Woods as follow: A38MLGF Living room- northeast, A1WLGF Living room- southwest facing, A142HAGF Living room- southwest facing, A162HAGF Living room- north facing.

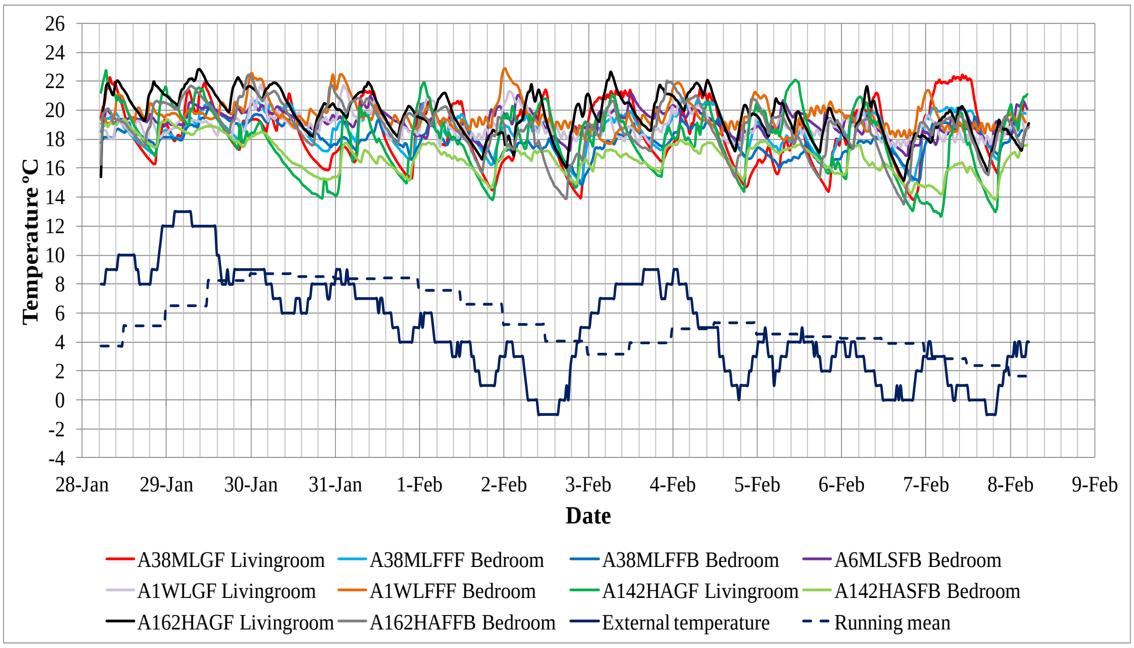

Figure 6.22: The livingrooms and the bedrooms monitored in the five houses at Oxley Woods in the winter.[29]

Concerning the indoor relative humidity monitored at the case studies during the summer, the findings showed the relative humidity was within the comfort range of 40% - 60%. The average relative humidity at Bridport indicates a range of 49.9%-60.1% while at Oxley Woods from 41.5% to 47.2%. In winter, the mean value of indoor relative humidity at Oxley Woods varied from 32.1% to 48.5%. The analysis suggests difference between the ranges of average relative humidity of the spaces monitored at Oxley Woods during the winter (January to February, 2013) was higher (16.4%) when compared to the difference between the ranges of mean value of relative humidity (5.7%) in the summer (June to July, 2012). The indoor relative humidity was moderately higher in all the spaces monitored at Bridport than the spaces monitored at Oxley Woods throughout the monitoring period in the summer.

6.3.2 Analysis of Opening and Closed Sessions of the Windows at Oxley Woods

Low-density houses with a good security located far from source of noise with windows open for more than 50% of the time can significantly improve the thermal environment of

[29] The sensors were positioned in the spaces monitored at Oxley Woods as follow: A1WLFFF Bedroom- southeast facing, A6MLSFB Bedroom- northwest facing, A38MLFFF Bedroom- southeast facing, A38MLGF Living room- northeast facing, A38MLFFB Bedroom- northeast facing, A142HASFB Bedroom- southeast facing, A142HAGF Living room- southwest facing, A162HAGF Living room- north facing, A162HAFFB Bedroom- southeast facing, A1WLGF Living room- southwest facing.

the internal spaces in summer (DCLG 2012b, p.10). Also, indoor occupants that regularly use windows instead of mechanical ventilation are likely to reduce energy required for cooling (Macintosh & Steemers, 2005) and therefore improve overall performance of dwellings (Rijal & Stevenson, 2010). The findings from the window opening sessions at Oxley Woods in the summer show that the windows of the ground and the upper floors' spaces (A38MLGFL, A38MLFFFB, A38MLFFBB)[30] of the houses located along the outer streets of the development were closed for more than 50% of the time for security and to reduce noise from the high street while the windows were left open for a short period of time during the day (Figures 6.23 and 6.24). The window opening sessions were also influenced by an increase in the internal temperature of the spaces which was mainly caused by a change in the external temperature. The windows of the spaces in the ground and the upper floors of the houses (A142HAGFL, A142HASFBB, A1WLFFFB)[31] located along the inner and the other streets with less traffic were left open for more than 50% of the time in the summer (Figures 6.25 and 6.26). The percentage of window opening sessions in the houses located far from the high street and the spaces located on the upper floors were considerably higher when compared to window opening sessions of the houses along the high street and the spaces in the ground floors. In winter, the windows were not open for most of the time throughout the monitoring period to reduce heat loss and improve the internal condition of the houses as the external temperature was constantly low during the survey.

[30] A38MGFL (A38 Milland ground floor living area- the sensor was positioned at the northeast orientation), A38MLFFFB (A38 Milland first floor front bedroom- the data logger was placed at the southeast orientation), A38MLFFBB (A38 Milland first floor back bedroom- the sensor was placed at northeast orientation).

[31] A142HAGFL (A142 Holden ground floor living area- the data logger was placed at the southwest orientation), A142HASFBB (A142 Holden second floor back bedroom- the sensor was positioned at the southeast orientation), A1WLFFFB (A1 Welles first floor front bedroom- the sensor was placed at the southeast orientation).

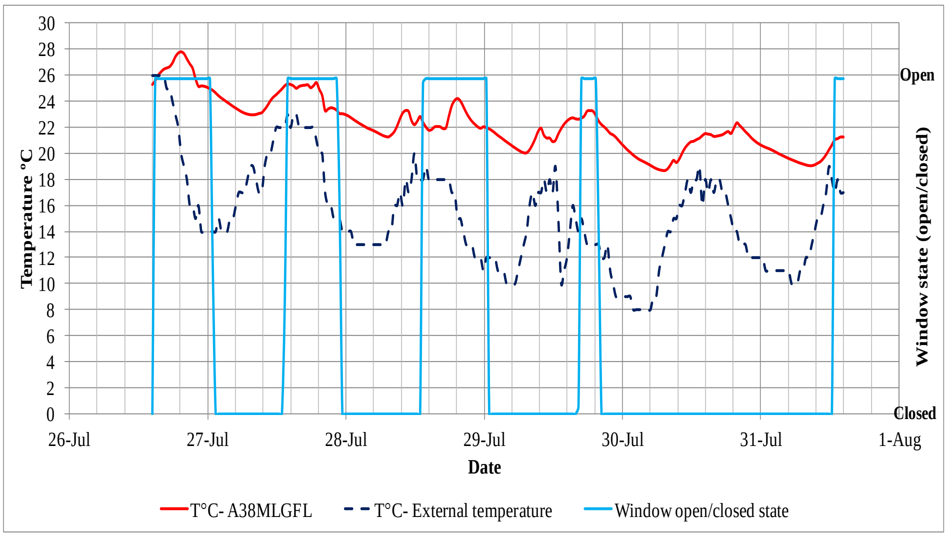

Figure 6.23: Window opening and closed sessions in A38MLGFL located in the ground floor along the high street at Oxley Woods during the summer.

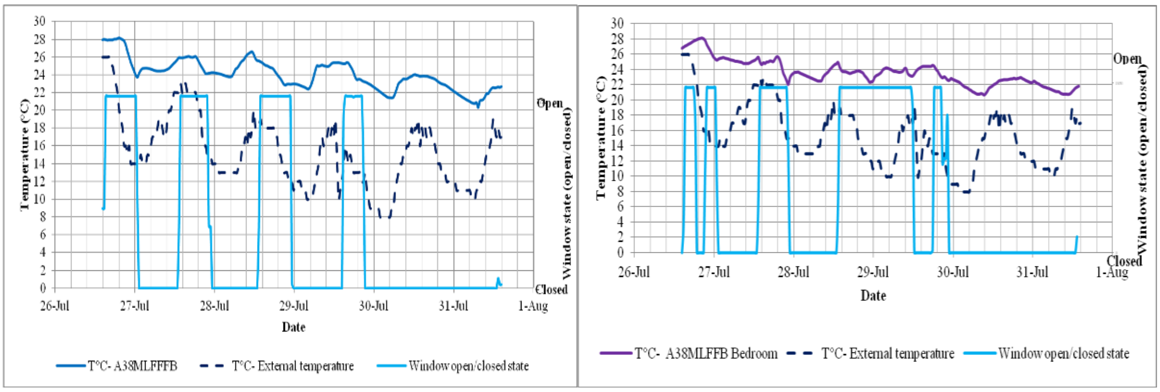

Figure 6.24: Window opening and closed sessions in A38MLFFFB and A38MLFFBB located in the upper floor along the high street at Oxley Woods during the summer.

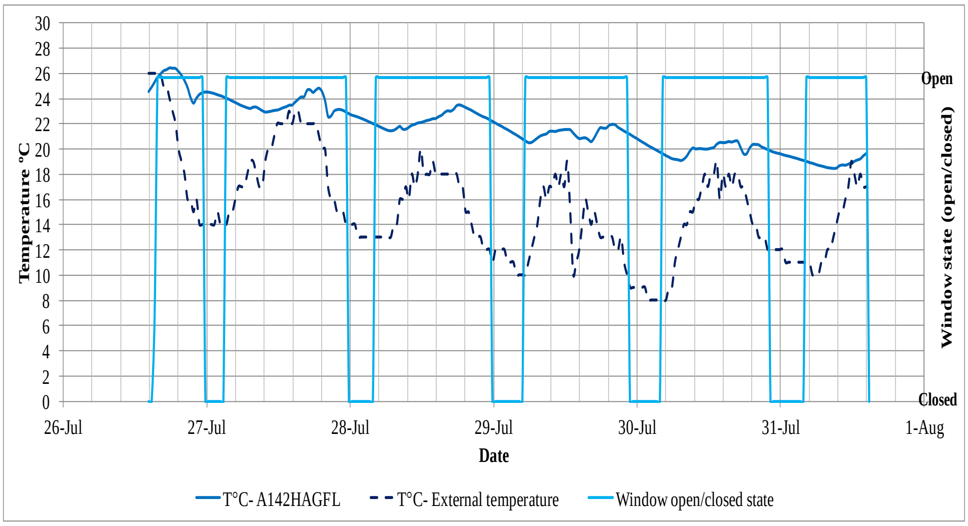

Figure 6.25: Window opening and closed sessions monitored in A142HAGFL (rear window) located in the ground floor along one of the quiet streets at Oxley Woods during the summer.

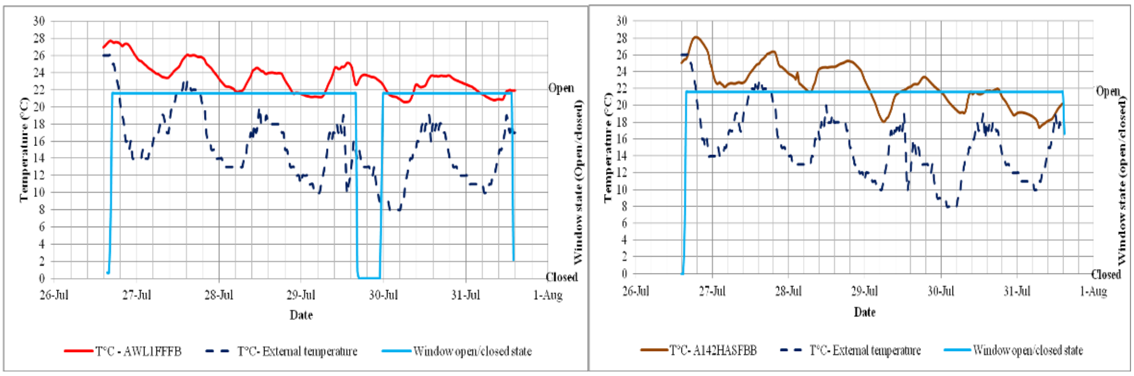

Figure 6.26: Window opening and closed sessions monitored in AWL1FFB and A142HASFBB located in the upper floors along the inner street and the street with less traffic at Oxley Woods during the summer.

6.4 Comfort Surveys

Subjective questionnaires were also administered throughout the monitoring period to the occupants of the flats monitored at Bridport and the houses monitored at Oxley Woods. As discussed in Chapter 4, a total of 141 and 106 administered questionnaires were returned during the summer and the winter surveys respectively. In all, 93 male (66%) and 48 female (34%) responses were received in the summer; while in the winter there were 58 male (55%) and 48 female (45%) responses. Table 6.4 below summarises frequency and percentage of gender distribution of responses from the two case studies during the comfort surveys in the summer.

Table 6.4: Gender distribution of responses from the case studies during the summer

	Gender distribution of responses (frequency)		Gender distribution of responses (percentage)	
Case Study	Male	Female	Male (%)	Female (%)
Bridport House	46	5	90	10
Oxley Woods	47	43	52	48

6.4.1 Analysis of Comfort Surveys

The responses on age distribution of the participants during the summer and the winter comfort surveys indicate that 98% are above 30 years. The analysis suggests the respondents have the ability to understand the thermal environment and vote accordingly. When compared, the results of the post-occupancy surveys suggest that over 75% of the participants are above 30 years with over 64% and 62% of the subjective questionnaires administered in the afternoon and at the evening during the summer and the winter surveys respectively.

6.4.2 Thermal Comfort Votes

The analysis of the comfort surveys on thermal sensation (Figures 6.27 and 6.28) shows a distribution clustered around the central categories with more than half of the responses feeling ‘comfortably warm’ with a moderately even distribution of votes varying between ‘neither cool or warm’ and ‘slightly warm’ in the summer. The results suggest that only 38% feel ‘warm’ at Oxley Woods while 75% feel ‘warm’ at Bridport during the summer (Figure 6.27), despite the external temperatures were higher during the surveys in Oxley Woods.

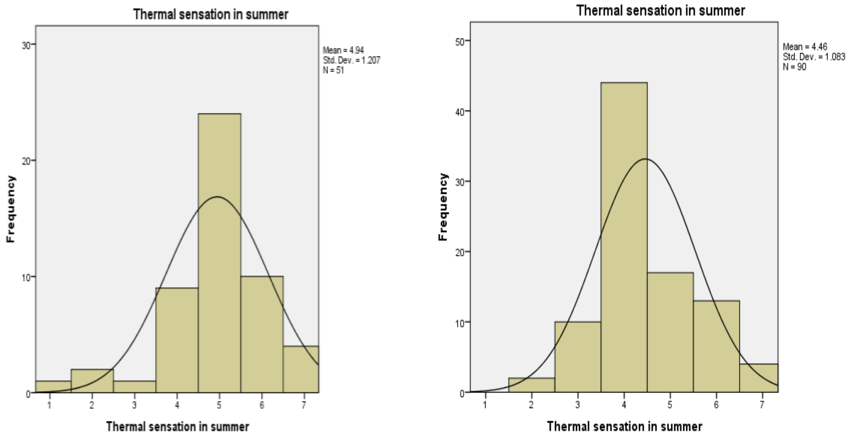

Figure 6.27: Distribution of thermal sensation votes at Bridport (left) and Oxley Woods (right) in the summer (1= cold, to 7= hot).

The mean distribution of thermal sensation votes in the winter showed a drift towards ‘neutral’ with more than 87% responses indicating ‘slightly cool’, ‘neutral’ and ‘slightly warm’. Linking the results with those of the post occupancy surveys suggested that 75% of the occupants at Oxley Woods are also generally satisfied with how they feel in the winter (Figure 6.28).

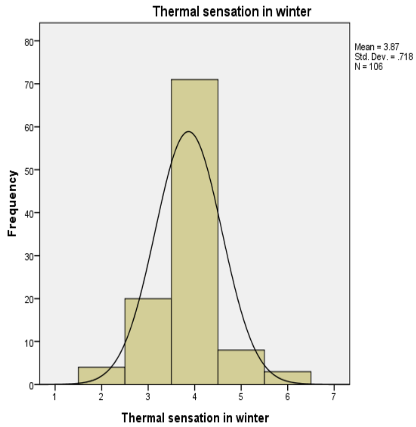

Figure 6.28: Distribution of thermal sensation votes at Oxley Woods in the winter (1= cold, to 7= hot).

Further analysis highlights that majority of the occupants at Oxley Woods have lived in the houses between 19 and 36 months while over 90% of the residents owning the properties and majority of the residents spent more hours in the house per day. This suggests they have a better understanding of how to adapt to their indoor environment when compared to the occupants at Bridport, who have lived in the building for six months at the time of the survey.

In some of the spaces monitored (A1WLGFL, A6MLSFBB, A38MLFFFB, A162HAGFL and A162HAFFBB) at Oxley Woods, more than 20% of the recorded temperatures were above the comfort range (22-25ºC).

Regression analysis to test the relationship between the internal temperature and the external temperature suggests that the internal temperature of the spaces monitored at Oxley tend to rise above 25ºC when the external temperature rose above 19ºC which is an indicator for increased mortality in the summer as mentioned by Hajat, *et al.* (2002); while the average internal temperature was within the comfort range (23.2ºC) at Bridport when the temperature rose above 19ºC (Figure 6.29). In the winter, the indoor temperature was within the comfort range at Oxley Woods with a difference over 2.6ºC between the internal temperature in the summer and the winter (Figure 6.30). The analysis shows that comfort is within a range of 2.7ºC at Bridport while it is within a range of 6.3ºC at Oxley Woods in the summer.

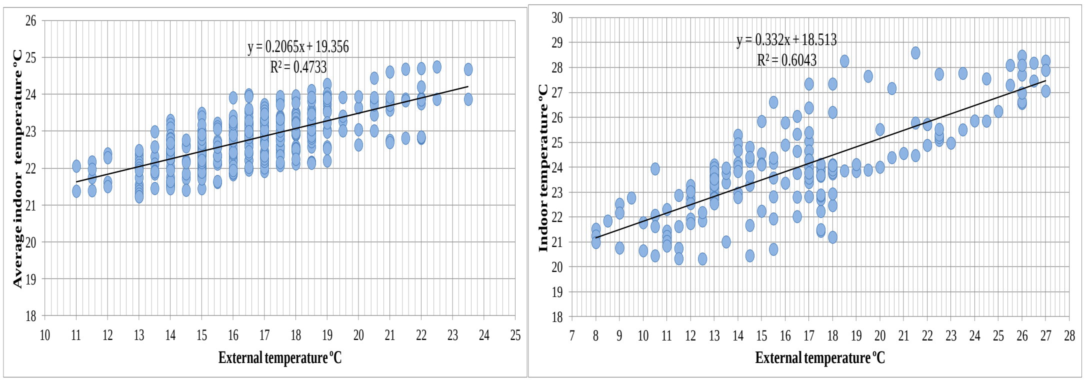

Figure 6.29: Relationship between the internal temperature and the external temperature at Bridport (left) Oxley Woods (right) in the summer.

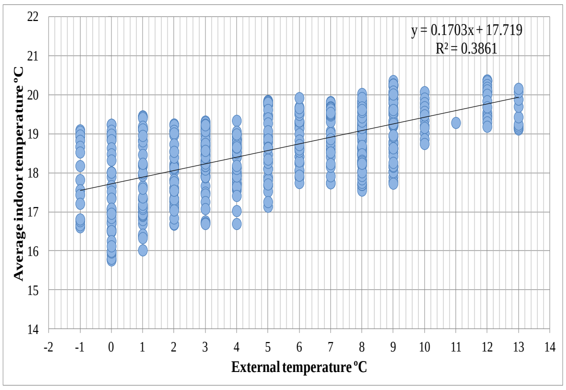

Figure 6.30: Relationship between the internal temperature and the external temperature at Oxley Woods in the winter.

The findings from the test to understand the relationship between the average indoor temperature in the living areas and the bedrooms monitored at Bridport and the external temperature suggest the mean internal temperature of 23.8ºC for all the living areas and 23.1ºC for all the bedrooms when the external temperature was 19ºC in the summer. Also, the mean internal temperatures in the living areas and the bedrooms monitored at Oxley Woods were 24ºC and 25.2ºC (Figure 6.31). The analysis shows a difference of 0.6ºC between the average internal temperature of the living areas and the bedrooms at the beginning of the monitoring period at Bridport and a difference of 1ºC towards the end of the survey in the summer. At Oxley Woods, the difference between the living areas and the bedrooms was 0.8ºC at the start of the summer survey and a difference of 1.4ºC was noticed towards the end of the monitoring period due to a change in the external temperature. The analysis suggests that the bedrooms are much warmer than the living rooms at Oxley Woods while the living areas are warmer than the bedrooms at Bridport in the summer. In winter, the internal spaces at Oxley Woods were not free-running (Figure 6.32). Pearson tests suggest there is a strong correlation between the internal temperatures of all the spaces monitored at Bridport and Oxley Woods and the external temperatures in the summer (Tables 6.5 and 6.6).

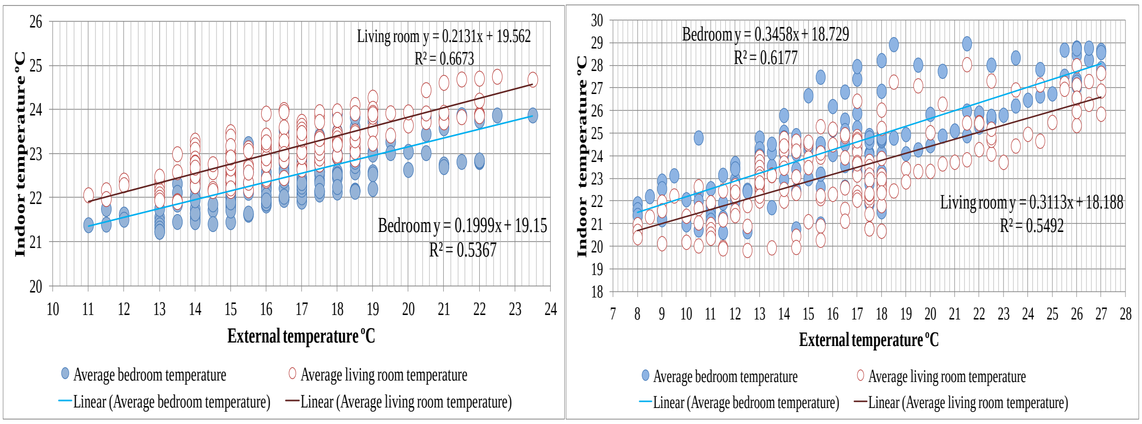

Figure 6.31: Relationship between the mean internal temperature of the living areas and the bedrooms monitored at Bridport (left) and Oxley Woods (right) and the external temperature in the summer.

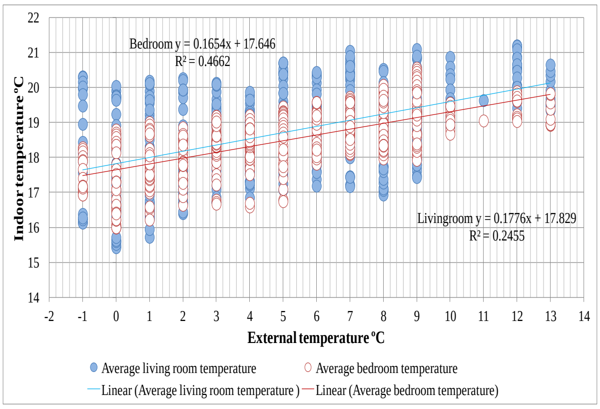

Figure 6.32: Relationship between the mean internal temperature in the living areas and the bedrooms monitored at Oxley Woods and the external temperature in the winter.

Table 6.5: Correlation between the internal temperature and the external temperature at Bridport in the summer

Space	**N**	**Pearson correlation**
FL1GFL	316	0.716**
FL1FFB	316	0.615**
FL7FFFB	316	0.544**
FL35SFL	316	0.386*

**correlation is significant at the 0.01 level (2-tailed).
*correlation is significant at the 0.05 level (2-tailed).

Table 6.6: Correlation between the internal temperature and the external temperature at Oxley Woods in the summer and the winter

Season	**Summer**		**Winter**	
Space	**N**	**Pearson correlation**	**N**	**Pearson correlation**
A1WLGFL	166	0.762**	263	0.270*
A1WLFFFB	263	0.815**	263	0.321*
A6MLSFBB	263	0.531**	263	0.460**
A38MLGFL	263	0.709**	263	0.239*
A38MLFFFB	263	0.809**	263	0.276*
A38MLFFBB	166	0.694**	263	0.441**
A142HAGFL	263	0.674**	263	0.308*
A142HASFBB	263	0.692**	263	0.630**
A162HAGFL	263	0.595**	263	0.636**
A162HAFFBB	166	0.796**	263	0.625**

**correlation is significant at the 0.01 level (2-tailed).
*correlation is significant at the 0.05 level (2-tailed).

Analysis to find out the relationship between thermal sensation and the external temperature at Oxley Woods in the summer suggests 'neutral' when the external temperature reached 13ºC (Figure 6.33). At Bridport, the analysis indicates 'neutral' for the external temperature at 15ºC with possibility for higher neutrality when the outdoor temperature rose above 22ºC in the summer suggesting higher neutral temperature by 2ºC at Bridport than Oxley Woods. However, the neutral temperature at Oxley Woods in the winter was lower due to seasonal change and the houses were heated.

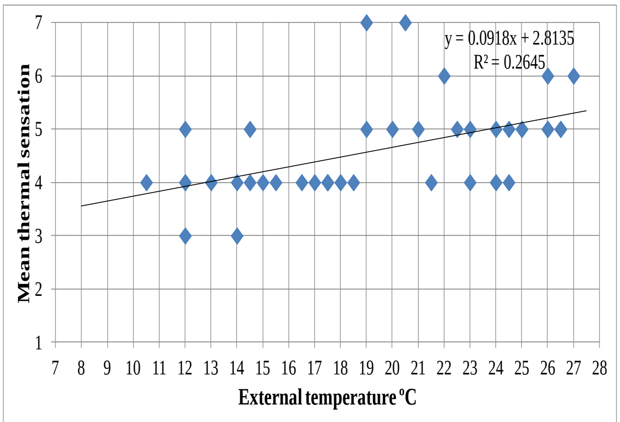

Figure 6.33: Relationship between thermal sensation and the external temperature at Oxley Woods in the summer.

Considering the average internal temperature, the analysis indicates ‘neutral’ at 20.4ºC and 21.2ºC Bridport and Oxley Woods in the summer respectively (Figure 6.34). The analysis further shows suggest 0.8ºC higher neutral temperature at Oxley Woods than Bridport in the summer. The result suggests the internal spaces at Oxley Woods are expected to be warmer than the internal spaces at Bridport and higher adaptation of the occupants at Oxley Woods to the internal spaces. In winter, the ‘neutral’ temperature at Oxley Woods was lower.

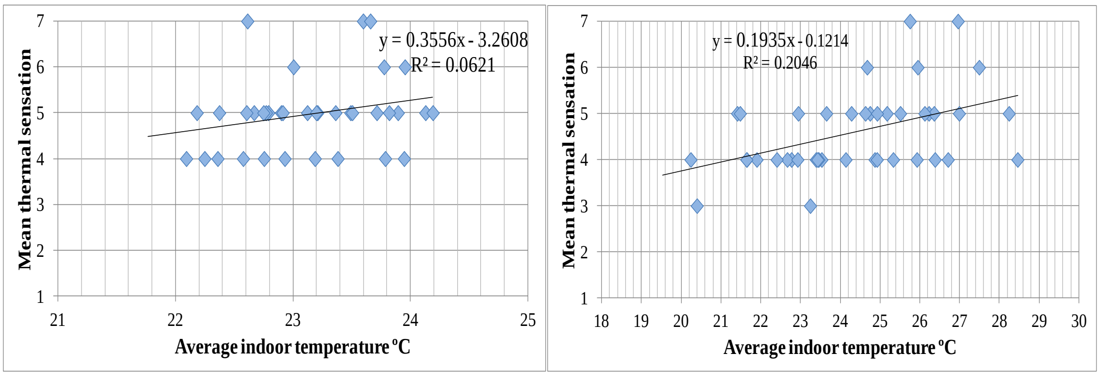

Figure 6.34: Relationship between thermal sensation and the mean indoor temperature in the flats monitored at Bridport (left) and the houses monitored at Oxley Woods (right) in the summer.

Also, the neutral temperature in the living areas at Bridport was within a wide range of temperatures while neutrality in the bedrooms was 20.6ºC during the summer (Figure 6.35). At Oxley Woods, the neutral temperature was 20.2ºC for the living areas and 22ºC for the bedrooms in the summer (Figure 6.36). The results show higher thermal adaptation for the residents at Oxley Woods than Bridport in the summer. In the heating period (winter), the responses indicate 19.2ºC and 19ºC neutral temperature for the living areas and the bedrooms monitored at Oxley Woods respectively also suggesting comfort within a big range for the spaces with low R^2 values indicating no relationship .

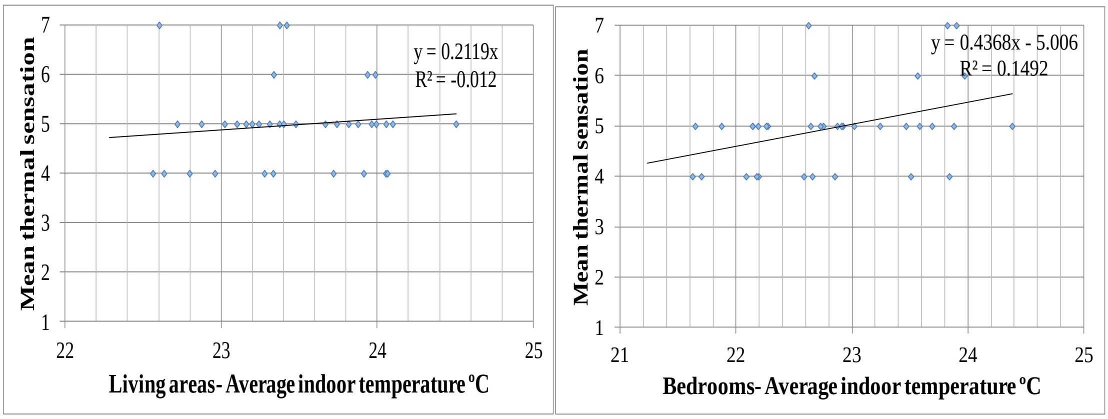

Figure 6.35: Relationship between thermal sensation and the mean indoor temperature in the living areas (left) and the bedrooms (right) monitored at Bridport in the summer.

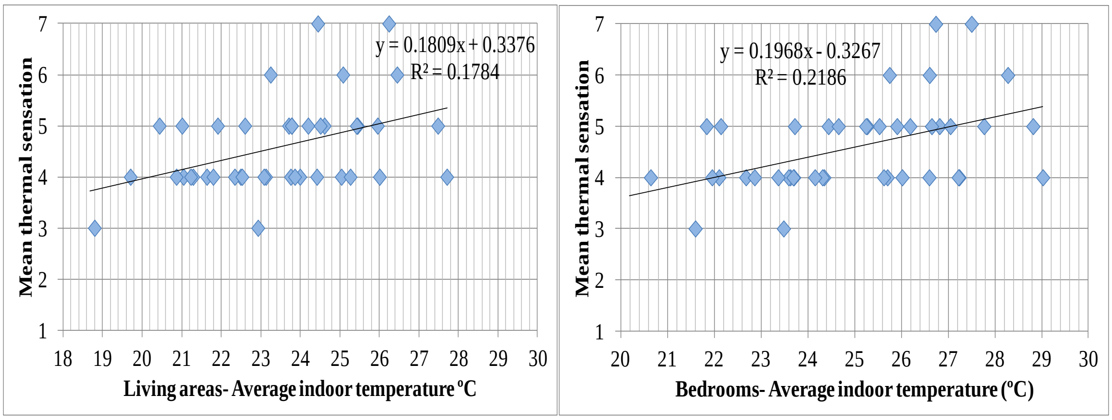

Figure 6.36: Relationship between thermal sensation and the mean indoor temperature in the living areas (left) and the bedrooms (right) monitored at Oxley Woods in the summer.

Thermal neutrality for the external temperature at Oxley Woods was lower than Bridport while neutrality was higher when considering the average internal temperature at Oxley Woods. The analysis suggests than the bedrooms are much warmer than the livings areas in the summer at Oxley Woods and vice versa at Bridport. In the winter, the living areas are slightly warmer than the bedrooms at Oxley Woods. Statistical test suggests the female respondents feel less warm than the male occupants at Oxley Woods ($r=0.215$, $p<0.05$) in the summer. Comparing the results with the post-occupancy surveys show female occupants are more comfortable with the thermal conditions of the dwellings in the summer ($r=0.446$, $p<0.05$). In addition, the younger occupants feel warmer than the elderly occupants at Oxley Woods in the summer ($r=-0.328$, $p<0.05$). Significance is noticed between time of the day and thermal sensation in summer at Bridport ($r=0.441$, $p<0.05$) as the occupants feel less warm in the morning than in the afternoon and the evening. Linking the results with the post-occupancy surveys, significance is found between time of the day and overall thermal comfort in summer at Stadthaus ($r=-0.595$, $p<0.05$) and in winter at Bridport ($r=0.418$, $p<0.05$). In addition, significance is observed between time of the day and thermal sensation in winter at Stadthaus ($r=-0.658$, $p<0.05$), time of the day and thermal satisfaction in winter at Stadthaus ($r=0.595$, $p<0.05$). The results suggest the occupants' feeling of hot or cold and thermal satisfaction are influenced by the time of the day, as the occupants feel warmer during the daytime when the external temperature increased.

Table 6.7: Mean responses for thermal sensation (from 1= cold, to 7= hot) and thermal preference in the summer and the winter (from 1=much cooler to 5=much warmer) from the comfort surveys.

	Thermal sensation		Thermal preference	
	Summer	Winter	Summer	Winter
Bridport	4.94	-	2.41	-
Oxley Woods	4.46	3.87	2.87	3.14

6.4.3 Thermal Preference Votes

The responses from the summer surveys show that the occupants usually preferred to be 'cooler'. The mean distribution of votes indicates that more than half of the responses preferred to be 'cooler' at Bridport with a drift towards 'no change' at Oxley Woods (Figure 6.37). The results were rather different in the winter at Oxley Woods with well over 84% preferring no change to the thermal environment (Figure 6.38). The results indicate that there is an agreement with the feelings of comfort experienced by the occupants and the preference for temperature in the summer and the winter (Table 6.7). The younger occupants preferred to be much cooler than the elderly occupants at Oxley Woods ($r=0.399$, $p<0.05$) in the summer.

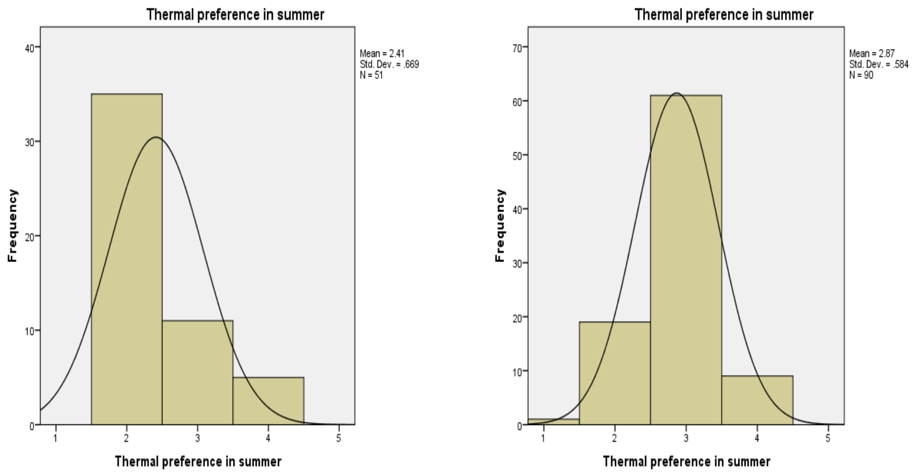

Figure 6.37: Distribution of thermal preference votes at Bridport (left) and Oxley Woods (right) in the summer (from 1- much cooler to 5- much warmer).

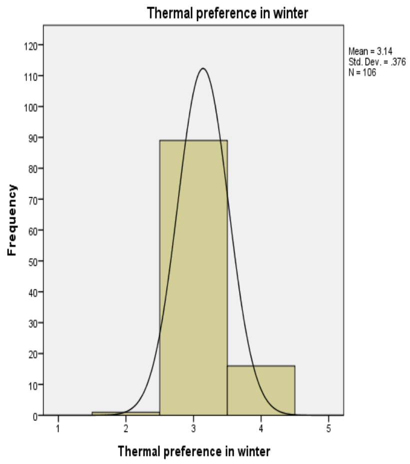

Figure 6.38: Distribution of thermal preference votes at Oxley Woods in the winter.

In order to understand the relationship between thermal preference and the temperatures (internal and external) measured at the case studies during the monitoring periods, regression analysis was also carried out. The analysis suggests the respondents indicated 'no change' when the external temperature was 15ºC at Bridport and 14.1ºC at Oxley Woods in the summer. The results show a very low R^2 value at Bridport and Oxley Woods indicating no relationship. Also in the winter, the analysis suggests the occupants preferred 'no change' to the thermal environment.

The temperature at which the respondents preferred 'no change' within the flats at Bridport was 22ºC while the occupants at Oxley Woods preferred 'no change' at 20.2ºC within the houses in the summer. The occupants at Bridport preferred 'no change' at

1.8ºC higher than the occupants at Oxley Woods (Figure 6.39). The results suggest the occupants at Oxley Woods that can adapt to the thermal environment over a wide range of temperatures than the occupants at Bridport. On the contrary in the winter, the respondents at Oxley Woods preferred ‘no change’ at a significant higher indoor temperature of 23.9ºC suggesting preference for higher indoor temperature (2.7ºC) in the winter than in the summer.

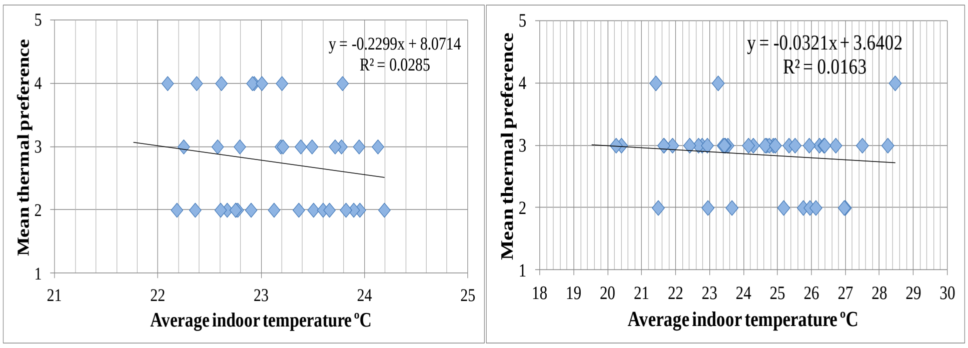

Figure 6.39: Relationship between thermal preference and the average indoor temperature in the flats monitored at Bridport (left) and the houses monitored at Oxley Woods (right) in the summer.

The preferred temperature for the living areas as shown in Figure 6.40 below was 22.7ºC and the bedrooms monitored was 21.2ºC at Bridport in the summer. Also, the respondents preferred ‘no change’ when the internal temperatures did not rise above 19ºC and 20.8ºC for the living areas and the bedrooms monitored at Oxley Woods (Figure 6.41). In winter, the occupants preferred ‘no change’ at 20.7ºC for the living areas and 20.6ºC for the bedrooms (Figure 6.42). The analysis suggests a preference for higher temperature of 1.5ºC in the living areas than the bedrooms at Bridport while at Oxley Woods, the occupants preferred ‘no change’ in the bedrooms at 1.8ºC higher than the temperature in the living areas. The findings suggest the occupants at Bridport preferred higher temperature in the living areas than the bedrooms while the respondents at Oxley Woods preferred higher temperature in the bedrooms than the living areas. The findings also indicate a slight difference of 0.1ºC between the preferred temperature in the living areas and the bedrooms at Oxley Woods which indicate the occupants preferred no change at the same range of the internal temperature in the living areas and the bedrooms in the winter. Pearson test suggests thermal preference and thermal sensation in the summer are strongly correlated at Bridport ($r=-0.564$, $p<0.05$) and Oxley Woods ($r=-0.755$, $p<0.05$). Also, there is a strong correlation between the two variables at Oxley Woods in the winter ($r=-0.600$, $p<0.05$)

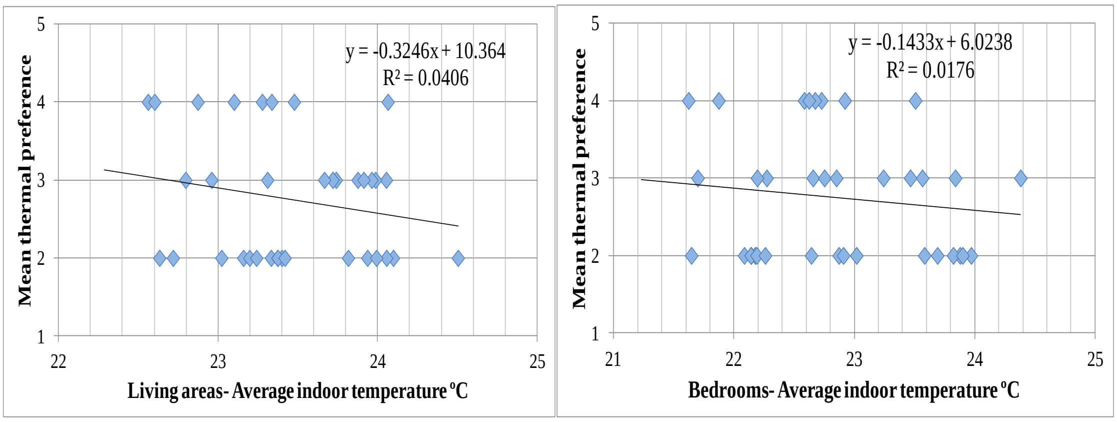

Figure 6.40: Relationship between thermal preference and the mean indoor temperature in the living areas (left) and bedrooms (right) monitored at Bridport in the summer.

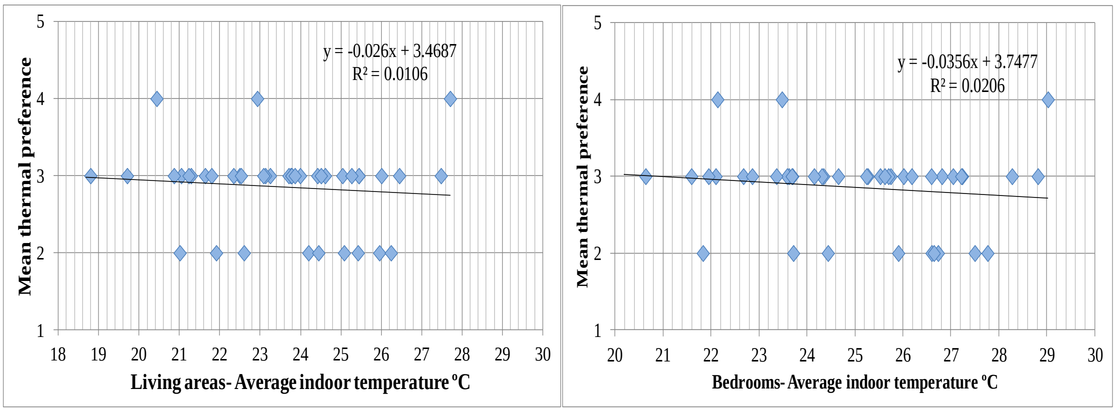

Figure 6.41: Relationship between thermal preference and the indoor temperature in the living areas (left) and the bedrooms (right) monitored at Oxley Woods in the summer.

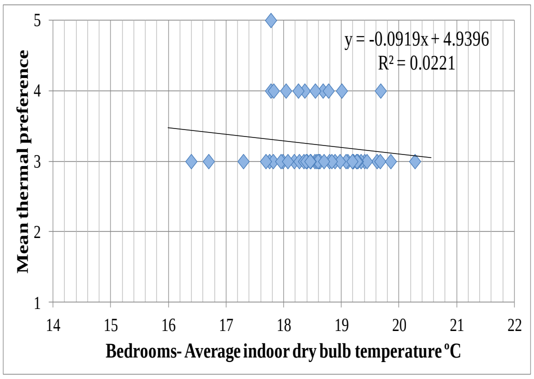

Figure 6.42: Relationship between thermal preference and the mean indoor temperature in the bedrooms monitored at Oxley Woods in the winter.

The participants' responses on thermal acceptability during the summer surveys at Bridport and Oxley Woods show at least 88% indicate the thermal environment at the case studies was right for them (Table 6.8). The responses during the winter survey also show a higher degree of thermal acceptability at Oxley Woods with 93% indicating that the thermal environment of the case study was right for them. Significance is noted between gender and thermal acceptability in the summer at Oxley Woods ($r=0.254$, $p<0.05$) as there was overwhelming responses from male occupants indicating the indoor environment was right for them than female occupants. At Oxley Woods, the elderly occupants significantly accept the thermal environment more than the younger occupants ($r=-0.331$, $p<0.05$). Also, the occupants that preferred 'no change' significantly accept the thermal environment in the summer at Oxley Woods ($r=-0.381$, $p<0.05$) than the occupants that preferred change. There is a strong correlation between thermal acceptability and thermal sensation in the summer at Bridport ($r=0.348$, $p<0.05$) and Oxley Woods ($r=0.504$, $p<0.05$)

Table 6.8: Thermal acceptability distribution of responses from the case study buildings during the summer and the winter

	Thermal acceptability (Summer)				Thermal acceptability (Winter)			
	Yes	No	Yes (%)	No (%)	Yes	No	Yes (%)	No (%)
Bridport	49	2	96.1	3.9	-	-	-	-
Oxley Woods	79	11	88.0	12.0	98	8	92.5	7.5

6.4.4 Control Votes

Regarding the control used in the last half hour to regulate the thermal environment of the case studies, 77% and 79% of the respondents at Bridport and Oxley Woods respectively indicate regular use of window (Figure 6.43). Comparing the results with the post-occupancy surveys' result suggest that across the case studies, more than two-third of the respondents use window to adjust the thermal environment. However, there was a noticeable shift in the use of fan between the case studies during comfort surveys in the summer as 82% indicated the use of fan at Oxley Woods while only 12% indicated the use of fan at Bridport. The analysis suggests a frequent use of fan to reduce high internal temperature within the indoor spaces at Oxley Woods in the summer. There is a correlation between use of window and thermal sensation in summer at Bridport ($r=0.437$, $p<0.05$) and Oxley Woods ($r=0.219$, $p<0.05$). Significance is noticed between thermal preference and use of control (window) in the summer ($r=-0.353$, $p<0.05$) and door ($r=-0.382$, $p<0.05$) at Oxley Woods.

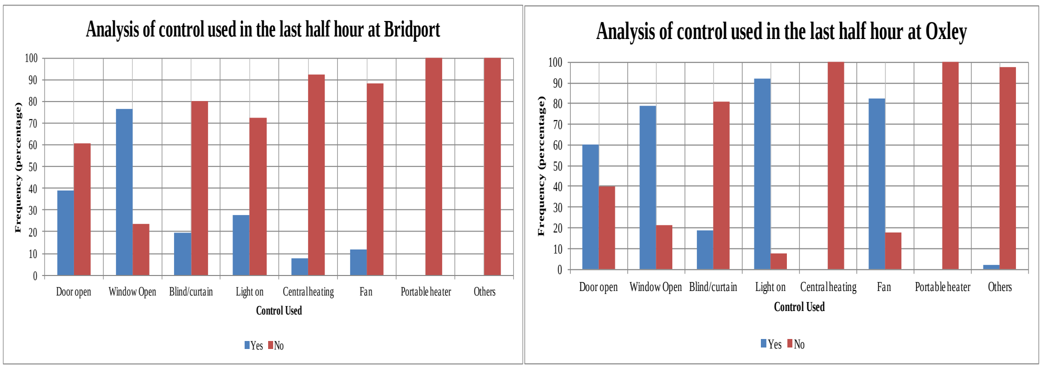

Figure 6.43: Distribution of control used in the last half hour votes at Bridport (left) and Oxley Woods (right) in the summer.

Further analysis suggests the respondents at Bridport mentioned the use of portable fans for regulation of the internal spaces in the summer. The responses on the control used in the last 30-minute also show 64% at Oxley Woods use central heating to heat the indoor environment during the winter survey.

6.4.5 Preference for Clothing Votes

The clo value of clothing insulation put on by the respondents during the summer surveys was between 0.2-0.6 clo for all sitting activities (not exceeding 1.2 met) at the case studies. The participants' responses during the comfort surveys in the summer show 57% and 85% at Bridport and Oxley Woods in that order indicate 'no change' to clothing currently wearing. However during the winter survey, the results were rather different at Oxley Woods with clo value between 0.9-1.2 clo and more than 97% prefer 'no change' to clothing currently wearing. Significance is noticed between thermal sensation and clothing preference in the summer at Oxley Woods ($r=-0.331$, $p<0.05$) and in the winter at Oxley Woods ($r=-0.270$, $p<0.05$). The respondents that preferred to be much cooler preferred less clothing than they are currently putting on at Bridport ($r=0.422$, $p<0.05$) and Oxley Woods ($r=0.271$, $p<0.05$) in the summer. Significance is recorded between gender and clothing preference in the summer at Oxley Woods ($r=-0.387$, $p<0.05$) as male occupants indicate they were not wearing more clothing than preferred in the summer. The occupants that accept the thermal environment considerably indicated they were not wearing more clothing than they preferred in the summer at Oxley Woods ($r=-0.495$, $p<0.05$). The younger occupants notably indicate they were wearing more clothing than they preferred in the summer at Oxley Woods ($r=0.336$, $p<0.05$). Comparing the results with findings from environmental monitoring suggests average internal temperatures of 22.6ºC and 23.9ºC at Bridport and Oxley Woods respectively and almost half of the respondents at Bridport indicated change to clothing currently wearing in the summer despite the monitoring period in the summer was mild and wet.

6.4.6 Activity Votes

The respondents were asked to indicate activity carried out in the last 15-minute. The results at the two case studies show 75% of responses for sedentary activities in the summer (Figure 6.44). The result during the winter survey also shows over 93% responses were either doing sedentary work or standing relaxed during the winter, suggesting that more than two-thirds of the participants during the summer and the winter surveys were not doing rigorous work in the last half hour which could arbitrary influence their feeling of hot or cold (Figure 6.45). Significance is found between thermal acceptability and activities done in the last 15-minutes at Oxley Woods ($r=-0.495$, $p<0.05$). Relationship exists between preference for clothing and activities carried out in the summer at Oxley Woods ($r=-0.270$, $p<0.05$) as category of the occupants that have done rigorous tasks in the last 15 minutes indicate that they were wearing more clothing than they preferred. Significance also exists between age and activities done at Oxley Woods ($r=-0.327$, $p<0.05$) as the younger occupants were doing more rigorous activities in the last 15 minutes than the elderly occupants which suggests why the younger occupants feel much warmer and preferred to be much cooler than the elderly occupants. Also, the occupants that have carried out rigorous tasks in the last 15 minutes preferred to be much cooler at Bridport ($r=0.384$, $p<0.05$) in the summer.

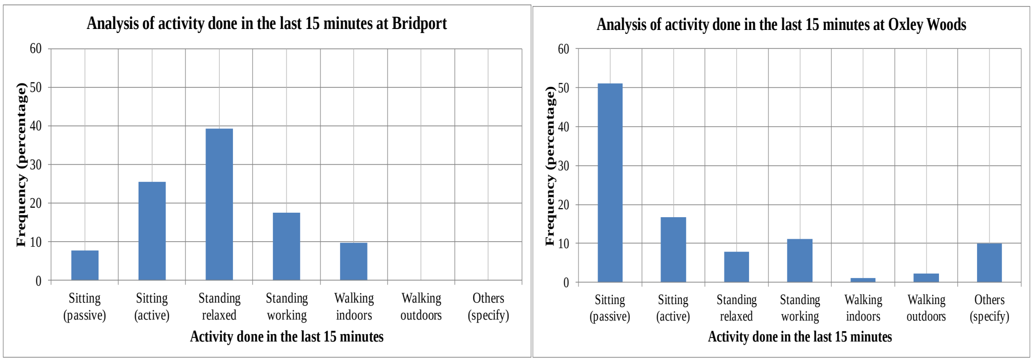

Figure 6.44: Distribution of activity carried out in the last 15-minute votes at Bridport (left) and Oxley Woods (right) in the summer.

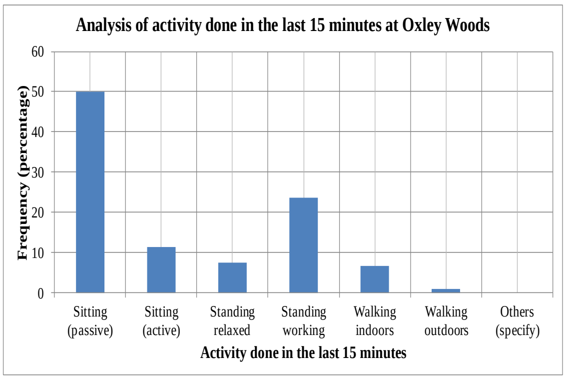

Figure 6.45: Distribution of activity carried out in the last 15-miute votes at Oxley Woods in the winter.

According to CIBSE (2010), one of the practical approaches that can be used to reduce the discomfort of indoor occupants during hot summer days is by taking either warm or cold drinks. The participants' responses on drinks consumed in the last 10 minutes during the comfort surveys in the summer show more than half of the occupants consumed cold drinks with the highest levels of cold drinks consumed at Oxley Woods. On the contrary in the winter, well over 77% of responses indicate they consumed hot drinks in the last 10 minutes. Significance is noticed between drinks consumed and thermal acceptability at Oxley Woods in winter ($r=0.262$, $p<0.05$). The occupants consumed cold drinks more often in the afternoon and the evening than in the morning during the summer at Bridport ($r=0.478$, $p<0.05$), Oxley Woods ($r=0.549$, $p<0.05$) and vice versa in the winter at Oxley Woods ($r=0.269$, $p<0.05$). A link is recorded between drinks consumed and thermal sensation in the summer at Bridport ($r=0.442$, $p<0.05$) and Oxley ($r=0.320$, $p<0.05$) as the occupants that feel much warmer take more cold drinks frequently than hot drinks in the summer.

On the occupants' preference for higher air movement into the thermal environment at the case studies, the responses show well over 76% preferred 'no change' to air movement in the summer. In the winter, more than 95% of the respondents indicate no preference for higher air movement. The results suggest more than two-third of the occupants preferred 'no change' to air movement at the case studies with the lowest preference for higher air movement at Bridport in the summer. Significance is noticed between preference for higher air movement and thermal acceptability at Oxley Woods in the summer ($r=-0.577$, $p<0.05$) and at Oxley Woods in the winter ($r=-0.442$, $p<0.05$). There is a correlation between preference for higher air movement and thermal sensation at Oxley Woods in the summer ($r=-0.576$, $p<0.05$). The participants that preferred to be much cooler also considerably preferred higher air movement into the internal spaces at Oxley Woods ($r=0.626$, $p<0.05$) in the summer while the occupants that preferred to be much warmer preferred no air movement at Oxley Woods ($r=0.203$, $p<0.05$) in the winter. Taking into consideration preference for air movement and clothing preference at Oxley Woods, the residents that preferred higher air movement preferred less clothing than they were currently wearing in the summer ($r=0.541$, $p<0.05$). The occupants that preferred no higher air movement indicate they were not wearing more clothing than they preferred in the winter ($r=0.230$, $p<0.05$). The younger occupants preferred higher air movement into the internal spaces than the elderly occupants at Oxley Woods ($r=0.556$, $p<0.05$) in the summer.

6.4.7 Experience of Overheating Votes

The respondents were asked if they have experienced any overheating today at the case studies. The responses during the summer surveys show at least 77% indicate no overheating experience during the day with the highest responses at Oxley Woods (Table 6.9) despite warm conditions of the internal spaces as found out during the monitoring periods. Comparing the results with findings from the comfort surveys suggest overheating is more perceived and recorded by the occupants at Bridport than Oxley Woods. This may be due to occupancy duration, ownership status, understanding of the control provided and frequent use of windows. However, environmental monitoring results suggest frequent occurrence of summertime high temperatures within the indoor spaces at Oxley Woods than Bridport. Significance is noticed between overheating experience and external temperature at Bridport in the summer ($r=-0.331$, $p<0.05$). Taking into account the statistical tests conducted, frequency of overheating experience recorded during the summer was much higher in female occupants than male occupants at Oxley Woods ($r=-0.326$, $p<0.05$). The participants that indicate the thermal environment were right for them have not experienced overheating during the day at Oxley Woods ($r=-0.495$, $p<0.05$) in the summer. The category of occupants that have experienced overheating preferred change to clothing currently wearing at Oxley Woods ($r=0.492$, $p<0.05$) in the summer. The residents that have experienced overheating during the day preferred higher air movement into the internal spaces at Bridport ($r=0.719$, $p<0.05$) and Oxley Woods ($r=0.612$, $p<0.05$) in the summer. The younger occupants' responses indicate overheating experience more often than the elderly occupants at Oxley Woods ($r=0.274$, $p<0.05$) in the summer. The occupants that feel much warmer indicate they experienced overheating in the house at Oxley Woods ($r=-0.502$, $p<0.05$) in the summer. The category of occupants that preferred to be much cooler have experienced overheating during the day at Oxley Woods ($r=0.429$, $p<0.05$) in the summer.

Table 6.9: Overheating experience distribution of responses from the case studies during the summer and the winter

	Overheating experience (Summer)				Overheating experience (Winter)			
	Yes	No	Yes (%)	No (%)	Yes	No	Yes (%)	No (%)
Bridport	12	39	23.5	76.5	-	-	-	-
Oxley Woods	14	76	15.6	84.4	0	106	0	100

6.5 Overheating Analysis

Analysis of overheating in the monitored spaces at Bridport and Oxley Woods using the static CIBSE criteria of 5%/25ºC and 1%/28ºC for the living areas and 5%/24ºC and 1%/26ºC for the bedrooms is provided below. In addition, the dynamic thermal comfort criteria (BSEN15251) of evaluating overheating with 5% of hours above and below the Cat. II upper and lower markers to indicate warm discomfort and cold discomfort in all the monitored spaces at the two case studies will be presented.

6.5.1 Analysis of the Overheating at Bridport and Oxley Woods, Using the Static CIBSE Criteria

Analysis of the risk of overheating at Oxley Woods was considered using Figures 6.46 and 6.47 below to illustrate the high percentage of hours that exceeded 25ºC and 28ºC for all the living areas and Figure 6.48 to show the percentage of hours above 24ºC and 26ºC for all the bedrooms. The analysis suggests that 100% of the living areas monitored were above 25ºC for more than 10% of the time, 50% of the living areas exceeded 25ºC for more than 20% of the time and 25% of the living areas exceeded 25ºC for more than 30% of the time. The findings also suggest that 80% of the bedrooms exceeded 24ºC for more than 10% of the time. The results indicate that most of the monitored spaces recorded temperatures that exceed the thresholds of moderately warm overheating risk.

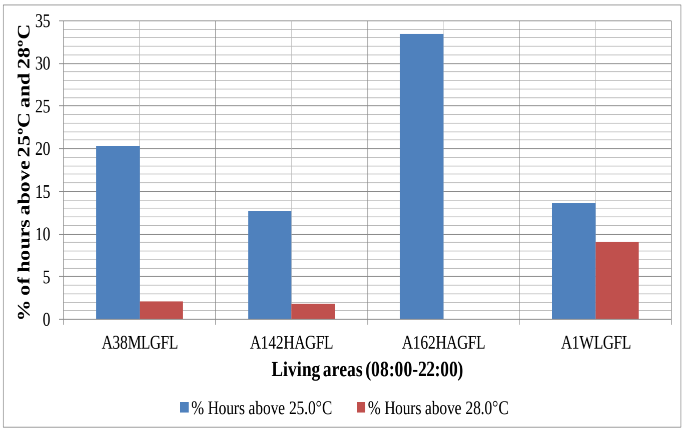

Figure 6.46: Monitored temperatures and overheating risk criteria, free-running living areas (08:00-22:00) at Oxley Woods.

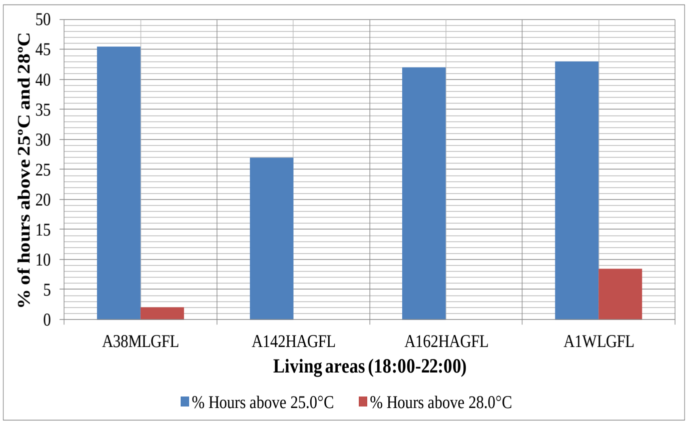

Figure 6.47: Monitored temperatures and overheating risk criteria, free-running living areas (18:00-22:00) at Oxley Woods.

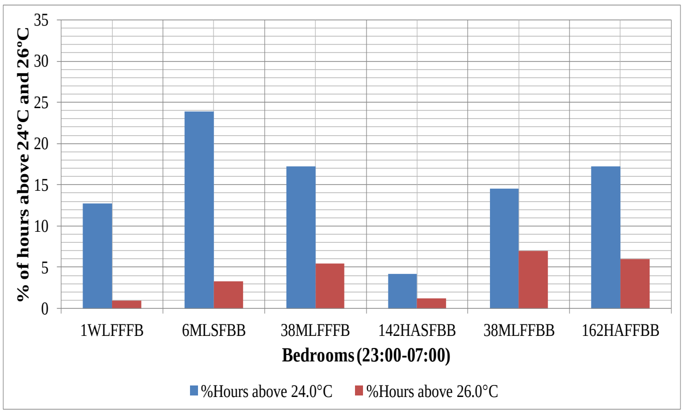

Figure 6.48: Monitored temperatures and overheating risk criteria, free-running bedrooms at Oxley Woods.

Considering all the eight living rooms monitored at the case studies from 08:00-22:00, four living rooms (that is, 50%) are above the 5%/25ºC mark of moderately warm overheating and well above 70% when taking into consideration the evening time from

18:00-22:00 as the occupants are expected to occupy the house at the evening period generating more internal heat. Looking at the 1%/28ºC indicator of extremely hot summertime, three of the houses (that is, 43%) were above the mark most of the time (Figure 6.47). Taking into account the eight bedrooms monitored at the case studies at the evening time from 23:00 to 07:00, 56% above the 5%/24ºC and 67% above the 1%/26ºC indicator (Figure 6.48). The results indicate that bedrooms in the houses at Oxley Woods are warmer than the bedrooms at Bridport, which is a block of flats. The findings show that the designs and the overall urban form of the buildings influence the thermal conditions of the spaces monitored. The design of Bridport shows that the average floor area of the bedrooms monitored at Bridport is $14m^2$ and the average volume is $40m^3$. While the average floor area of the bedrooms monitored at Oxley Woods is $9m^2$ and the average volume is $21.2m^3$. The results suggest the tendency of frequent high internal temperatures in the bedrooms monitored which may affect the residents who would be uncomfortable and find it difficult to sleep well during the night-time in the summer.

The results indicated that the temperature in all the living rooms at Oxley Woods rose above 25ºC for 20% and 28ºC for 3.3% of the monitoring period (Figure 6.46). At Bridport, the temperature exceeded 25ºC for 1% and none recorded above 28ºC as the weather conditions during the time of the survey were wet and mild.

The results also suggest slight differences in the design can also influence overheating. For instance, floor-to-ceiling heights at Bridport are 300mm higher than at Oxley Woods with bigger openings. Significance is observed between pleasant experience and floor-to-ceiling height at Bridport (=0.397, $p<0.05$). The internal spaces at Bridport indicate low temperatures while the internal spaces at Oxley Woods indicate high temperatures in the summer. However, further analysis to establish relationship between the internal temperature and floor-to-ceiling height across the three case studies will also be considered in Chapter 7.

Linking various housing parameters with thermal comfort of the occupants at the case studies, significance is noticed between the size of the spaces and thermal sensation in summer at Bridport as the occupants in the bigger apartments (maisonettes) feel cooler than the occupants in the smaller flats ($r=0.462$, $p<0.05$). The occupants in the lower floors are thermally satisfied with the internal conditions of the flats in the summer than the occupants in the upper floors at Bridport ($r=-0.409$, $p<0.05$). There is a correlation between level of floor and thermal sensation in summer at Oxley Woods ($r=0.423$, $p<0.05$) as the respondents in the upper floors feel warmer than the occupants in the lower floors. This may likely due to shading from the urban forms as most of the housing prototypes at Oxley Woods are terraced. The occupants in the lower floors are more pleased with their experience at Bridport ($r=-0.397$, $p<0.05$). Also, the occupants living in the bigger apartments are more pleased with their experience than the occupants in the smaller apartments at Bridport ($r=0.400$, $p<0.05$). The residents in the bigger apartments indicate living areas as the warmest space while the occupants in the smaller apartments (flats) indicate bedrooms as the warmest space at Stadthaus which suggests a significance between size of the spaces and warmest space at Stadthaus ($r=-0.592$, $p<0.05$). The respondents indicate the spaces in the upper floors (the bedrooms) as the warmest space at Oxley Woods ($r=0.420$, $p<0.05$).

There is a correlation between control frequency and orientation at Bridport ($r=0.446$, $p<0.05$) as the occupants in the south-facing spaces use control more often than the occupants in the north-facing spaces. Significance is also indicated between orientation and pleasant experience at Bridport ($r=0.743$, $p<0.05$). The occupants that are living in the south-east facing and the south-west facing spaces feel much warmer in the summer at Stadthaus ($r=0.633$, $p<0.05$). Significance is noticed between orientation and use of shading device at Oxley Woods ($r=-0.514$, $p<0.05$). There is a correlation between preference for clothing and the floor levels at Oxley Woods ($r=-0.222$, $p<0.05$) as the respondents at the upper floors prefer ‘no change’ to clothing currently wearing than the respondents at the ground floor spaces in the winter. There is a link between the orientation of the houses and thermal preference in summer at Oxley Woods ($r=-0.240$, $p<0.05$) as the occupants in the south-facing houses and the spaces prefer to be cooler than the occupants living in the spaces facing other orientations. The occupants in bigger houses are more comfortable with the thermal environment in winter than the occupants in smaller houses at Oxley Woods ($r=-0.500$, $p<0.05$). The link between the variables highlighted suggest the effect of these differences especially size of the internal spaces including floor-to-ceiling height in influencing the potential of summertime overheating in dwellings.

6.5.2 Analysis of the Overheating at Bridport and Oxley Woods, Using the Dynamic Adaptive Comfort Criteria

Overheating was also examined using the adaptive comfort criteria, Category II 'normal level of expectation level'. Comparing the monitored hourly temperatures with the running mean of the daily mean outdoor temperature (T_{rm}) suggested an anticipated drift towards much warmer internal temperatures as T_{rm} increased (Figures 6.49-6.52). The variations in indoor temperatures for a certain T_{rm} value differ from one household to another. During the monitoring period in the summer, some of the spaces monitored (A1WLFFFB, A6MLSFBB, A38MLFFFB, A142HASFBB, A1WLGFL, A38MLFFBB, A162HAFFBB) were above the Category III 'acceptable, moderate level of expectation' (T_{rm}>18°C) mark which indicate extreme cases of high temperatures above the recommended Category II mark (Figure 6.49). Other spaces monitored (A38MLGFL, A142HAGFL, A162HAGFL) in the houses at Oxley Woods were observed to be cooler with minimum difference in the everyday temperatures. Some houses were observed to be regularly lower than the Category II indicator, in mild weather (Figure 6.50). At Bridport, the adaptive comfort criteria suggested that some of the monitored spaces such as FL35SFL, FL1GFL within the flats were within the Category II indicator (Figures 6.51 and 6.52). Similarly, during the winter survey at Oxley Woods, the results indicate all the spaces monitored were below the Category II upper mark and further analysis to assess the overheating risk will not be required for the winter survey. However, charts showing percentage of hours that fall between different BSEN15251 thermal comfort categories for all the spaces monitored in the summer and the winter will be discussed.

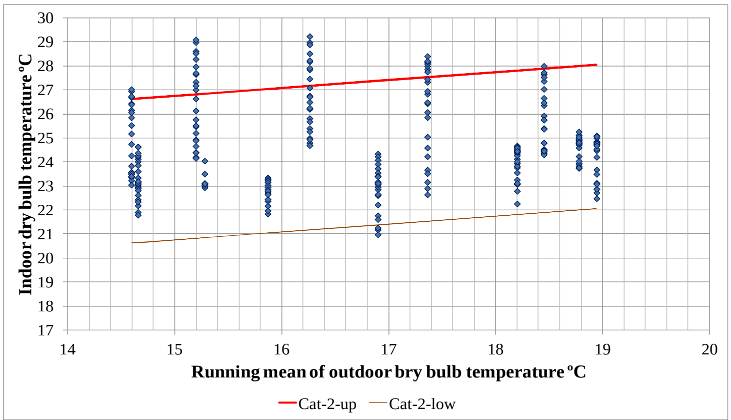

Figure 6.49: Temperatures recorded in A6MLSFBB at Oxley Woods (between 20th and 31st July, 2012) suggesting warm discomfort, compared to the BSEN15251 thresholds.

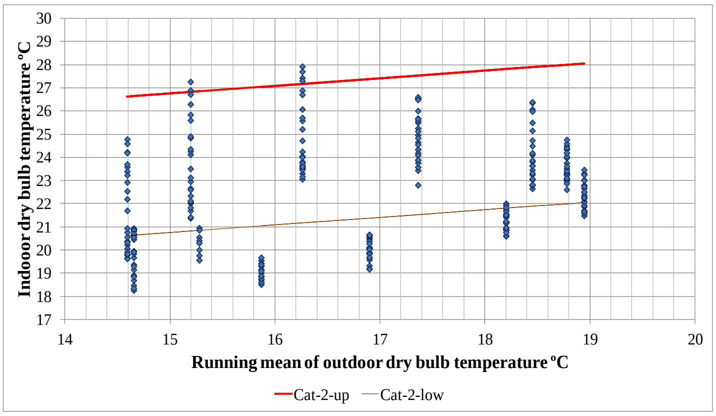

Figure 6.50: Temperatures recorded in A142HAGFL at Oxley Woods (between 20th and 31st July, 2012) suggesting cold discomfort, compared to the BSEN15251 thresholds.

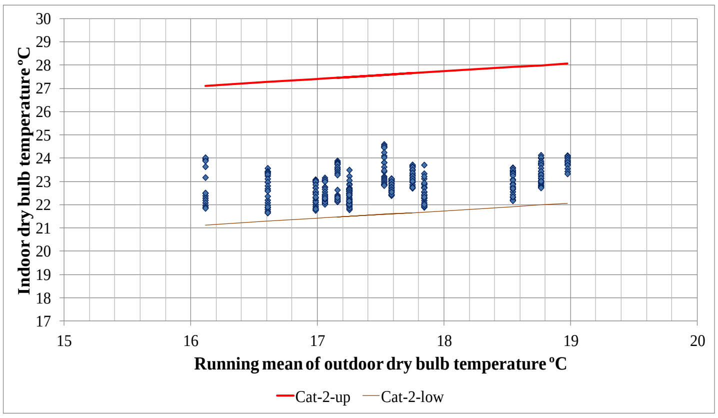

Figure 6.51: Temperatures recorded in FL1GFL at Bridport (between 29th June and 12th July, 2012) suggesting no discomfort, compared to the BSEN15251 thresholds.

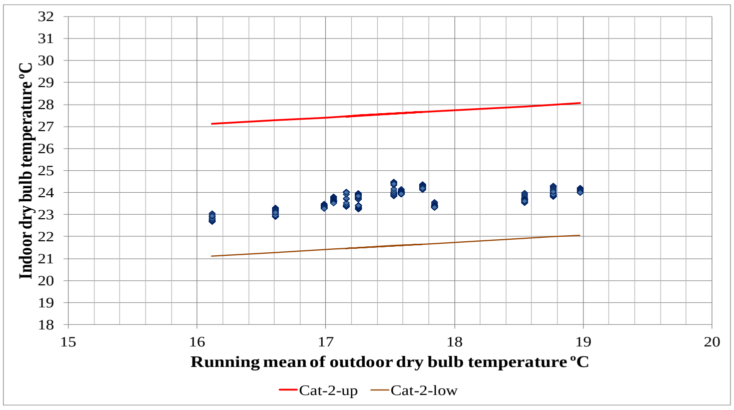

Figure 6.52: Temperatures recorded in FL35SFL at Bridport (between 29th June and 12th July, 2012) suggesting no discomfort, compared to the BSEN15251 thresholds.

Taking into consideration the Category II threshold ‘normal level of expectation’ for period between 08:00-22:00 for the living areas and between 23:00-07:00 for the bedrooms, there was one living area and six bedrooms (42%) that exceeded 5% of hours above the Category II upper threshold. Also, six of the living rooms (35%) and four of the bedrooms (24%) exceeded 5% of hours below the Category II lower marker (Figures 6.53 and 6.54). Combining all the spaces monitored during the summer at Bridport and Oxley Woods, the results indicate 47% exceeded 5% of hours above the Category II upper indicator and 67% exceeded 5% of hours below the Category II lower threshold. The analysis suggests that there is significant overheating potential in the houses. Linking the results with the findings from comfort surveys on activity carried out in the last 15 minutes indicate more than 75% of the respondents carried out various activities that are less rigorous which could not arbitrary lead to higher internal gains and thus influence the occupants' feeling of hot or cold. This suggests high internal temperatures observed at the case studies were not as a result of higher internal gains from the occupants' actions but mainly from external temperature through the buildings' envelopes. The respondents that indicated less rigorous activities in the last 15-minute at Bridport ($r=0.283$, $p<0.05$) did not experience overheating in the summer.

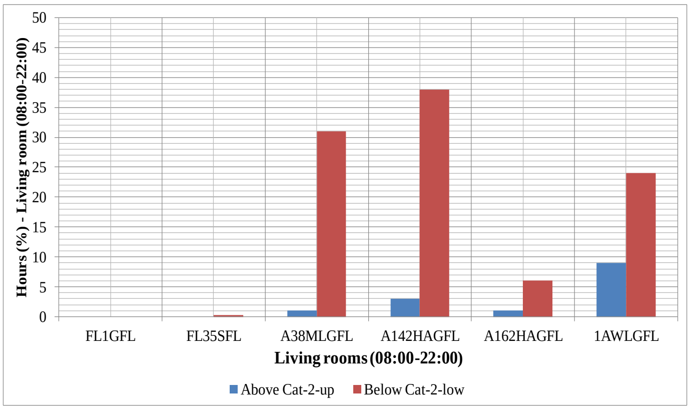

Figure 6.53: Percentage of hours of living room temperatures (between June and July, 2012) in BSEN15251 Cat. II thermal comfort category (Bridport and Oxley Woods).

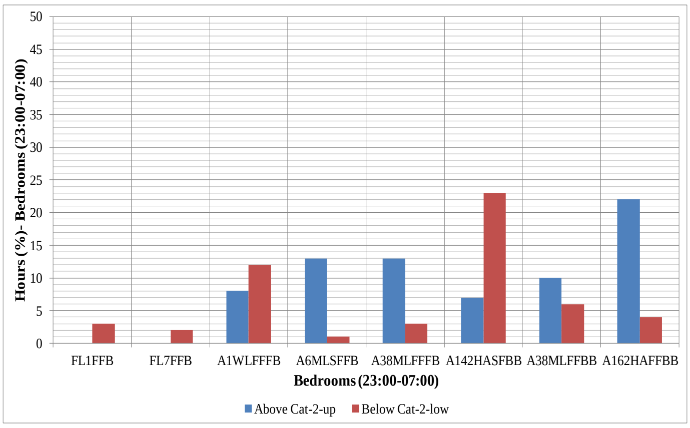

Figure 6.54: Percentage of hours of bedroom temperatures (between June and July, 2012) in BSEN15251 Cat. II thermal comfort category (Bridport and Oxley Woods).

In order to classify and compare the internal temperatures in all the spaces monitored at Bridport and Oxley Woods during the summmer and the winter surveys into the approved BSEN15251 thermal comfort standard, the bar charts (Figures 6.55-6.57) indicating percentage of hours that fall between the different BSEN15251 thermal comfort categories as earlier considered by Lomas & Giridharan (2012) were applied. Figure 6.55 shows the percentage of hours above the Category II upper and below the Category II lower boundaries for all the spaces monitored at Oxley Woods in the summer. Taking into account 5% of hours above the Category II upper threshold, the analysis suggests over 70% of all the spaces monitored at Oxley Woods indicate warm discomfort in the summer (Figure 6.56) while none of the spaces monitored at Bridport suggests warm discomfort (Figure 6.57). In addition, some of the spaces monitored at Bridport and Oxley Woods indicate cold discomfort (that is, 5% of hours below the Category II lower marker) in the summer due to low temperatures observed in the spaces monitored at night-time when the external temperatures dropped. A chart showing one of the spaces monitored at Oxley Woods where low internal temperatures were observed due to decrease in the external temperatures at night-time is shown in Figure 6.58 to further highlight the relationship between the external temperature and the internal temperature at the case studies. Also, comparison between different thermal comfort categories in BSEN15251 was also carried out for the average indoor temperature of all the flats monitored at Bridport and the houses monitored at Oxley Woods. The results suggest cold discomfort above 5% in all the flat monitored at Bridport and the houses monitored at Oxley Woods in the summer (Figure 6.57).

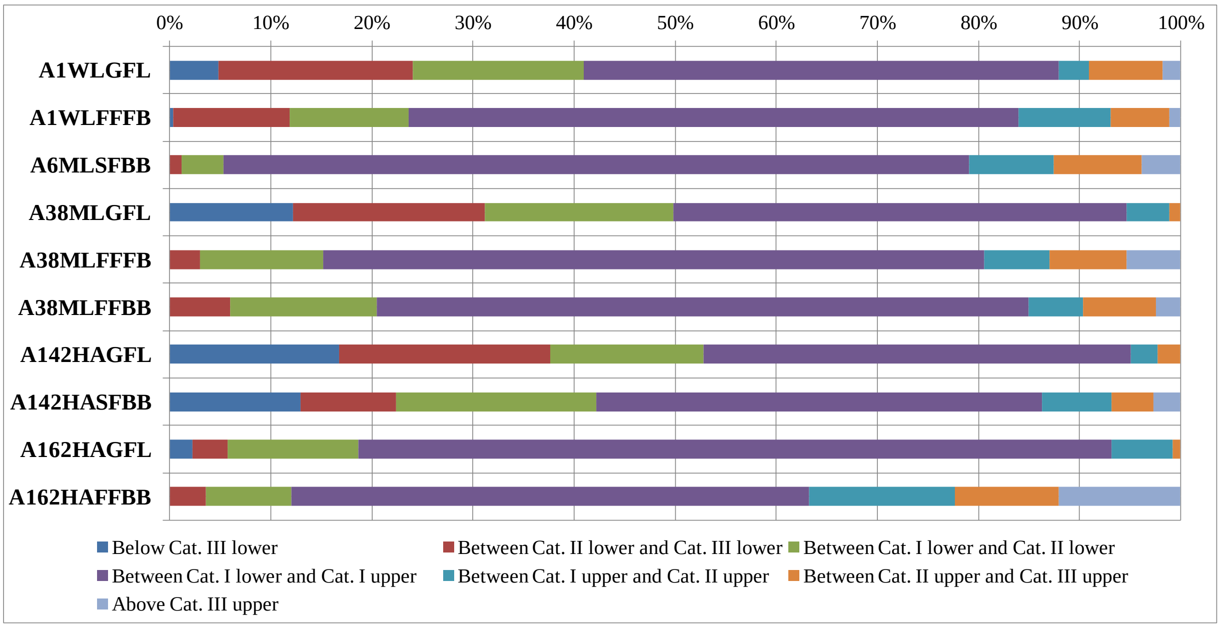

Figure 6.55: Percentage of hours of temperatures recorded within the internal spaces of the houses monitored at Oxley Woods in the summer that fall between different BSEN15251 thermal comfort thresholds (The summer period- between 20th July and 31st July, 2012).

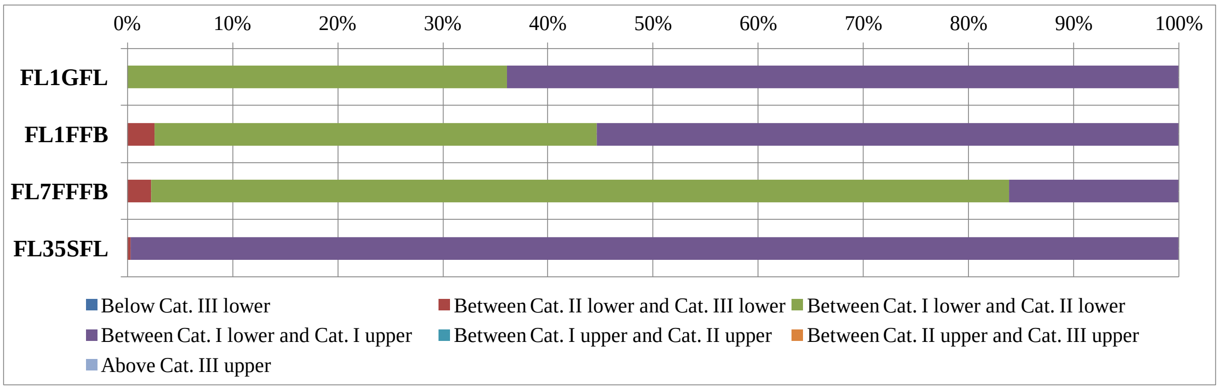

Figure 6.56: Percentage of hours of temperatures recorded within the internal spaces of the flats monitored at Bridport in the summer that fall between different BSEN15251 thermal comfort thresholds (The summer period- between 20th July and 31st July, 2012).

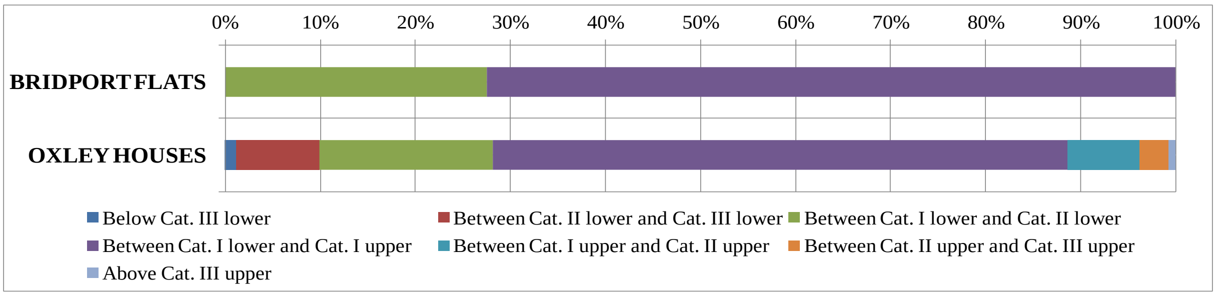

Figure 6.57: Percentage of hours of temperatures recorded in the flats monitored at Bridport and the houses monitored at Oxley Woods in the summer that fall between different BSEN15251 thermal comfort thresholds (The summer period- between 20th July and 31st July, 2012).

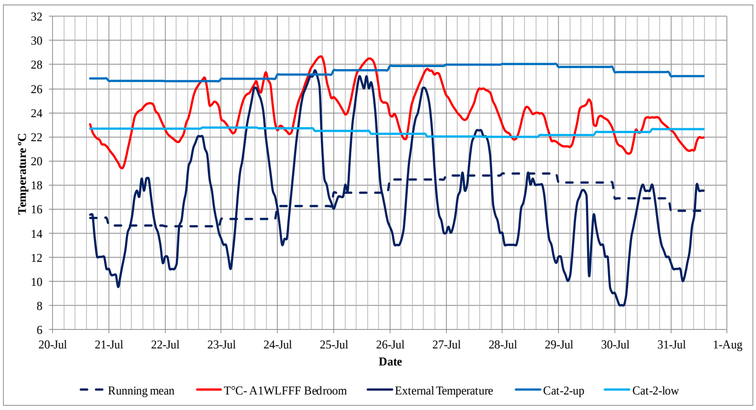

Figure 6.58: Monitored temperatures in A1WLFFFB at Oxley Woods (between 20th July and 31st July, 2012) in BSEN15251 thermal comfort thresholds indicating hours of temperature above Cat. II upper indicator and below Cat. II lower marker.

A strong correlation is found between the average internal temperature of the bedrooms and the external temperature at Oxley Woods in the summer (r=0.6177) and in the winter (r=0.4662). The results show low temperatures were frequently observed within the internal spaces monitored at Oxley Woods in the winter (r=0.3861) while high temperatures were often recorded in the summer (r=0.6043).

Tables 6.10 and 6.11 below summarise the internal temperatures in all the living areas and the bedrooms monitored at Bridport and Oxley Woods in the summer and the winter. The day-time hours considered for the living areas are between 08:00-22:00 while the night-time hours considered for the bedrooms are between 23:00-07:00. The total hours for the summer surveys in the spaces monitored at Bridport and Oxley Woods were 316 hours and 263 hours respectively except the three spaces at Oxley Woods (A1WLGFL, A38MLFFBB and A162HAFFBB) with a shorter monitoring period of 166 hours.[32] In the winter, all the spaces at Oxley Woods were also analysed based on the monitored hours of 263 carried out during the survey. The analysis suggests the difference between the minimum temperature in the living rooms and the bedrooms monitored at Bridport is slightly higher than the minimum temperature in the living rooms at Oxley Woods while the maximum temperature recorded in the living rooms and the bedrooms monitored at Bridport is significantly lower than the maximum temperatures measured in the living areas and the bedrooms at Oxley Woods. The mean day-time and mean night-time

[32] Threshold values: 5% of 316 hours- 16 hours, 5% of 263 hours- 13.5 hours and 5% of 166 hours- 8.5 hours. Night-time hours of 316 hours- 104 hours, night-time hour of 263 hours- 88 hours and night-time hours of 166 hours- 56 hours.

temperatures in the living rooms and the bedrooms monitored at Oxley Woods are slightly higher than the mean day-time and night-time temperatures in the living areas and bedrooms at Bridport. The results also suggest frequent occurence of high temperatures in the spaces monitored at Oxley Woods than Bridport. The results further suggest that the spaces at Oxley Woods are much warmer than the spaces at Bridport. Further comparison between the three case studies will be carried out using the results from dynamic thermal simulations that will be discussed in Chapter 7.

Table 6.10: Summary of measured indoor temperatures in the living rooms monitored at Oxley Woods and Bridport in the summer and the winter.

Name of space	Max. temp (ºC)	Min. temp. (ºC)	Mean day-time temp (ºC)	Mean temp (ºC)	CIBSE: Total hours above 28ºC	CIBSE: Day time hours above 25ºC	BSEN15251: Total hours above Cat 1 upper marker	BSEN15251: Total hours above Cat 2 upper marker	Max. temp (ºC)	Min. temp. (ºC)	Mean day-time temp (ºC)	Mean temp (ºC)	CIBSE: Total hours above 28ºC	CIBSE: Day time hours above 25ºC	BSEN15251: Total hours above Cat 1 upper marker	BSEN15251: Total hours above Cat 2 upper marker
Living areas- Oxley Woods (summer)									**Living areas- Oxley Woods (winter)**							
A1WLGFL	30.0	19.8	24.2	23.5	15	23	20	15	21.8	17.5	19.2	18.9	0	0	-	-
A38MLGFL	28.1	18.2	23.2	22.6	4	34	14	3	22.3	14.0	18.9	18.4	0	0	-	-
A142HAGFL	28.0	18.3	22.8	22.4	3	21	13	6	22.7	12.7	18.5	18.0	0	0	-	-
A162HAGFL	27.3	18.6	24.1	23.7	0	56	18	2	22.1	15.3	20.2	19.6	0	0	-	-
Living areas- Bridport (summer)									**Living areas- Bridport (winter)**							
FL1GFL	24.6	21.7	23.2	22.9	0	1	0	0	-	-	-	-	-	-	-	-
FL35SFL	25.0	22.7	23.8	23.7	0	2	0	0	-	-	-	-	-	-	-	-

*Threshold values: 5% of 316 hours- 16 hours, 5% of 263 hours- 13.5 hours and 5% of 166 hours- 8.5 hours.

Table 6.11: Summary of measured indoor temperatures in the bedrooms monitored at Oxley Woods and Bridport in the summer and the winter.

Name of space	Max. temp (ºC)	Min. temp. (ºC)	Mean night time temp (ºC)	Mean temp (ºC)	CIBSE: Total hours above 28ºC	CIBSE: Night time hours above 26ºC	BSEN15251: Total hours above Cat 1 upper marker	BSEN15251: Total hours above Cat 2 upper marker	Max. temp (ºC)	Min. temp. (ºC)	Mean night time temp (ºC)	Mean temp (ºC)	CIBSE: Total hours above 28ºC	CIBSE: Night time hours above 26ºC	BSEN15251: Total hours above Cat 1 upper marker	BSEN15251: Total hours above Cat 2 upper marker
Bedrooms- Oxley Woods (summer)									**Bedrooms- Oxley Woods (winter)**							
A1WLFFFB	28.7	19.4	22.5	23.9	14	2	42	18	22.8	17.7	19.3	19.6	0	0	-	-
A6MLSFBB	29.2	21.0	24.2	24.7	18	6	55	33	21.1	17.1	19.0	19.2	0	0	-	-
A38MLFFFB	29.5	20.0	23.3	24.5	25	9	51	34	20.6	15.1	18.1	18.6	0	0	-	-
A38MLFFBB	29.1	20.8	23.7	24.3	18	12	25	16	20.5	14.9	18.0	18.1	0	0	-	-
A142HASFBB	29.8	18.0	21.7	23.2	16	2	36	18	19.4	13.9	16.5	17.0	0	0	-	-
A162HAFFBB	30.5	20.8	23.8	25.7	40	10	61	37	21.9	13.5	17.4	18.7	0	0	-	-
Bedrooms- Bridport (summer)									**Bedrooms- Bridport (winter)**							
FL1FFB	24.7	21.3	22.3	22.8	0	0	0	0	-	-	-	-	-	-	-	-
FL7FFFB	23.8	21.2	22.0	22.3	0	0	0	0	-	-	-	-	-	-	-	-
Summer									**Winter**							
Bridport flats	24.2	21.7	22.5	22.6	0	0	0	0	-	-	-	-	-	-	-	-
Oxley houses	28.5	19.5	22.6	23.9	3	2	30	10	20.4	15.8	18.0	18.6	0	0	-	-

*Threshold values: 5% of 316 hours- 16 hours, 5% of 263 hours- 13.5 hours and 5% of 166 hours- 8.5 hours.

In order to understand the amount of energy required to keep the internal environment of the houses at Oxley Woods comfortable for the occupants, the actual annual gas bills of the four out of the five houses monitored at Oxley Woods were collected for further analysis. According to OFGEM (2013), between 9,000kWh and 13,500kWh of gas is required annually for small dwellings including flats to medium-size dwellings (usually between 5-bed and 6-bed house). The finding shows 100% of the houses used more than 9,000kWh of gas per annum while 50% consumed more than 11,250kWh of gas which is the mid-value between the lower and upper thresholds recommended by OFGEM (Figure 6.59). The analysis also suggests 25% of the houses used more than 13,500kWh of gas, the upper threshold recommended for medium-size houses per annum. Comparing this with the results from environmental monitoring obtained during the summer surveys further confirm that A1WL is the warmest house out of the houses monitored at Oxley Woods with highest actual annual gas consumption rising above the recommended threshold by OFGEM. A38ML and A162HA (same prototype-C, 2-storey, area-76.84m²) have a similar range of annual gas consumption rate. While A142HA with a bigger internal floor area, additional spaces and number of floors (prototype G, 3-storey, area-

100.5m²) indicates a similar range of annual gas consumption suggesting a tendency that the occupants are taking further adaptive actions to reduce annual energy consumption levels in the house. Linking the results to the results from window opening actions indicate the occupants at A142HA open windows for more than 80% of the time during the monitoring period in the summer.

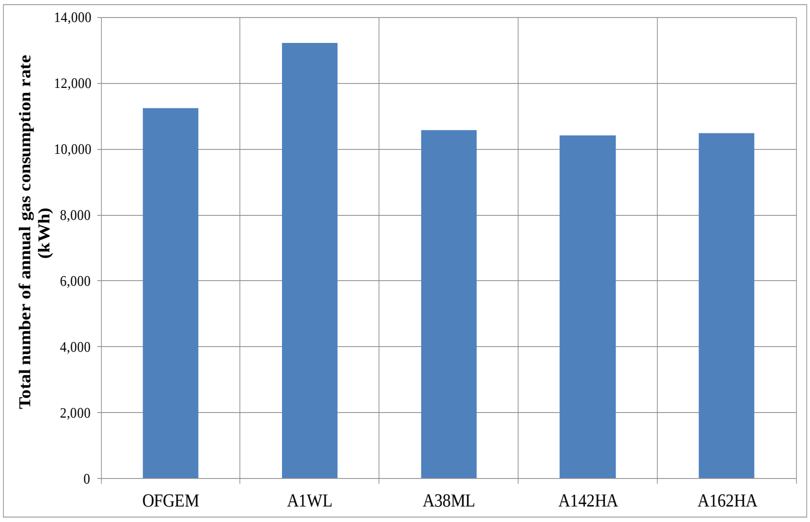

Figure 6.59: Actual annual gas consumption rate for the four houses at Oxley Woods showing the consumption rate along with OFGEM mid-threshold for small house to medium house.

6.6 The Applicability of Using the Dynamic Adaptive Comfort Standard (BSEN15251) for Evaluation of Overheating

Considering the analysis of overheating using the static criteria indicates 50% of the living areas were above 5%/25ºC and 56% of the bedrooms were above 1%24ºC. In addition, the static criteria suggests, 43% of the living areas were over 1%/28ºC and 67% of the bedrooms were above 1%/26ºC. On the contrary, the application of the dynamic adaptive comfort criteria to evaluate overheating at the case studies provides a better understanding that a little proportion of the houses monitored indicates warm discomfort due to summertime high temperature within the internal spaces. The dynamic adaptive comfort standard suggests that only 1 living area and 42% of the bedrooms were more than 5% above the Category II upper marker in the summer. Moreover, 35% of the living areas and 24% of the bedrooms were below the Category II lower indicator. The results show that the dynamic thermal comfort standard considers a range of comfort zones in different buildings that provides comfortable internal conditions for the occupants than the static criteria even during summertime high temperature. The analysis suggests that the standard (BSEN15251) is more consistent for the evaluation of indoor occupants' comfort within the thermal environment in different locations.

The standard (BSEN15251) used for the evaluation of thermal comfort of housing in real life situation, can be used for prediction of thermal comfort in houses. The standard helps to understand the temperature at which the occupants will probably consider most comfortably warm or cold. Although the standard at first meant for evaluation of the thermal environment in non-residential buildings especially offices, it has been widely considered for evaluation of indoor occupant's comfort in dwellings (Nicol & Humphrey, 2010). In addition, the BSEN15251 standard provides the ability for occupants in the houses to carry out different tasks within the internal spaces and occupy different spaces at different times of the day. The standard also supports the occupants to change clothing insulation for adaptation to the thermal environment, consumed drinks either cold or warm, open or closed windows, change sitting positions, moving near or away from heat source, adjusting controls in the space occupied and even sleep for a short period of time during the day. This improves indoor occupants' capability to adapt to the thermal environment.

Generally, free-running houses are likely to observe a lower internal temperature than office environments due to differences in thermal properties of building envelopes, density, as offices have a higher density of occupants and higher internal gains than houses. In addition, the annual cost of energy for running houses influences indoor occupants to take some further adaptive measures in reducing the overall cost of energy consumption in running the houses (Nicol & Humphrey, 2002). This study shows that all the houses monitored during the summer are operated as free-running. Taking into consideration previous studies on thermal comfort in houses, further investigations focusing on environmental monitoring of different spaces within the house will provide additional knowledge about comfort in dwellings.

6.7 Comparison of Findings from this Study with Findings from the Previous Studies on Overheating in Dwellings

Various studies have investigated overheating in dwellings. The houses are constructed between 1919 and post-1990s and built with conventional building materials (Wright *et* *al.*, 2005; Firth & Wright, 2008; Sakka *et al.*, 2012; Lomas & Kane 2012, 2013; Beizaee *et al.,* 2013) but none of the houses monitored was built with prefabricated timber indicating this is the first study that solely focuses on overheating in prefabricated timber houses. Considering the average seasonal external temperature in the previous studies, the mean temperature during the summer of 2009 was 16.4ºC for Lomas & Kane (2012; 2013). The mean seasonal external temperature between July and August 2007 was 15.5ºC for Firth & Wright (2008); while 15.3ºC was recorded in all the locations monitored during the summer of 2007 for Beizaee *et al.* (2013). For this study, the average external temperature recorded at Bridport was 16.7ºC and Oxley Woods was 16.8ºC during the summer (June to July) of 2012. The analysis suggests the monitoring periods for this study were not extreme hot summertime periods and similar to other studies. Regarding prolong temperature during summertime, five days of prolong hot temperature with the mean temperature exceeding 24.1ºC was noticed in one of the days while average temperature of 22.2ºC was observed in the living areas and 22.4ºC in the bedrooms (Lomas & Kane, 2012; 2013). Mean internal temperature of 21.4ºC was observed in the living areas and 21.5ºC in the bedrooms (Wright & Firth, 2008); while mean temperature of 21.8ºC was recorded in the living areas and 21.6ºC for the bedrooms by Beizaee *et al.* (2013). In this study, the mean temperature for the living rooms and the bedrooms at Bridport was 22ºC and 21.8ºC respectively. The average temperature for the living areas was 23.7ºC and the bedrooms was 23.1ºC at Oxley Woods indicating higher mean internal temperatures observed within the internal spaces monitored in this study than previous studies.

Taking into account the percentage of high internal temperatures reported in the bedrooms using the CIBSE ‘static’ criteria for the period between 23:00-07:00, 21% of bedrooms exceeded 1%/26ºC threshold (Beizaee *et al.*, 2013). In this study, 67% of the bedrooms monitored rose above 1%/26ºC threshold despite the beginning of the monitoring period at the two case studies considered as mild and wet. For the period between 08:00-22:00 in the living areas, 27% of living areas rose above the 1%/28ºC threshold (Lomas & Kane, 2012; 2013), 4% of living areas exceeded 1%/28ºC threshold (Beizaee *et al.*, 2013). This study indicates 43% of the living areas exceeded 1%/28ºC marker suggesting extreme overheating above 50% of the 1%/26ºC for the bedrooms and 1%/28ºC for the living areas. In the previous studies, 58% of the living rooms rose above 5%/25ºC threshold (Lomas & Kane, 2012; 2013). In addition, 27% of the living rooms exceeded 5%/25ºC and 47% of the bedrooms exceeded 5%/24ºC (Beizaee *et al.*, 2013). For this study, 50% of the living areas rose above 5%/25ºC while 56% of the bedrooms exceeded 5%/24ºC thresholds. The results from this study suggest more than half of the living areas and the bedrooms indicate warm discomfort for most time of the time despite the monitoring periods in the summer for this study were cooler than the previous studies.

Comparing this study with previous studies using the dynamic adaptive thermal comfort model (BSEN15251), 36% and 29% of the living areas and the bedrooms were more than 5% of hours above the Category II upper indicator (Lomas & Kane, 2013). Furthermore, 28% of the living areas and 24% of the bedrooms exceeded 5% of hours above the Category II upper marker (Beizaee *et al.*, 2013). This study indicates 17% of the living areas, and 75% of the bedrooms exceeded 5% of hours above the Category II upper indicator suggesting frequent occurrence of overheating in the all the spaces especially the bedrooms of modern houses when compared to other houses built with conventional building materials. Considering the mean internal temperature and number of hours above 28ºC during the monitoring periods in the summer, this study identifies the houses with smaller internal spaces and less number of floors are warmer than the houses with bigger internal spaces and more number of floors (Table 6.12). However, this might be slightly different at Bridport for the apartments at the top floors.

Table 6.12: Comparison between the internal temperatures of the smaller and the bigger spaces monitored during the summer surveys.

Space	Case study	Mean temp (ºC)	Total hours above 28ºC	Floor level
A1WLGFL	Oxley Woods	23.5	15	Ground floor
A1WLFFFB	Oxley Woods	23.9	2	First floor
A6MLSFFB	Oxley Woods	24.7	6	Second floor
A38MLGFL	Oxley Woods	22.6	4	Ground floor
A38MLFFFB	Oxley Woods	24.5	9	First floor
A38MLFFBB	Oxley Woods	24.3	12	First floor
A142HAGFL	Oxley Woods	22.4	3	Ground floor
A142HASFBB	Oxley Woods	23.2	2	Second floor
A162HAGFL	Oxley Woods	23.7	0	Ground floor
A162HAFFBB	Oxley Woods	25.7	10	First floor
FL1GFL	Bridport	22.9	0	Ground floor
FL1FFB	Bridport	22.8	0	First floor
FL7FFFB	Bridport	22.3	0	First floor
FL35SFL	Bridport	23.7	0	Second floor

*Location of the logger positions: A1WLGFL-southwest facing, A1WLFFFB- southeast facing, A6MLSFFB- northwest facing, A38MLGFL- northeast facing, A38MLFFFB- southeast facing, A38MLFFBB- northeast facing, A142HAGFL- southwest facing, A142HASFBB- southeast facing, A162HAGFL- north facing, A162HAFFBB- southeast facing, FL1GFL- south facing, FL1FFB- southwest facing, FL7FFFB- east facing, FL35SFL west facing.

The previous studies indicated significant high temperatures in the living areas of upper floor flats investigated (Beizaee *et al.*, 2013; Lomas & Kane, 2013; Mavrogianni *et al.*, 2012). While significant high temperatures were observed in the upper floor bedrooms at Oxley Woods suggesting that frequent high temperatures also occur in the bedrooms of timber houses. Although the previous studies have considered overheating in dwellings, this study contributes to the on-going investigations on the extent of overheating potential in low-carbon emissions housing built with prefabricated timber. This study suggests the internal temperatures of timber houses were significantly higher than houses built with heavyweight materials and the internal temperatures strongly correlated with the external temperatures at the case studies (Table 6.13).

Table 6.13: Correlation between the internal temperatures and the external temperatures at Bridport and Oxley Woods in the summer

	Summer	
Name of space	**N**	**Pearson correlation**
A1WLGFL	166	0.762**
A1WLFFFB	263	0.815**
A6MLSFBB	263	0.531**
A38MLGFL	263	0.709**
A38MLFFFB	263	0.809**
A38MLFFBB	166	0.694**
A142HAGFL	263	0.674**
A142HASFBB	263	0.692**
A162HAGFL	263	0.595**
A162HAFFBB	166	0.796**
FL1GFL	316	0.716**
FL1FFB	316	0.615**
FL7FFFB	316	0.544**
FL35SFL	316	0.386*

**correlation is significant at the 0.01 level (2-tailed).
*correlation is significant at the 0.05 level (2-tailed).

This study further provides a better understanding of the neutral temperature in modern UK houses. The neutral temperatures at the case studies suggest the occupants are likely to be 'comfortably warm' at 20.4ºC for Bridport and 21.2ºC for Oxley Woods compared to the mean seasonal neutral temperature of 23.4ºC for naturally ventilated dwellings (Beizaee *et al.*, 2012). Also, high temperatures were observed in all different types of dwellings investigated (Beizaee *et al.*, 2013; Lomas & Kane, 2013); while the occupants of smaller spaces and houses are likely to have a higher neutral temperature when compared to the bigger houses as found out in this study (Table 6.14). However, further investigation to compare the neutral temperature and the preferred temperature of different houses from the various studies will be required.

Table 6.14: Predicted neutral temperature in the spaces monitored at Bridport and Oxley Woods in the summer.

					Summer	
Name of space	**Case study**	**Description**	**Area (m^2)**	**Min. ceiling height (m)**	**Neutral Temp. (°C)**	**R^2**
A1WLGFL	Oxley Woods	Living area	20.9	2.35	21.6	0.2769
A1WLFFFB	Oxley Woods	Bedroom	12.2	2.35	22.3	0.2722
A6MLSFBB	Oxley Woods	Bedroom	8.7	2.35	22.1	0.2047
A38MLGFL	Oxley Woods	Living area	20.9	2.35	20.0	0.1837
A38MLFFFB	Oxley Woods	Bedroom	12.2	2.35	22.5	0.2428
A162HAGFL	Oxley Woods	Living area	20.9	2.35	20.8	0.1435
A162HAFFBB	Oxley Woods	Bedroom	8.7	2.35	22.8	0.1715
FL1GFL	Bridport	Living area	29.7	2.65	20.0	0.0590
FL1FFB	Bridport	Bedroom	13.1	2.65	19.5	0.1118
FL7FFFB	Bridport	Bedroom	15.2	2.65	21.1	0.1735

*Location of the logger positions: A1WLGFL-southwest facing, A1WLFFFB- southeast facing, A6MLSFFB- northwest facing, A38MLGFL- northeast facing, A38MLFFFB- southeast facing, A162HAGFL- north facing, A162HAFFBB- southeast facing, FL1GFL- south facing, FL1FFB- southwest facing, FL7FFFB- east facing.

In terms of overall thermal comfort evaluation, not more than 10% responses indicate slightly uncomfortable at different season and a moderately noticeable shift from slightly uncomfortable to comfortable part of the scale observed in summer (Rijal & Stevenson, 2010). In this study, majority of the responses are in the 'slightly comfortable' part of the scale in the summer with a noticeable shift to the 'comfortable' and 'very comfortable' part of the scale in the winter. The results suggest more than half of the respondents are comfortable with the thermal environment despite high internal temperatures observed at the case studies. Regarding the window opening behaviour, Stevenson & Rijal (2009) and Rijal, *et. al.*, (2007) reported a zero average of window and door opening percentage in winter. Also in this study, the average percentage of window opening sessions in the spaces monitored in the winter was very low. However, in the summer, the studies indicate a higher percentage of window and door opening sessions. This study also found out the windows of more than half of the spaces monitored was open for more than 80% of the time throughout the monitoring period in the summer. However, high temperature was recorded in all the spaces monitored but the frequency of high temperatures reduced in the spaces with windows open for more than 80% of the time during the summer surveys (Figures 6.23-6.26).

6.8 Comparative Analysis of Findings and Discussions on Post-occupancy, Environmental Monitoring and Comfort Surveys

This section presents the results from the post occupancy evaluations, indoor monitoring, and thermal comfort surveys from the buildings.

The post-occupancy evaluations indicate that over 70% of the occupants report on the warm and hot part of the scale with most of them indicating ‘satisfied’ with the thermal conditions of their indoor spaces which suggests that overheating occurs. The comfort surveys provided a different picture, as 75% and 38% responses feel ‘warm’ at Bridport and Oxley Woods respectively in the summer. Further analysis shows that over 90% of Oxley Woods’ residents owned the house with at least 3 occupants in more than 50% of the houses who have been living in the house for more than two years, which could suggest they have a better understanding of controlling and adjusting the internal environment of the house thereby increasing their adaptive capacity. Significance is noticed between occupancy type and effect of control ($r=0.416$, $p<0.05$), occupancy duration and use of shading device ($r=-0.390$, $p<0.05$). Also, there is a correlation between number of occupants and thermal sensation ($r=0.478$, $p<0.05$) in the summer which further suggests the tendency of the residents at Oxley Woods to feel significantly less warm than the residents at Bridport during the summer surveys despite higher internal temperatures.

In all the spaces monitored at Oxley Woods, the bedrooms are much warmer than the living rooms in the summer. At Bridport, the living areas are warmer than the bedrooms in the summer. On the contrary, in the winter, the living rooms are slightly warmer than the bedrooms at Oxley Woods. The internal temperature of all the spaces monitored at the two studies and the external temperature are strongly correlated, which indicates that the internal temperature at the case studies is strongly connected to the external temperature due to low thermal mass of the building fabric. The average neutral temperature for all the spaces monitored was 0.8ºC lower at Bridport than Oxley Woods in the summer indicating higher adaptation of the occupants at Oxley Woods to higher internal temperatures. Also, the average neutral temperature for all the bedrooms monitored was 1.7ºC higher than the average neutral temperature for all the living rooms monitored at Oxley Woods in the summer. The result suggests higher adaptation of the occupants to higher indoor temperatures in the bedrooms than the living rooms. The neutral temperature was slightly higher (0.2ºC) in the living areas than the bedrooms in the winter. Tables 6.15 and 6.16 summarise the neutral temperature and the preferred temperatures in the internal spaces monitored and overall values for Bridport and Oxley Woods in the summer.

Table 6.15: Comparison between the average neutral and the preferred temperatures for the living areas and the bedrooms monitored at Bridport and Oxley Woods in the summer.

Space	Case study	Mean temp (ºC)	Neutral temp-Tneutral (ºC)	Preferred temp-Tpreferred (ºC)
Average living area	Bridport	23.2	Within a wide range of temperatures	22.7
Average bedroom	Bridport	22.5	20.6	21.2
Average living area	Oxley Woods	22.9	20.2	19.0
Average bedroom	Oxley Woods	24.1	22.0	20.8

Table 6.16: Comparison between neutral and preferred temperatures at Bridport and Oxley Woods in the summer

Case study	Mean temp (ºC)	Tneutral (ºC)	Tpreferred (ºC)
Bridport	22.6	20.4	22.0
Oxley Woods	23.9	21.2	20.2

Considering the comfort surveys, more than 50% and 30% of the respondents preferred to be ‘cooler’ at Bridport and Oxley Woods in the summer respectively. While over 84% of the respondents preferred ‘no change’ to the thermal environment at Oxley Woods in the winter. The preferred temperature was higher (1.8ºC) at Bridport than Oxley Woods in the summer. The findings suggest the ability of the residents at Oxley Woods to adapt to a wide range of temperatures. On the contrary in the winter, the preferred temperature was higher (2.7ºC) at Oxley Woods when compared to the preferred temperature in the spaces monitored at Oxley Woods in the summer. For the living areas and the bedrooms monitored, the occupants at Oxley Woods indicate a preference for lower temperature (1.8ºC) in the living areas than the bedrooms. There was a slight difference of 0.1ºC between the preferred temperature in the living areas and the bedrooms at Oxley Woods in the winter. This suggests the occupants preferred the same range of internal temperature in the living areas and the bedrooms monitored in the winter. The results also suggest a significant relationship between the occupants’ feeling of hot or cold and thermal preference at Bridport ($r=-0.564$, $p<0.05$) and Oxley Woods ($r=-0.755$, $p<0.05$) in the summer and at Oxley Woods during the winter ($r=-0.600$, $p<0.05$).

Regarding thermal acceptability of the case studies, over 88% responses accept the thermal environment at Bridport and Oxley Woods in the summer. Over 93% responses accept the thermal environment during the winter survey suggesting a higher degree of thermal acceptability across the case studies despite warm internal conditions in the summer at Oxley Woods. Also, more than 92% indicate the use of control to improve the thermal environment of the case studies with 65% signifying frequent use of control to adjust the thermal environment during the post-occupancy surveys. Comparing the results with the comfort surveys and environmental monitoring, over 77% indicate the use of control, in particular windows to regulate the thermal environment at Bridport and Oxley Woods in the summer and high temperatures were also observed in some of the spaces (A1WLFFFB, A142HASFBB) at Oxley Woods where the windows were left open for more than 80% of the monitoring period in the summer. This may be due to orientation of the spaces. For instance, A1WLFFFB is located in the southeast orientation and A142HASFBB is also located in the southeast orientation.

The comments gathered from the residents throughout the period of the surveys suggests that the internal spaces in the upper floors can be very hot requiring windows not to be closed for ventilation. There is a correlation between the use of windows and the occupants' feeling of hot or cold in the summer at Oxley Woods (0.219, $p<0.05$). The respondents open doors more often for natural ventilation at Oxley Woods than Bridport in the summer ($r=0.367$, $p<0.05$). The occupants frequently use a fan at night in the upper floors (where the bedrooms are located) to reduce the impact of the late evening sun penetrating into the internal spaces ($r=-0.362$, $p<0.05$) and the use of internal blinds throughout the late evening to keep the direct sunlight out ($r=-0.282$, $p<0.05$). The residents often adjust windows (open/closed) as well as blinds (up/down) at the south-east facing spaces in the morning and to the rear part in the afternoon depending on the position of the sun at Oxley Woods ($r=-0.292$, $p<0.05$). The occupants at the spaces in the south-east orientation use control (shading device) more often than the other occupants at Oxley Woods ($r=-0.514$, $p<0.05$).

The elderly occupants indicate comfortably warm in the summer but the internal temperature recorded in the spaces show frequent occurence of high internal temperatures, which suggests summertime high temperatures may greatly affect the overall well-being of the indoor occupants at the case studies especially the vulnerable occupants. The responses across the case studies suggest the willingness of the participants to use some form of external shuttering or shading if permitted. In addition, change in use of the internal spaces at different seasons was noticed at the case studies, in particular at Oxley Woods. One of the occupants noted that the south-facing bedroom in the house is used for drying clothes in the summer due to high temperature perceived in the space but sleep in the bedroom in the winter as it is considered much warmer than the other spaces in the winter. There is a correlation between the occupants' feeling of hot or cold and orientation in the summer at Oxley Woods ($r=0.200$) and in the winter ($r=0.239$). In the summer, the ground floor spaces were reported to be much cooler in the morning especially the hallway and living areas but get warmed up when the external temperature rises at Oxley Woods ($r=0.423$, $p<0.05$). The occupants are thermally satisfied when they frequently use control (shading device) to improve internal conditions at Oxley Woods in the summer ($r=0.486$, $p<0.05$). However, the internal temperature tends to rise or drop quickly when the outdoor temperature changes at Bridport ($r=0.4733$) and Oxley Woods ($r=0.6043$) which further suggests frequent occurence of high internal temperature during summertime with potential for higher internal temperatures at Oxley Woods as found out in this study.

The findings from environmental monitoring suggests that the internal temperatures in all the living areas monitored at Bridport are lower than the temperatures in all the living rooms monitored at Oxley Woods in the summer. The results indicate 1.3ºC differences between the mean temperature of all the living areas monitored at Bridport and Oxley Woods. Regarding the period between 08:00-22:00 and 18:00-22:00, the mean temperature in all the living areas was 0.5ºC lower at Bridport than Oxley Woods in the summer. For the bedrooms, the results indicate a minimum of 1.3ºC difference between the average temperature of the bedrooms monitored at Bridport and Oxley Woods for the period between 23:00-07:00 in the summer. Taking into consideration the static CIBSE criteria, overheating appears to be more frequent at Oxley Wood than Bridport. The internal temperatures in the living rooms rose above 25ºC for 20% and 28ºC for 3.3% at Oxley Woods, while at Bridport exceeded 25ºC for 1% and none above 28ºC. It is possible that such differences are attributed to design related parameters, such as higher floor-to-ceiling heights, wider openings, etc., but such comparison could not be made directly, due to the lower external temperatures during the monitoring of Bridport. In principle, the spaces with higher floor-to-ceiling heights and wider openings tend to be more comfortable in the summer period than the spaces with lower floor-to-ceiling heights and smaller openings as the internal spaces get warm quickly. Also warm air rises quickly and fresh air comes in at a faster rate in the spaces with higher floor-to-ceiling heights and wider openings than the spaces with lower floor-to-ceiling heights and reduced size of openings.

When evaluated against the adaptive thermal comfort criteria, of the eight living areas monitored, well over 50% indicated moderately warm overheating risk for the Category II upper threshold applied over the period of monitoring. Applying 1%/26ºC indicator in the night period from 23:00-07:00 to the eight bedrooms monitored, the results suggest that well over 67% were at extreme overheating risk. Using the approved BSEN15251 thermal comfort model to categorise and compare the percentage of hours that fall between the different BSEN15251 thermal comfort categories in bar charts, over 70% of all the spaces monitored at Oxley Woods indicate the percentage of hours above 5% the Cat. II upper indicator suggesting warm discomfort while none of the spaces monitored at Bridport indicate warm discomfort in the summer. In the living areas and the bedrooms, 25% and 100% respectively indicate warm discomfort at Oxley Woods in the summer. Combining all the spaces monitored at Oxley Woods in the summer suggest the case study is warmer than Bridport with up to 5% of the total hours above the Cat. II upper threshold indicating warm discomfort in all the houses monitored at Oxley Woods in the summer.

Comparing the findings from this study with findings from previous studies suggest high temperatures were more frequent in the houses. High temperatures were observed in many living areas in previous studies but this study provides a better understanding that overheating occurs in all the internal spaces of modern houses in the UK. However, consideration of minimum space standards could help reduce the frequent occurrence of high temperature within the internal spaces of houses during summertime high temperature. Taking into account the results from the post-occupancy surveys, environmental monitoring, and the comfort surveys consistently suggest that overheating occurs, which appears to be attributed to the shortfall in minimum housing space standards and high level of insulation in timber houses. This suggests that excess heat gains cannot be easily dissipated and contribute to the increase of the internal temperatures and consequently overheating in the space.

6.9 Summary

This chapter discussed the results from the post-occupancy surveys carried out at the three case studies to evaluate thermal performance of timber housing in the UK. The post-occupancy results on the respondents' feeling of hot and cold in the summer and the winter were discussed. The results indicated overwhelming responses on the warm part of the scale suggesting the occupants feel much warmer in the summer. The responses suggested the residents were satisfied with the thermal environment of the case studies with lowest levels of evaluation for thermal satisfaction at Bridport. The post-occupancy results also indicated a noticeable shift in the occupants' responses to 'comfortable' and "very comfortable" part of the scale with lowest levels of evaluation for overall thermal comfort in the summer at Bridport. The occupants' responses during the post-occupancy surveys indicated high level of control at the case studies with half of the occupants indicating satisfaction for control at the case studies. The participants also indicated the bedroom as the warmest space at case studies but the results from environmental monitoring suggested otherwise at Bridport as the internal temperature of the living areas were much higher than the bedrooms. The responses during the surveys showed that the occupants were generally pleased with their experience at the case studies.

The results from environmental monitoring showed the monitoring periods at the two case studies (Bridport and Oxley Woods) did not suggest extreme summertime external temperatures, which could contribute to frequent occurrence of high internal temperatures in the spaces monitored. The mean external temperatures at the case studies were considerably lower than the average external temperatures obtained in London and Luton during the hottest month (August) in 2012. The mean internal temperatures in all the spaces monitored were within the comfort range. However, high temperatures were recorded for long hours within the internal spaces at Oxley Woods. The results from the winter survey indicated that the internal temperatures did not rise above the comfort range. The outcomes from the survey suggested high temperatures were noticed in all the spaces monitored.

This study found out that the occupants of the houses with smaller internal floor area indicated higher neutrality than the occupants of the houses with bigger internal floor area suggesting they adapt better to the internal conditions of the houses. More than half of the respondents indicated preference to be cooler in the summer at Bridport despite frequent warm conditions noticed during environmental monitoring at Oxley Woods than Bridport. In addition, thermal acceptability of the internal conditions by the respondents was higher at the case studies in the summer despite higher internal temperatures observed during the summer surveys especially at Oxley Woods. Further analysis of the surveys indicated that the occupants feel warmer in the upper floors than the ground floors of the houses. Thermal sensation was found to be correlated to voting time of the day in the summer which suggests occupants' feeling of hot tend to increase as the external temperature for the day increases. Comparing the post-occupancy survey and the comfort survey' results, the female occupants feel less warm in the summer than the male occupants at the case studies, which further indicate higher adaptability of the female occupants to the thermal environment.

Considering the factors influencing the occupants' decision to live at the case studies, the younger occupants decide to live at Oxley Woods due to location while the occupants with smaller household size decide to live at Stadthaus. The result further suggests that the apartments at Stadthaus are smaller when compared to Bridport and Oxley Woods. Due to the smaller size of the apartments at Stadthaus, male occupants decide to live in the apartments than the female occupants as they consider it affordable in terms of cost without considering the running cost. The residents that feel warmer in the summer use windows and doors to improve internal conditions of the houses at Oxley Woods while the occupants at Bridport only use windows as doors could not be used for ventilation regularly for safety reasons. Fans were used more often at night in the upper floors as well as internal blinds to keep direct sunlight out of the houses. The results further suggest the difference between further adaptive measures taken by the occupants living in urban and suburban dwellings to adjust the thermal conditions of the internal spaces. This may also contribute to higher dissatisfaction observed at Bridport as only half of the residents indicated high level of control to regulate the internal environments of the apartments.

Evaluation of the risk of overheating at the case study buildings using the CIBSE 'static' criteria and the dynamic adaptive comfort (BSEN15251) model was carried out. The findings from the analysis for the static comfort model showed 50% of the living areas monitored at Bridport and Oxley Woods exceeded the 5%/25ºC threshold. The results suggested overheating occurred in half of the living areas monitored at the buildings. Also, 43% of the living areas monitored at the buildings exceeded the 1%/28ºC threshold suggesting extreme summertime overheating occurred in the living areas. Considering the bedrooms monitored during the summer, 56% exceeded the 5%/24ºC threshold and 67% exceeded the 1%/26ºC threshold. The results also suggested extreme summertime overheating in the bedrooms using the static 'CIBSE' model. The results from the approved BSEN15251 standard indicated warm discomfort in 70% of the spaces at Oxley Woods in the summer while the results suggested warm discomfort in 50% of the spaces at Oxley Woods and Bridport in the summer.

Comparing the findings from the surveys suggest higher thermal satisfaction of the occupants at Oxley Woods than Bridport despite higher internal temperatures observed at Oxley Woods. This chapter concluded that overheating occurs in the houses and the occupants are thermally satisfied despite higher internal temperatures observed at the buildings in the summer. The respondents indicated preference to be much cooler in the summer when the temperature rises. The results also showed that the occupants at Oxley Woods have a better understanding for control than Bridport. The next chapter will discuss the results from dynamic thermal simulations.

Chapter 7 Analysis of Data and Findings on Dynamic Thermal Modelling and Simulation

7.1 Introduction

"Immediate action is required to gain a better understanding of overheating in dwellings; a point of concern for current and more recently built homes, not just future designs. A suitable model for determining overheating of new homes needs to be validated or identified and a combination of desk research and practical testing is necessary. Such is the dearth of test data from UK homes that activity this summer is likely to be required. This will enable the opportunity to develop an improved simplified tool for assessing overheating; a critical step which determines the direction of the subsequent development of the carbon compliance tool."

- DCLG (2012b: Investigation into Overheating in Homes: Literature Review, pp. 70-71).

As earlier explained in Chapter 6, findings from the surveys (post-occupancy and comfort surveys) and environmental monitoring indicate a potential of summertime high internal temperatures; this chapter considers dynamic thermal modelling and simulation using DesignBuilder software (3.2.0 version) to further examine the potential of summertime overheating at the three case studies (Bridport, Oxley Woods and Stadthaus). Dynamic thermal modelling and simulations are necessary for this study due to the limited period (2 weeks) of conducting environmental monitoring at Bridport and Oxley Woods which was carried at different times as the results could only be compared for the two buildings within the periods. Moreover, physical measurements were not conducted at Stadthaus due to limited permission granted to access the building and it is important to understand the performance of the development along with the two other buildings monitored in the summer for comparison.

The scope and method considered for the simulations as well as various assumptions made for the modelling will be considered. The case studies were considered as free-running and emphasis will not be on heating and cooling during the period of simulation. The parameters (floor-to-ceiling height, size of windows) considered for thermal modelling and simulation in the buildings will be examined. Also, the results from the calibrated data will be explained. The comparison of the results with monitored data will be discussed and the data with any significant variations will be mentioned. The reasons for the variations will also be highlighted. The internal temperatures that were predicted during dynamic thermal simulations of the internal spaces will be discussed.

Analysis of the risk of summertime overheating using the static criteria and the dynamic adaptive comfort model will be presented. Overheating will be evaluated in all the spaces considered in Chapter 6. In addition, overall calculated internal temperatures in the five houses at Oxley Woods will be examined. The results will provide a good picture of thermal performance of the case studies under the same external weather conditions as London Islington TRY and St Albans TRY weather data files will be used for the simulations. The carbon emissions scenarios for the two TRY weather files used are classified as medium as discussed by Du *et al.* (2011).

The findings from dynamic thermal simulations will be outlined and compared with the findings previously examined in Chapter 6. Similarities and differences between the results will also be presented. In the last part of this chapter, the overall lessons from the comparative analysis from the surveys and dynamic thermal simulations will be discussed.

7.2 Scope and Method

The focus on all the case studies investigated is to understand the thermal performance of the buildings using the same external weather conditions. The modelling, calibration and analysis of the simulated data provide the means to achieve reliable results from dynamic thermal simulations that will further support the findings from the field surveys as discussed in Chapter 6.

The modelling of the buildings was done in accordance with the approved designs in order to analyse the performance of the building by comparing the results. In addition, few assumptions were made such as ventilation rate, general lighting required was properly checked to reflect the features in the buildings in the real world situation. The wall construction, floors, roofs, windows, doors discussed in Chapter 5 were done accordingly and thermal properties of the buildings’ components were considered.

7.2.1 Assumptions for Predicting Current Performance of the Case Studies

Based on the field surveys carried out at the case studies as discussed in Chapter 6, it was possible to estimate variables like the building total floor areas, density (people/m²), hours of occupancy, area of openings (windows, doors), metabolic actions used for dynamic thermal simulations especially at Bridport and Oxley Woods where environmental monitoring and comfort surveys were conducted in the summer and the winter. However, some assumptions (such as outside air change rate) were made across the three case studies to represent input variables into dynamic thermal modelling and simulations that cannot be easily calculated in terms of quantity. In addition, assumptions regarding the infiltration rate, general lighting, task and display lighting were calculated where required using guidelines based on recommendations stated in CIBSE (2006, 2010). The three case studies were operated as free-running in the summer; therefore, no assumptions regarding set-points were made on mechanical means of cooling and heating of the internal spaces.

The weather data files for the current year, in reference to the year 2002 (Test Reference Year- TRY) were employed. The simulation period between 1st May and 30th September was considered as a typical summer period in the UK for analysis. Since the aim of the research is to investigate the potential of high internal temperature in the buildings, the winter period between 1st October and 30th April will not be considered for dynamic thermal simulation. Moreover, the results from environmental monitoring did not suggest overheating occurs in the winter.

Concerning the infiltration rate at atmospheric pressure, which is described as unintended flow of air through the envelope, possible cracks was placed at 0.12ach for Bridport and Stadthaus (CLT panels) while it was placed at 0.15ach for Oxley Woods (SIP) as the buildings were not built to passive standards and they will require further modifications to meet the requirements for passive design. The outside air described as the most crucial variable to calculate precisely and the most vital parameter to take into consideration when carrying out dynamic thermal modelling and simulation of free-running houses was considered. The rate of outside air change (ach) for internal spaces in two storey dwellings with cross ventilation during summertime high temperature should not exceed 8ach (DECC, 2009); while dwellings with all the internal spaces (including bedrooms, bathrooms) and other circulation spaces such as atrium with no cross ventilation should not exceed 5ach (DECC, 2009; DesignBuilder 2009, p.110). The outside air change rate was placed at 4.0ac/h for Oxley Woods and Stadthaus while it was placed at 5.0ac/h for Bridport due to the larger sizes of floor area of internal spaces and windows as well as higher floor-to-ceiling heights. The scheduled natural ventilation settings are often considered for the thermal modelling of the buildings for a fast and easy calculation of external ventilation, internal ventilation and infiltration (DesignBuilder, 2009). For the scheduled natural ventilation settings to be used for the simulations, the following conditions were assumed. All the external windows and doors were closed at night and kept open during the daytime. The impact of the ventilation settings for the modelling indicated that natural ventilation was scheduled (for instance, from 07:00-22:00) to show the conventional use of the spaces monitored at the case study buildings in the summer.

The general lighting required within the internal spaces was relatively small (placed at 2.0W/m²) as most of the internal spaces considered were using energy saving bulbs. Task and display lighting used for certain activities such as desk lamp for reading, bed-side lamp was left at best practice (0.5W/m²) as the hours of using task and display lighting were minimal due to shorter nights in summertime.

The calculated internal temperatures at the case studies were analysed using the CIBSE static comfort criteria (5%/25ºC and 1%/28ºC for living areas as well as 5%/24ºC and 1%/26ºC for bedrooms) and the dynamic thermal comfort BSEN15251 standard as discussed in Chapter 6 in order to evaluate the risk of overheating. Since the temperatures at which indoor occupants find most comfortable must be within the comfort range (22-25ºC) as explained in Chapter 2, overheating analysis was carried out using the two criteria. Comfort within the thermal environment is subjective and often desired or preferred at certain range of temperature. The use of assumptions were limited in this study to provide calculated values for the internal conditions of the buildings throughout a typical summertime since environmental monitoring carried discussed in Chapter 6 was carried within a limited period of time (June-July). The dynamic thermal simulation provided a wider picture of the performance of UK timber houses in summer.

7.2.2 Thermal Modelling and Calibration

Modelling and calibration were employed in order to calculate precisely the internal temperatures of the case studies investigated under a free-running condition. Preference was set on the charts that provide a close range as well as a similar pattern between environmental monitoring data and calculated data (internal temperature) of hours over 26ºC and 28ºC, the CIBSE point of references for evaluating internal temperature of bedrooms and living rooms respectively (CIBSE, 2006). All the internal spaces monitored at Oxley Woods (A1WLGFL, A1WLFFFB, A6MLSFBB, A38MLGFL, A38MLFFFB, A38MLFFBB, A142HAGFL, A142HASFBB, A162HAGFL, A162HAFFBB)[33] and three of the spaces monitored (FL1GFL, FL1FFB, FL7FFFB)[34] at Bridport were considered for the calibration as environmental monitoring period at Bridport in the summer was considered mild and wet. The calibration was done for all the spaces highlighted using the two weather data files (London Islington TRY and St Albans TRY) considered in this chapter (Figures 7.1-7.5).

The case studies were modelled with the application of DesignBuilder simulation software as discussed in Chapter 4. The weather data files generated by the Prometheus Group from the University of Exeter were used (Eames *et al.*, 2011). The floor area of the internal spaces at the case studies and volume were taken into consideration. For instance, two-bed flat at Bridport (area 80m² and volume 212m³), two-bed house with no study at Oxley Woods (area 77m² and volume 181m³) and two-bed apartment at Stadthaus (area 65m² and volume 153m³) were considered for the spaces highlighted as discussed in Chapter 4. In addition, floor-to-ceiling heights were also taken into consideration during the modelling at Bridport (2.65m), Oxley Woods (2.35m) and Stadthaus (2.35m). The living areas across the three case studies were at least 6m deep while all the bedrooms have a minimum depth of 3m. The area of the open windows must not be less than 1/20 of the floor area of the internal spaces (BSI, 1991). All the dimensions of the windows and doors including the areas were checked and the appropriate U-values were assigned to the openings as stated in the specification documents and verified on site where

[33] Where A1WLGFL is (A1 Welles ground floor living area), A1WLFFFB (A1 Welles first floor front bedroom), A6MLSFBB (A6 Milland second floor back bedroom), A38MLGFL (A38 Milland ground floor living area), A38MLFFFB (A38 Milland first floor front bedroom), A38MLFFBB (A38 Milland first floor back bedroom), A142HAGFL (A142 Holden ground floor living area), A142HASFBB (A142 Holden second floor back bedroom), A162HAGFL (A162 Holden ground floor living area) and A162HAFFBB (A162 Holden first floor back bedroom).

[34] FL1GFL- Flat 1 ground floor living area, FL1FFB- Flat 1 first floor bedroom and FL7FFB- Flat 7 first floor front bedroom.

possible. The window height at Bridport is 2.1m, Oxley Woods is 1.35m and Stadthaus is 1.0m with up to 35% window to wall ratio at Bridport.

The simulation of the entire buildings (for instance at Bridport with area 4,220m² and volume 11,183m³; Stadthaus with floor area 2,750m² and volume 6,462.5m³) was done since no retrofit interventions was required for the models which could possibly require changing some of the variables. Therefore, it was possible to carry out dynamic thermal simulation for the buildings. Some of the crucial parameters that could arbitrarily affect the reliability of the modelling and overall results of the simulation were identified and properly checked for necessary adjustment before the simulation was carried out. All the spaces that were prone to heat gain from internal sources such as appliances were checked. The opening and closing sessions of windows and doors were adjusted accordingly to meet the occupants' lifestyle as observed during environmental monitoring and comfort surveys.

Forecast regarding window opening actions of indoor occupants during night-time are crucial and cannot be easily made (Lomas & Giridharan, 2012; Porrit *et al.,* 2012); however, priority must be given to reliable results with precise window opening actions that produce a similar pattern of results with measured data (Strachan, 2008). Concerning the window opening actions of the occupants during night-time, the opening and closing sessions were done in accordance with the results obtained from the state loggers used to monitor opening and closing sessions during environmental monitoring. For instance in A1WLFFFB at Oxley Woods where the windows monitored were left open for more than 80% of the time during monitoring period in the summer, the window opening sessions for the period of simulation was set between 07:00 and 23:00 indicating at least 75% window opening time as reflected in the calibration shown in Figure 7.1. In the spaces where the windows opening and closing actions of the occupants were not monitored, opening and closing sessions that best represent the occupants' lifestyle were used. The window opening actions observed during the field surveys provided a reliable means for calculation since the actions to open or close windows during the period is subjective and based on the occupants' preference for higher air movement within the space at night-time.

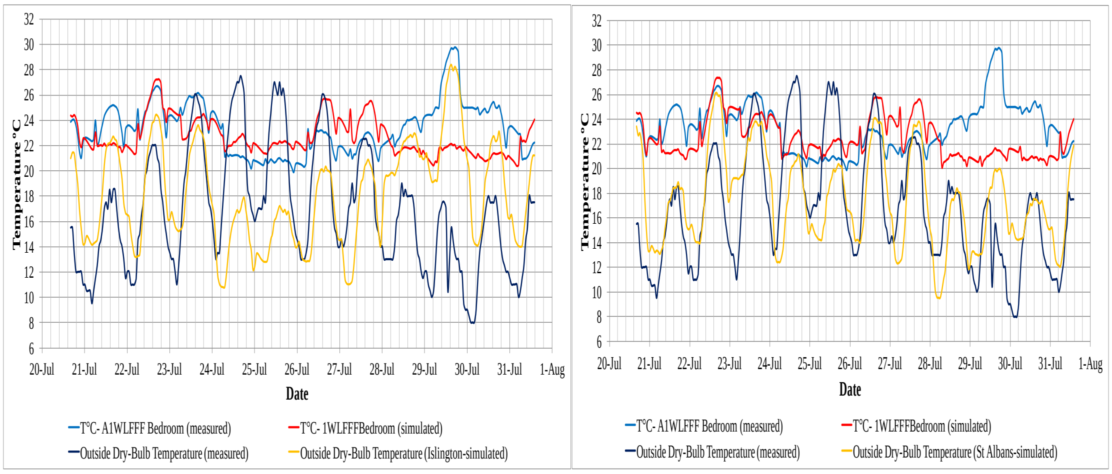

Figure 7.1: Calibration of monitored and calculated temperatures in A1WLFFFB and external temperature for London Islington-TRY (left) and St Albans-TRY (right).

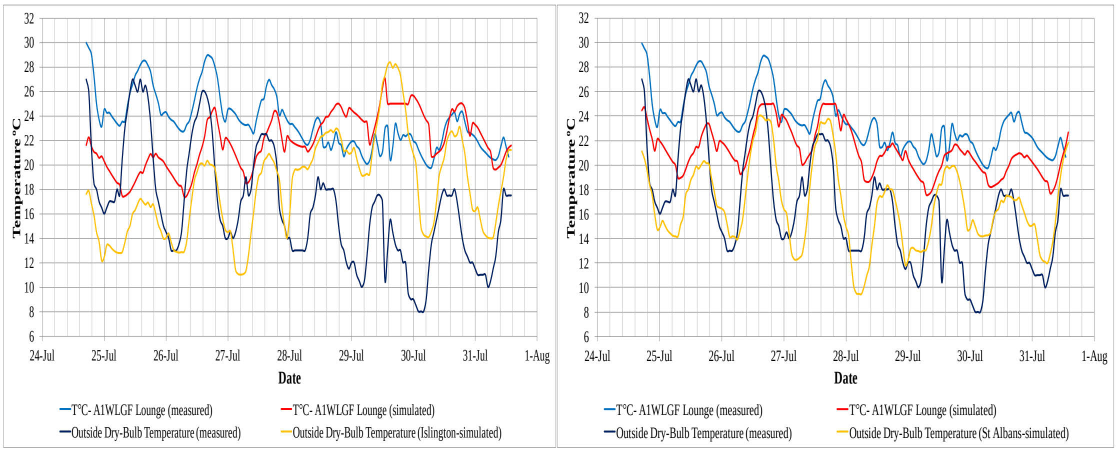

Figure 7.2: Calibration of monitored and calculated temperatures in A1WLGFL and external temperature for London Islington-TRY (left) and St Albans-TRY (right).

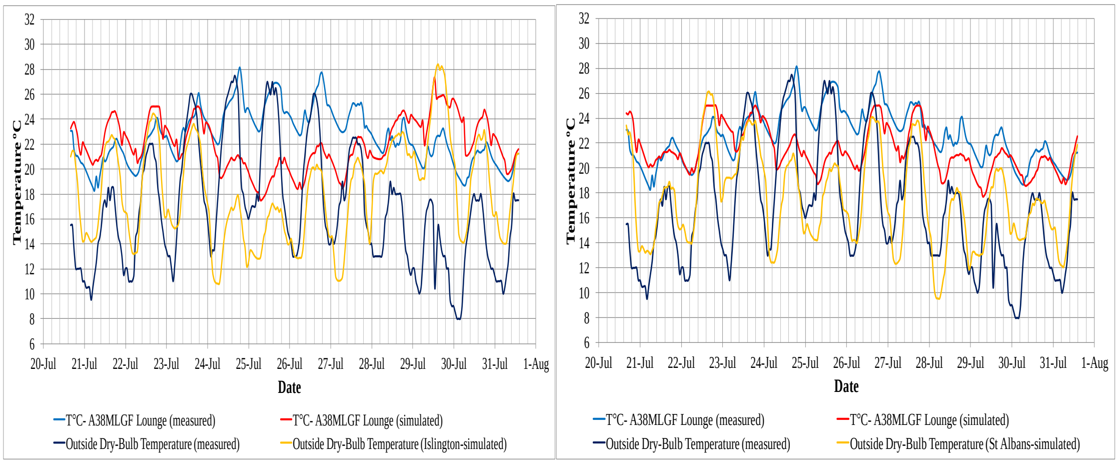

Figure 7.3: Calibration of monitored and calculated temperatures in A38MLGFL and external temperature for London Islington-TRY (left) and St Albans-TRY (right).

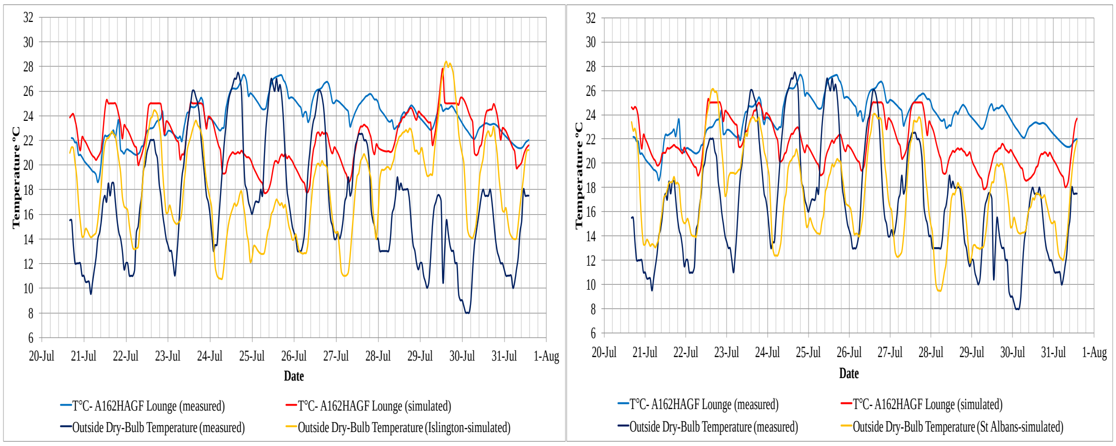

Figure 7.4: Calibration of monitored and calculated temperatures in A162HAGFL and external temperature for London Islington-TRY (left) and St Albans-TRY (right).

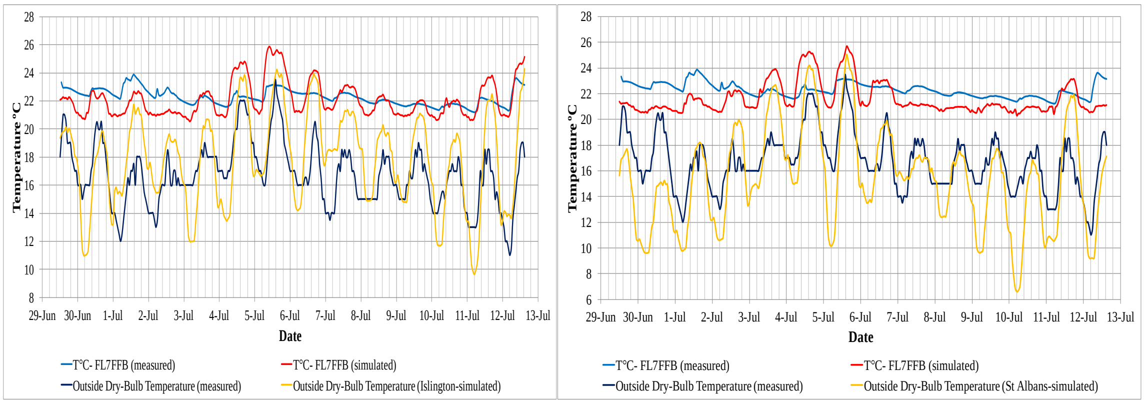

Figure 7.5: Calibration of monitored and calculated temperatures in FL7FFB and external temperature for London Islington-TRY (left) and St Albans-TRY (right).

Since the models were set as free-running across the case studies, the calculated internal temperatures were mainly influenced by window opening sessions and fabric of the houses and no heating and cooling were introduced which could change the overall outcome of the simulation. Looking at the calibration of the calculated data and the monitored data in the internal spaces considered, the peak temperatures indicate alignment with the data obtained during environmental monitoring in the summer. The differences between the maximum temperatures of simulated data and monitored data was usually within a range of 2ºC as earlier considered by Lomas & Giridharan (2012) for most part of the calculated data to be considered credible when carrying out overheating analysis (Lomas *et al.*, 1997). The findings from the values obtained during calibration of calculated data and monitored data suggest a high degree of alignment between the simulated data and the monitored data for the average day-time temperature in the living areas, the average night-time temperature in the bedrooms as well as number of hours that rose above the CIBSE point of reference (28ºC) within the internal spaces.

7.3 Clarification of the Weather Data Files Used For the Modelling

The Test Reference Year (TRY) weather files for the 2000s were considered for the simulation. Generally in the UK, dynamic thermal modelling and simulation of buildings for compliance are carried out using the TRY weather files (Kershaw *et al.,* 2010). Also, the TRY weather files are used for energy analysis while the Design Summer Year (DSY) weather data files are used for assessing summertime overheating in buildings (Kershaw *et al.,* 2010; Eames *et al.,* 2011). The TRY weather files were considered for the simulation as the files consist of a representative year compiled of the mean months from more than two decades or a year indicating a hot but not an extreme design summer year (Kershaw *et al.*, 2010). Since 2012 (the year that the summer surveys were carried out) was not an extreme design summer year when compared to the summer of 2003 (the heat wave period in the UK), the TRY weather files were considered over the DSY weather files. The research investigates the performance of the case study buildings in the summer and not in an extreme summertime. Also, the TRY weather files were considered as they minimised the computational efforts required in dynamic thermal modelling of the case study buildings (Eames *et al.*, 2011). However, the TRY weather files may not accurately estimate the risk of summertime overheating but how well the TRY weather data files work depends on the database from which they were computed in order to evaluate the risk of overheating and carry out energy analysis of buildings (Kershaw *et al.,* 2010). This study considered the TRY weather files generated by the Prometheus Group of Exeter University which had been used in past studies for evaluation of the risk of summertime overheating (Kershaw *et al.*, 2010; Eames *et al.*, 2011). In addition, other studies focusing on the thermal performance of houses in summer have used the TRY weather files for evaluation of overheating risk (Pereira & Ghisi, 2011; Kendrick *et al.*, 2012).

The two TRY weather data files (London Islington and St Albans) used for the simulations were selected due to proximity of the sources of the weather data files to the case study buildings. Also the two weather files were chosen based on the available weather data files generated by the Group for comparison. The two files were considered to understand the thermal performance of the case study buildings under the same external weather conditions in the summer (not in an extreme summertime) at two different locations in the warmest region of the UK (that is, southeast of England).

7.4 Analysis of Predicted Current Typical Year (Test Reference Year-TRY) Temperatures

The findings from environmental monitoring conducted at the case studies examined in Chapter 6 suggest the mean external temperature at Bridport was 16.7ºC and 16.8ºC at Oxley Woods during the summer survey. Considering the simulated results from May to September indicate mean external temperature of 15.2ºC for London Islington TRY and 13.7ºC for St Albans TRY. The average external temperature of 17.6ºC is predicted for London Islington TRY between the 29th June and the 31st July which is the period for the monitoring at the case studies in the summer. Also, the mean external temperature of 15.7ºC is predicted for St Albans TRY for the monitoring period (that is, 29th June to 31st July). This suggests mean external temperature for a predicted current year is considerably lower than the mean external temperature observed during environmental monitoring at the two case studies. Also, analysis suggests the external temperature of London Islington rose above 25ºC for 62 hours and above 28ºC for 4 hours while St Albans external temperatures was more than 25ºC and 28ºC for 84 hours and 2 hours respectively. The findings suggest the possibility of high internal temperatures within the houses simulated with the two weather data files.

The running mean temperature of the simulated outdoor temperature, T_{rm}, as described in BSEN15251 (BSI, 2008) rose to 20.4ºC on 15th August for London Islington TRY and 18.4ºC on 28th July for St Albans TRY. The average running mean temperature was 15.6ºC for London Islington TRY and 14.1ºC at St Albans TRY. The analysis suggests that the summer period from the two weather files considered for this study was cooler when compared to the average running mean temperature observed during the monitoring periods at Bridport (17.5ºC) and Oxley Woods (16.8ºC) in the summer. Table 7.1 summarises features of London Islington TRY and St Albans TRY for the current year conditions.

Table 7.1: Description of London TRY and St Albans TRY external temperatures for the current year (May-September) used for dynamic thermal simulations

Year-2002 TRY	Temp above 25ºC (hours)	Temp above 28ºC (hours)	Maximum temp. (ºC)	Minimum temp. (ºC)	Mean temp. (ºC)	Maximum running mean (ºC)	Minimum running mean (ºC)
London Islington	62	4	28.4	2.5	15.6	20.4	8.7
St Albans	84	2	28.3	1.0	14.1	18.4	6.7

* The TRY external temperature for the 2000s is derived from the weather generator produced by the Prometheus Group (UKCP09).

The calculated mean internal temperature at Bridport was 20.1ºC with a peak temperature of 27.2ºC and a low of 13ºC for London Islington TRY. The mean temperature for St Albans TRY was 19.0ºC with a maximum of 27.3ºC and a minimum of 12.8ºC expected. For London Islington TRY at Oxley Woods, the mean temperature was 21.2ºC, a peak of 27.9ºC and a minimum of 16.9ºC simulated while mean temperature of 20.5ºC, a maximum of 27.8ºC and a low of 16.3ºC predicted for St Albans TRY. At Stadthaus, the mean temperature of 21.3ºC, a maximum of 27.6ºC and a minimum of 16.3ºC for London Islington TRY an average of 20.6ºC, a peak of 27.7ºC and a low of 15.9ºC for St Albans TRY. The analysis across the three case studies suggests Bridport is considerably cooler than the two other case studies while Oxley Woods appears to be warmer than Bridport and Stadthaus.

For the internal spaces, the calculated mean internal temperature in the living areas at Bridport was 20.7ºC and 22.2ºC in the bedrooms for London Islington TRY while mean temperatures of 19.7ºC and 21.8ºC predicted for the current year in the living areas and the bedrooms respectively at Bridport when considering St Albans TRY. At Oxley Woods, the mean temperature of 20.8ºC was observed in the living areas and 21.4ºC in the bedrooms for London Islington TRY. Concerning St Albans TRY at Oxley Woods, the predicted mean temperature in the living areas was 20.1ºC and 20.7ºC in the bedrooms. The analysis at the two case studies suggests higher temperatures in the bedrooms than the living areas. In addition, the results further indicate that the internal temperatures of the spaces at Oxley Woods are higher than the indoor spaces at Bridport when simulated as free-running using the same weather data files.

Taking into account, the internal spaces monitored at Bridport and Oxley Woods during the environmental monitoring for dynamic thermal simulation. The findings suggest at Bridport, the expected mean temperature in the hottest living area (FL35SFL) was 19.2ºC with a maximum temperature of 28.3ºC and a minimum of 12.9ºC for London Islington. For St Albans, the anticipated mean temperature in FL35SFL was 17.8ºC, a peak of 28.4ºC and a lowest of 13.3ºC. At Oxley Woods, the predicted average temperature in A142HAGFL (the hottest living area) was 22.0ºC with a maximum of 29.8ºC and a low of 19.5ºC for London Islington. The mean temperature of 21.4ºC, a peak of 28.6ºC and a minimum of 19.4ºC were calculated in A142HAGFL for St Albans. The hottest bedroom (FL1FFB) at Bridport indicated the average temperature of 21.8ºC while a maximum and minimum temperature was 30.4ºC and 18.7ºC for London Islington. Furthermore, the peak temperature of 28.9ºC and a low of 17.7ºC and mean temperature of 21.4ºC were predicted for St Albans. At Oxley Woods, the mean temperature of 22.2ºC, a maximum of 31.4ºC and a low of 17.2ºC were expected in A142HASFBB predicted as the hottest bedroom when considered for London Islington. Likewise, a peak temperature of 31.1ºC, a minimum of 16.1ºC and the average of 21.6ºC were expected in A142HASFBB for St Albans. Overall analysis suggests lower temperatures were anticipated in the living rooms and the bedrooms at Bridport than Oxley Woods.

In order to understand the relationship between the calculated average internal temperature and the external temperature at the case studies, regression analysis was considered. The analysis as shown in Figure 7.6 suggests that the predicted mean temperature in the bedrooms is higher than the living areas at Bridport with a considerable difference of over 4.5ºC when the external temperature is low. However, the trend changes when the external temperature rises as the living area appears to be warmer than the bedrooms once external temperature exceeds 2.0ºC for London Islington and St Albans. The spaces simulated under London Islington have higher temperatures than St Albans as expected due to dense urban environment at London Islington. In addition, the internal temperatures are within the comfort range until the external temperatures rise above 24ºC conforming to the monitored results observed at Bridport in the summer as the average internal temperature tend to rise above the comfort range when the external temperature also rose above 24ºC. At Oxley Woods, the mean internal temperature of the bedrooms is higher than the living rooms with 1.5ºC higher for London Islington and 1.0ºC for St Albans when the external temperature reduces with a slight difference of

0.1ºC higher in the bedrooms when the external temperature rises (Figure 7.7). In both cases (London Islington and St Albans), the bedrooms indicate higher temperature than the living areas at Oxley Woods throughout the simulated period for summertime in the current year. The indoor temperatures are also within the comfort range for most of the time until external temperature rose above 24ºC. The analysis suggests comfort is within a wider range at Bridport than Oxley Woods. The findings also suggest there is a strong correlation between the simulated internal temperature and the external temperature at the case studies as found out in Figures 7.6 and 7.7.

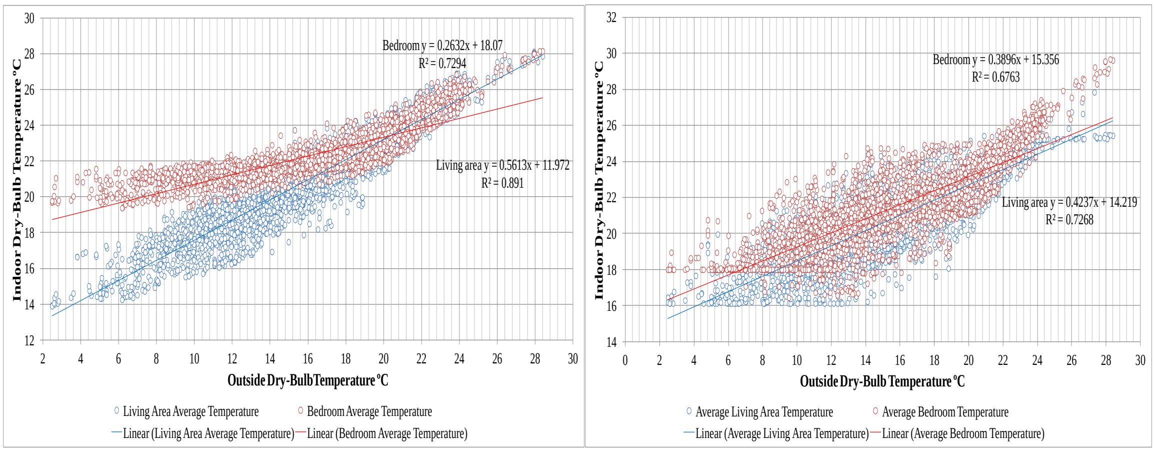

Figure 7.6: Relationship between the calculated mean internal temperature in the living areas and the bedrooms simulated at Bridport (left) and Oxley Woods (right) and the external temperature using London Islington TRY.

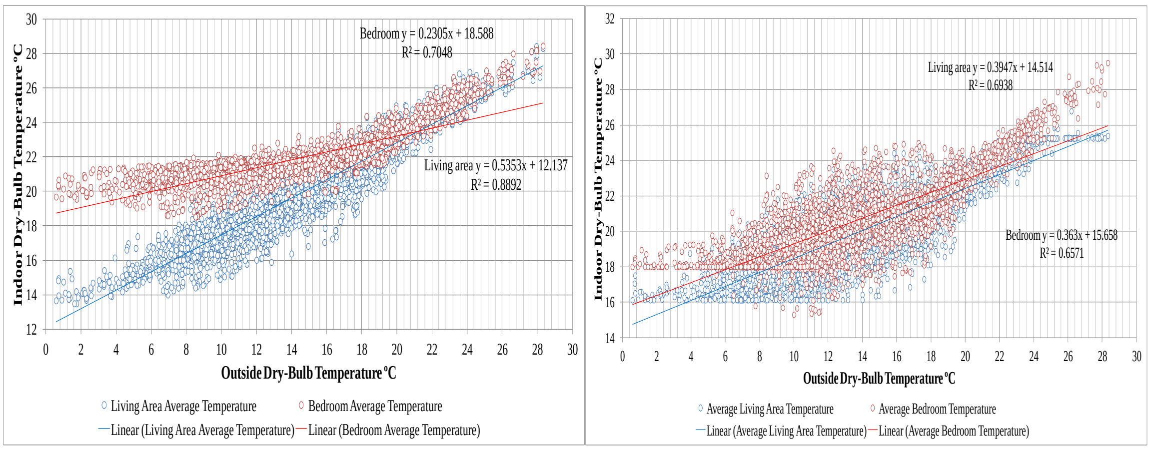

Figure 7.7: Relationship between the calculated mean internal temperature in the living areas and the bedrooms simulated at Bridport (left) and Oxley Woods (right) and the external temperature using St Albans TRY.

Concerning the houses at Oxley Woods using London Islington and St Albans weather data files, A142HA appears to be the warmest house in both cases with a difference of 0.4ºC when the external temperature reduces but rises up to 1.0ºC as the external temperature rises (Figure 7.8). A162HA appears to be the warmest house and A6ML the coolest house when the external temperature is low but there is a change in trend as the external temperature rises and the analysis suggests that A162HA is the coolest towards the end of the period while A142HA is the warmest. Across all the houses at Oxley Woods, the indoor temperature is within the comfort range until outdoor temperature increases more than 24.0ºC. The results further show that comfort is within the same range for the houses at Oxley Woods with a difference of up to 0.5ºC between the coolest and the warmest house at the beginning of the simulated period but the difference rose up to 2.0ºC towards the end of the period.

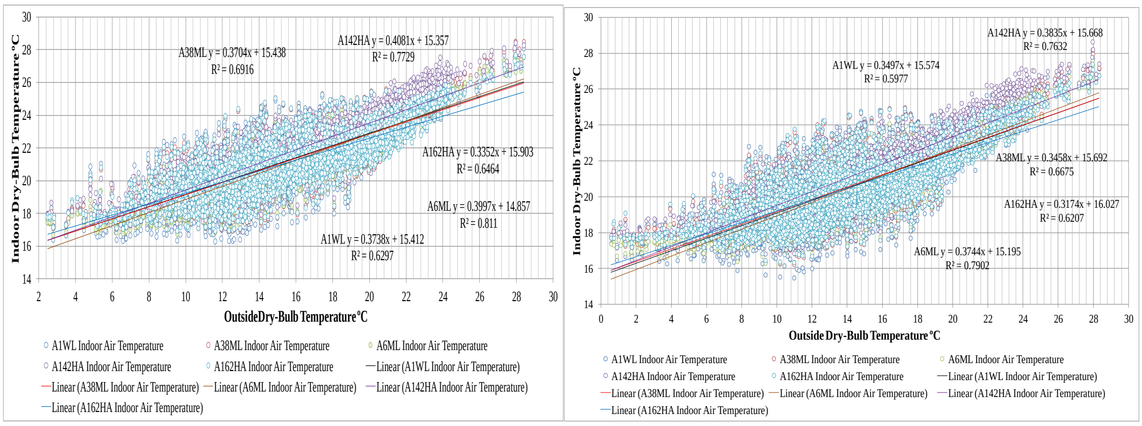

Figure 7.8: Relationship between the calculated mean internal temperature of the houses simulated at Oxley Woods and the external temperature using London Islington TRY (left) and St Albans (right).

Regression analysis was considered to understand the relationship between the calculated internal temperature at the case studies and the external temperature. The analysis suggests Oxley Woods and Stadthaus are considerably warmer than Bridport but Oxley Woods is moderately warmer than Stadthaus. The findings indicate higher temperature of 2.0ºC and 2.5ºC at Oxley Woods and Stadthaus than Bridport when the external temperature is low for London Islington, while 2.5ºC and 3.0ºC higher temperature was predicted at Oxley Woods and Stadthaus for St Albans when compared to Bridport (Figure 7.9). The internal temperatures across the three case studies appear to be within the same range when the external temperature rises above 24ºC. In both cases, Oxley Woods appears to be the warmest case study with temperature range from 16.1ºC to

26.4ºC for London Islington and from15.8ºC to 26.0ºC for St Albans. The findings indicate lower calculated internal temperatures at Bridport than Stadthaus and Oxley Woods. The analysis also suggests a difference of up to 1.5ºC between the anticipated internal temperature at Oxley Woods and Bridport when the external temperature is more than 22.0ºC. The results show Bridport is within a wider comfort range (2.0ºC) than Oxley Woods and Stadthaus. While Oxley Woods appears to be within a comfort range at 0.5ºC lower than Stadthaus at the beginning of the simulated period and vice versa towards the end of the period.

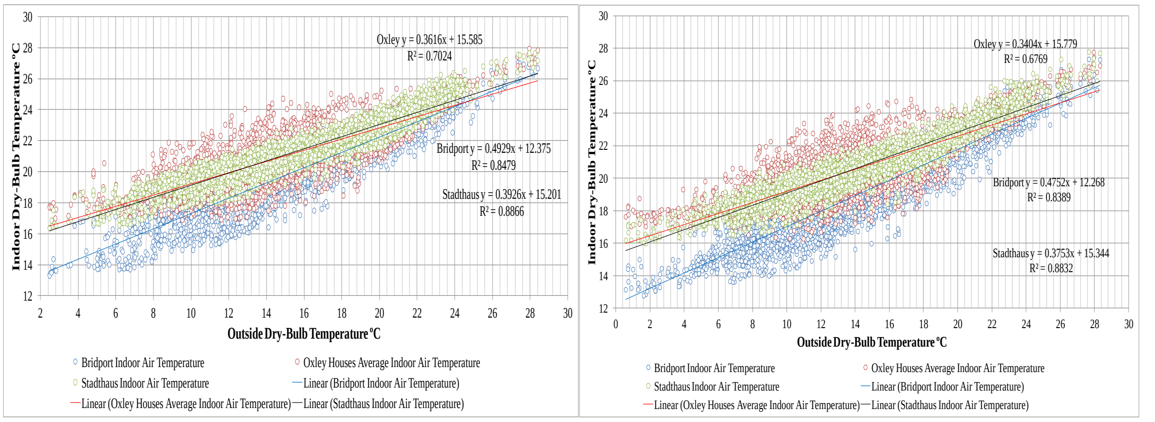

Figure 7.9: Relationship between the calculated mean internal temperature of Bridport, Oxley Woods, Stadthaus and the external temperature using London Islington TRY (left) and St Albans TRY (right).

Considering the internal floor area of the spaces at the case studies, the volume of a one-bed flat at Bridport is 154m³ and one-bed house (ground floor and upper floor) at Oxley Woods is 145m³ (that is, approximately 73m³ volume per floor). At Stadthaus, the volume of a one-bed apartment is 113m³, which suggests the possibility of internal spaces of smaller dwellings at Oxley Woods and Stadthaus to experience frequent high temperatures very quickly than the internal spaces of the bigger apartments at Bridport. The analysis suggests the internal temperatures of the bigger spaces at Bridport are likely to rise when there is extreme summertime high temperature. The findings suggest possibility of the three case studies indicating a similar range of calculated internal temperature when external temperature rises above 24ºC with a difference of 0.5ºC between the hottest case study (Oxley Woods) and the coolest (Bridport). However, the internal spaces at Bridport are likely to take longer time to cool when the internal temperature rises above comfort threshold for long period as shown in Figure 7.10.

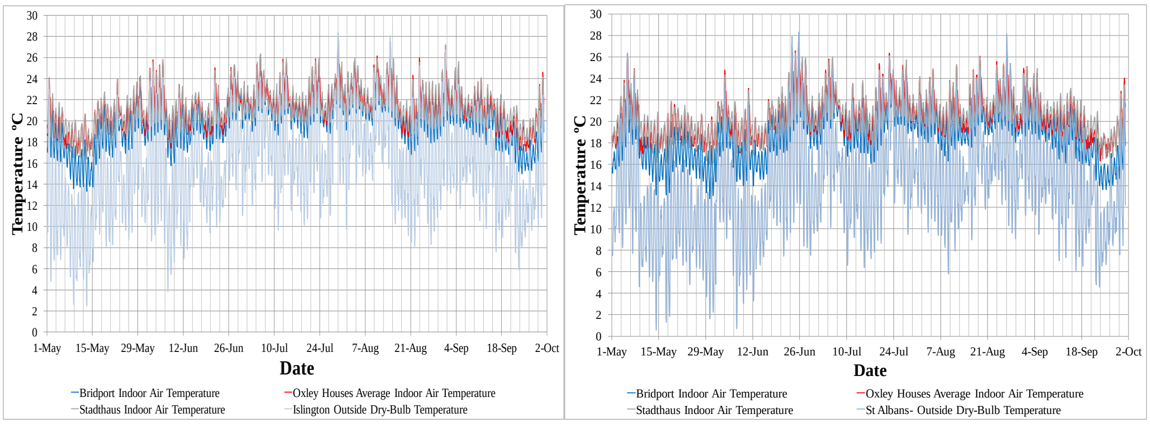

Figure 7.10: Calculated internal temperature of Bridport, Oxley Woods and Stadthaus and external temperature using London Islington TRY (left) and St Albans TRY (right).

7.5 Overheating Analysis of Predicted Current Year Indoor Temperatures

As considered in Chapter 6, overheating analysis of the simulated temperatures in the internal spaces at Bridport and Oxley Woods is analysed below using the static CIBSE criteria of 5%/25ºC and 1%/28ºC for the living areas and 5%/24ºC and 1%/26ºC for the bedrooms. Furthermore, findings from evaluation of the overheating risk at the internal spaces at the case studies using the approved dynamic thermal comfort criteria (BSEN15251) are discussed below with 5% of hours above and below the Cat. II upper and lower indicators to identify warm discomfort and cold discomfort in all the spaces considered at the two case studies.

7.5.1 Overheating Analysis Using the CIBSE Static Criteria at Bridport, Oxley Woods and Stadthaus

Figures 7.11 to 7.15 below show analysis of the risk of overheating at Bridport and Oxley Woods. The Figures (7.11-7.14) explain the percentage of hours above 25ºC and 28ºC for the living areas while Figure 7.15 illustrates the percentage of hours over 24ºC and 26ºC for the bedrooms considered. For London Islington and St Albans, the analysis shows that 57% of the living areas simulated were above 25ºC for more than 5% of the time and 14% of the living areas exceeded 25ºC for more than 10% of the time. The analysis also suggests that 50% of the bedrooms exceeded 24ºC above 5% of the time for London Islington while 13% of the bedrooms exceeded 24ºC above 5% of the time for St Albans.

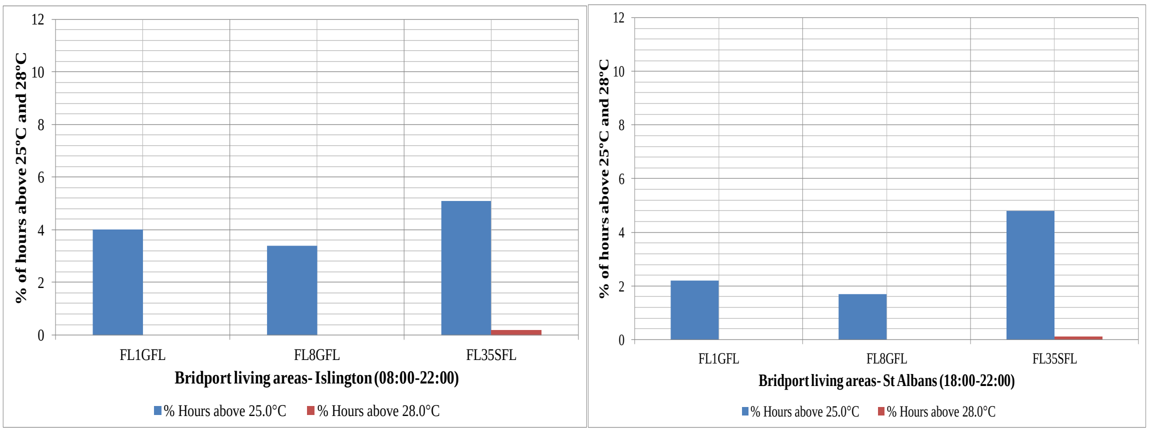

Figure 7.11: Calculated temperatures and overheating risk criteria, free-running living areas (08:00-22:00) and (18:00-22:00) at Bridport using London Islington TRY.

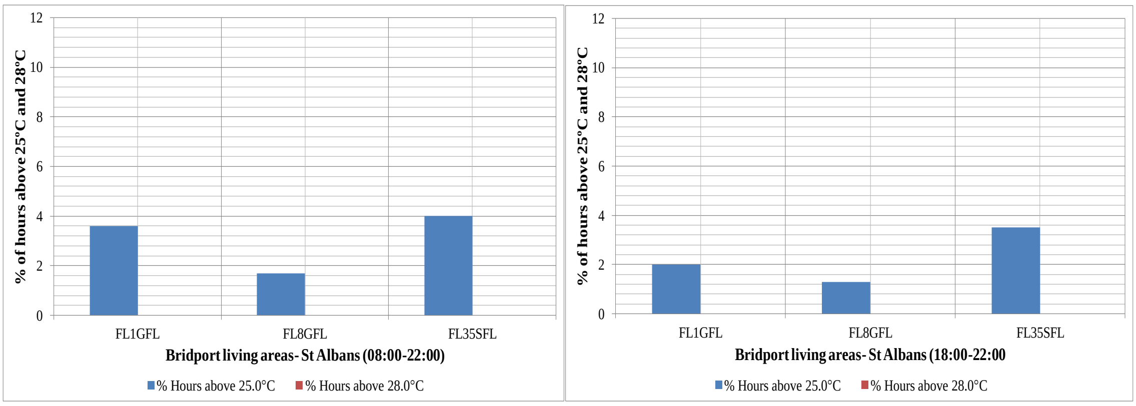

Figure 7.12: Calculated temperatures and overheating risk criteria, free-running living areas (08:00-22:00) and (18:00-22:00) at Bridport using St Albans TRY.

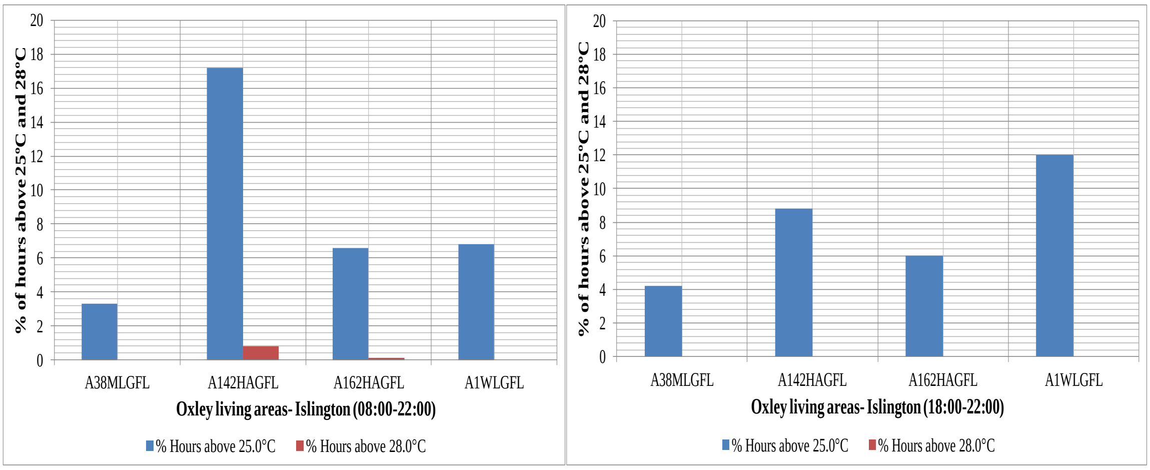

Figure 7.13: Calculated temperatures and overheating risk criteria, free-running living areas (08:00-22:00) and (18:00-22:00) at Oxley Woods using London Islington TRY.

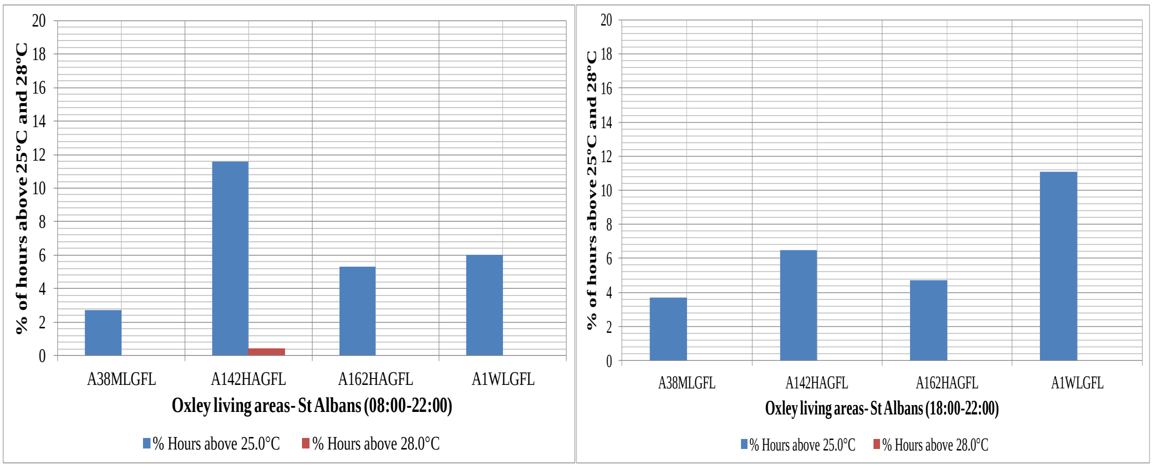

Figure 7.14: Calculated temperatures and overheating risk criteria, free-running living areas (08:00-22:00) and (18:00-22:00) at Oxley Woods using St Albans TRY.

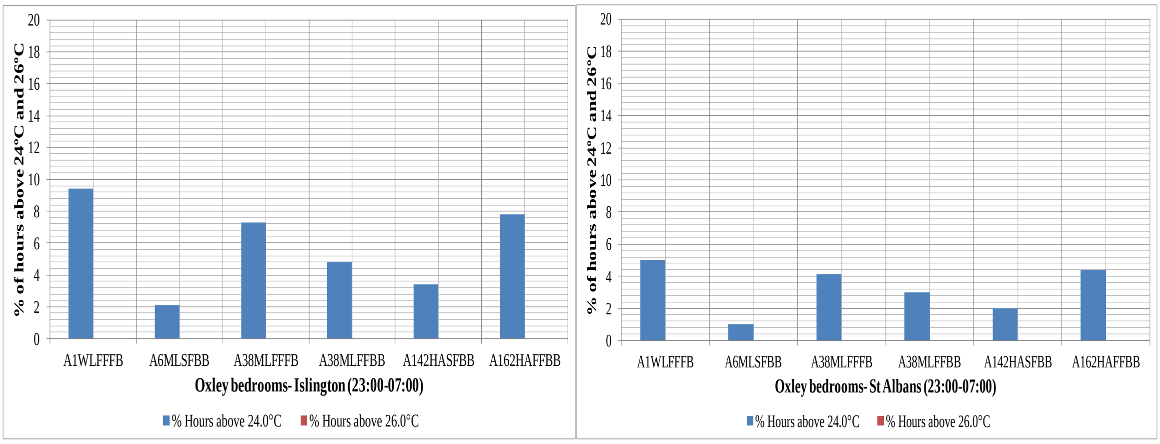

Figure 7.15: Calculated temperatures and overheating risk criteria, free-running bedrooms (23:00-07:00) at Oxley Woods using London TRY (left) and St Albans TRY (right).

Taking into account all the eight living areas simulated at Bridport and Oxley Woods from 08:00-22:00, four living rooms (that is, 50%) rose above the 5%/25ºC indicator of moderately warm overheating and more than 50% when looking at the evening time from 18:00-22:00 for London Islington. Also, three (that is, 38%) are above the 5%/25ºC marker from 08:00-22:00 and 50% rose above the marker from 18:00-22:00 for St Albans. Considering the 1%/28ºC indicator of extremely hot summertime, 33% and 22% of the houses simulated are above the threshold most of the time for London Islington and St Albans respectively.

Regarding the eight bedrooms simulated from 23:00 to 07:00, 50% rose above the 5%/24ºC for London Islington and 13% above the indicator for St Albans (Figure 7.15). None of the bedrooms simulated at the case studies were above the 1%/26ºC indicator at anytime. The analysis shows the bedrooms in the houses at Oxley Woods are likely to experience higher temperatures than the bedrooms at Bridport. The finding from the analysis is in agreement with the findings from overheating analysis using static criteria for the monitored data considered in Chapter 6. The results further indicate the potential of frequent occurrence of high indoor temperatures during summertime in the bedrooms simulated which may affect the overall well-being of indoor occupants.

At the three case studies simulated, the analysis suggests the calculated internal temperature rose above 5%/25ºC at Bridport for 2% and at Oxley Woods and Stadthaus for 5% from 08:00-22:00 for London Islington TRY suggesting tendency for overheating at the two case studies. The percentage of hours that rose above 5%/25ºC at Oxley Woods and Stadthaus was not more than 4% when considering St Albans TRY. For the night-time from 23:00-07:00, the internal temperatures across the three case studies were below 1%/26ºC for the simulated period. However, there is the possibility for indoor occupants to experience high internal temperature above 26ºC within the bedrooms at night in real life situation as this study found out from environmental monitoring analysed and discussed in Chapter 6. The weather data files suggest the external temperatures were considerably low when compared to the monitored data collected during the surveys.

The results further indicate the tendency of slight differences in the design in terms of floor to ceiling height and internal floor area, which change the overall volume of the case studies simulated as smaller spaces get warmer faster than bigger spaces and can also influence the indoor occupants' comfort. For instance, floor-to-ceiling height is 300mm lower at Oxley Woods and Stadthaus (2.35m) than Bridport (2.65m) with smaller area of openings at the two case studies than Bridport which suggests slow rate of ventilation and smaller volume of space which can quickly heat up thus causing the indoor spaces to be much warmer than the internal spaces at Bridport.

7.5.2 Overheating Analysis Using the Dynamic Adaptive Comfort Criteria at Bridport Oxley Woods and Stadthaus

Further analysis to evaluate the overheating risk at the case studies was carried out using the adaptive comfort criteria, the Category II 'normal level of expectation level'. The analysis shows the spaces simulated (A1WLFFFB, A6MLSFBB, A38MLFFFB, A142HASFBB, A38MLFFBB, A162HAFFBB) at Oxley Woods for London Islington and St Albans were above the Category III indicator. The results suggest excessive occurrence of high internal temperatures above the approved Category II marker (Figures 7.16-7.17). Some of the spaces simulated especially the ground floor living areas (A38MLGFL, A162HAGFL) in different houses at Oxley Woods were predicted to be cooler. At Bridport, the dynamic adaptive comfort criteria suggested that some of the simulated spaces such as FL1FFB, FL35SFL were above the Category II upper marker which was not observed during environmental monitoring as the weather condition was mild and wet. Moreover, some spaces (FL7FFFB, FL1GFL) within the apartments were between the Category II upper and lower markers for most of the time (Figure 7.19).

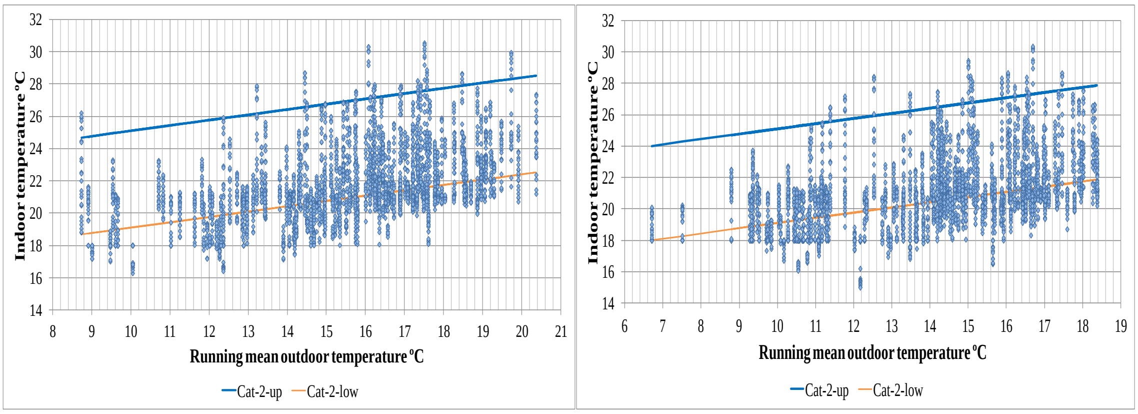

Figure 7.16: Calculated temperatures in A38MLFFFB suggesting warm and cold discomfort, compared to the BSEN15251 thresholds for London Islington TRY (left) and St Albans TRY (right).

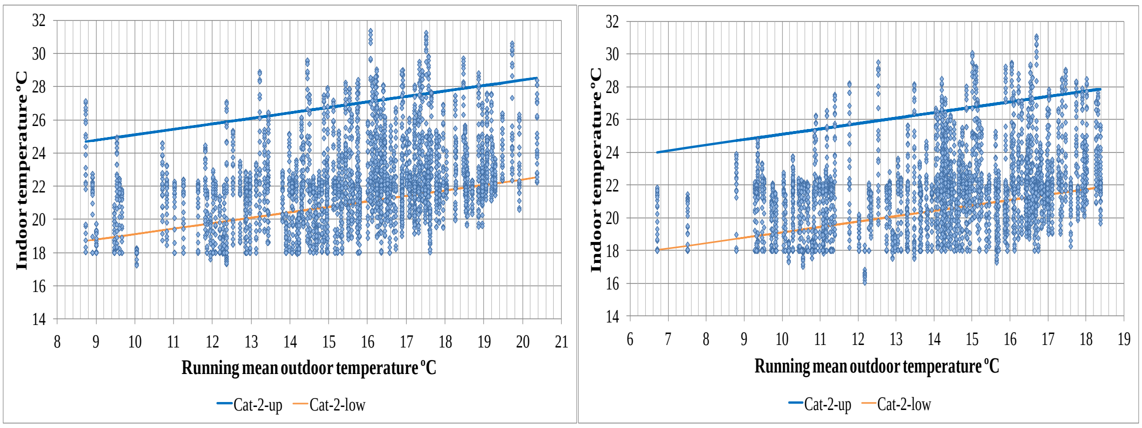

Figure 7.17: Calculated temperatures in A142HASFBB suggesting warm and cold discomfort, compared to the BSEN15251 thresholds for London Islington TRY (left) and St Albans TRY (right).

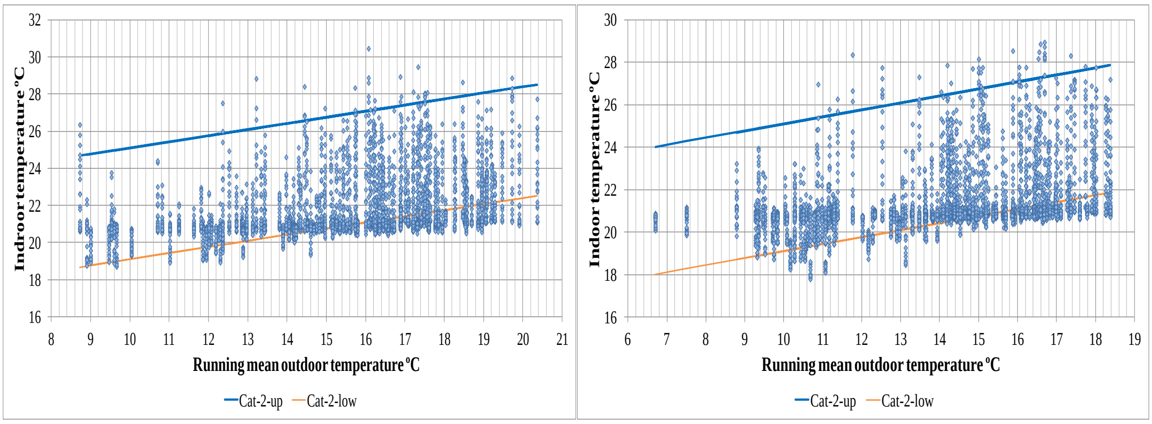

Figure 7.18: Calculated temperatures in FL1FFB suggesting warm and cold discomfort, compared to the BSEN15251 thresholds for London Islington TRY (left) and St Albans TRY (right).

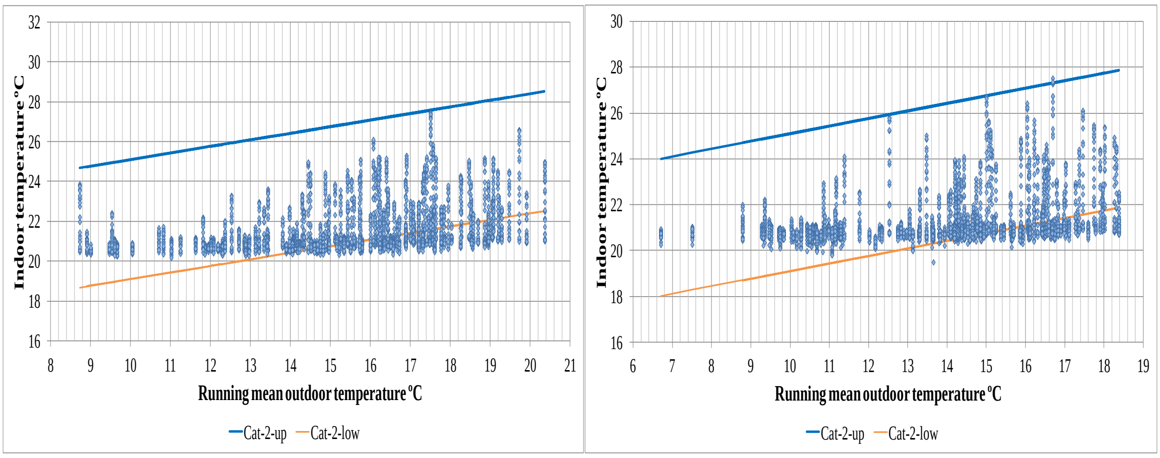

Figure 7.19: Calculated temperatures in FL7FFB suggesting no warm discomfort above 5% of the time but cold discomfort, compared to the BSEN15251 thresholds for London Islington TRY (left) and St Albans TRY (right).

Looking at the Category II threshold for the period between 08:00-22:00 in the living areas and between 23:00-07:00 in the bedrooms simulated at the case studies, none of the living areas and one bedroom (13%) rose more than 5% of hours above the Category II upper indicator. Also, all the living rooms (100%) and all the bedrooms (100%) exceeded 5% of hours below the Category II lower marker (Figures 7.20 and 7.21). Taking into account all the spaces simulated for the period at Bridport and Oxley Woods, the analysis suggests 7% exceeded 5% of hours above the Category II upper indicator while 100% exceeded 5% of hours below the Category II lower indicator. The simulation analysis shows the internal environments at the case studies are much cooler when compared to the results from the monitored data that suggest 47% and 67% exceeded 5% of hours above the Category II upper marker at Bridport and Oxley Woods respectively.

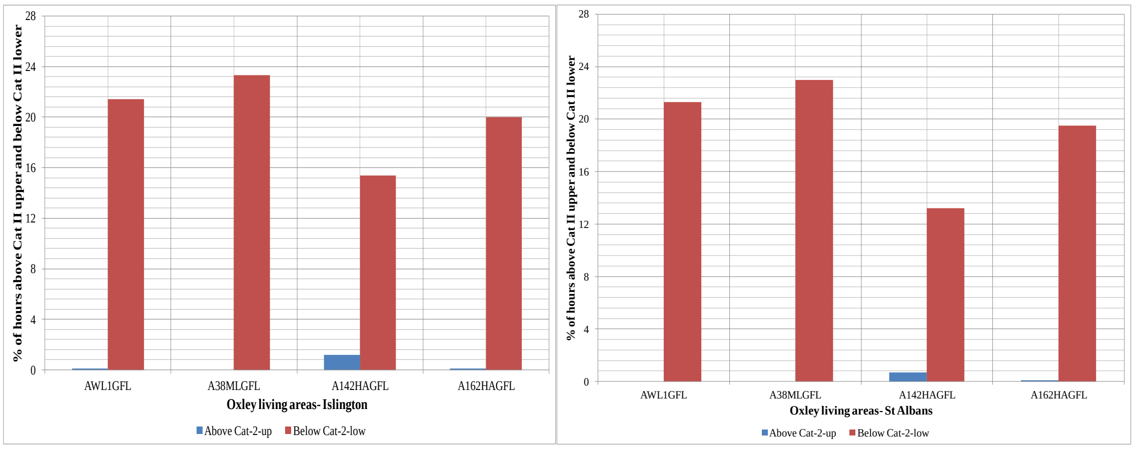

Figure 7.20: Percentage of hours of living areas temperatures calculated at Oxley Woods in BSEN15251 Cat. II thermal comfort category for London Islington (left) and St Albans (right).

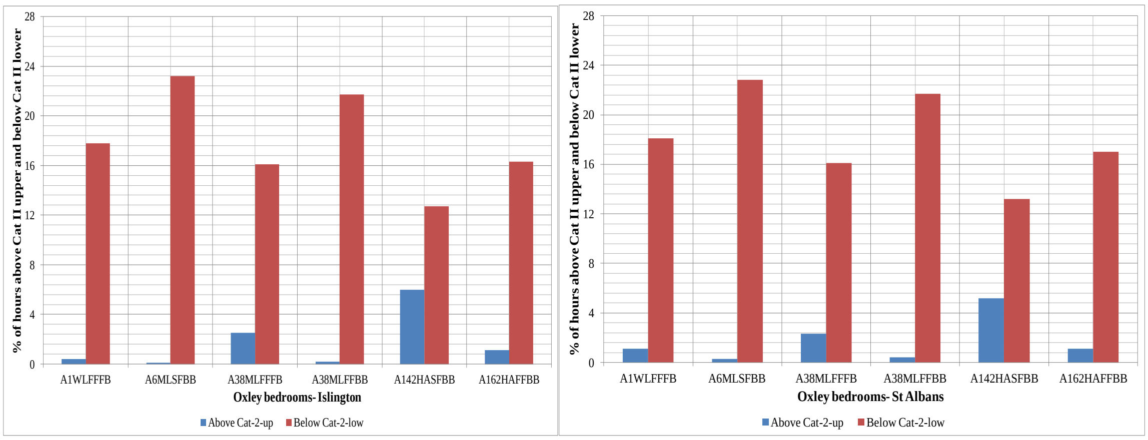

Figure 7.21: Percentage of hours of bedroom temperatures calculated at Oxley Woods in BSEN15251 Cat. II thermal comfort category for London Islington (left) and St Albans (right).

Also, the analysis conducted on the buildings using the dynamic adaptive comfort criteria to evaluate the risk of overheating suggests none of the three case studies exceeded 5% of hours above the Category II upper threshold for London Islington and St Albans. However, the analysis suggests that all the case studies exceeded 5% of hours below the Category II lower marker for London Islington and St Albans. The analysis further suggests tendency of cold discomfort even in modern houses during summertime when the external temperature decreases. The simulated results indicate the thermal environmental conditions at the case studies during summer did not suggest overheating while environmental monitoring suggests summertime overheating occurs in the spaces monitored at the buildings especially at Oxley Woods during the summer.

The calculated internal temperatures in the spaces considered for dynamic thermal simulations at Oxley Woods were analysed using the approved BSEN15251 thermal comfort standard. The bar charts (Figures 7.22-7.25) demonstrating percentage of hours that fall between the different BSEN15251 thermal comfort categories was applied for classification of the predicted temperatures. The Figures (7.22 and 7.23) indicate the percentage of hours above the Category II upper and below the Category II lower markers in the spaces simulated at Oxley Woods for London Islington and St Albans. Considering 5% of hours above the Category II upper indicator, none of the living areas and 17% of the bedrooms considered suggest warm discomfort at Oxley Woods. At Bridport, none of the living areas and the bedrooms indicate warm discomfort. On the contrary, the calculated internal temperatures in the spaces simulated at Bridport and Oxley Woods exceeded 5% of hours below the Category II lower marker for the period considered.

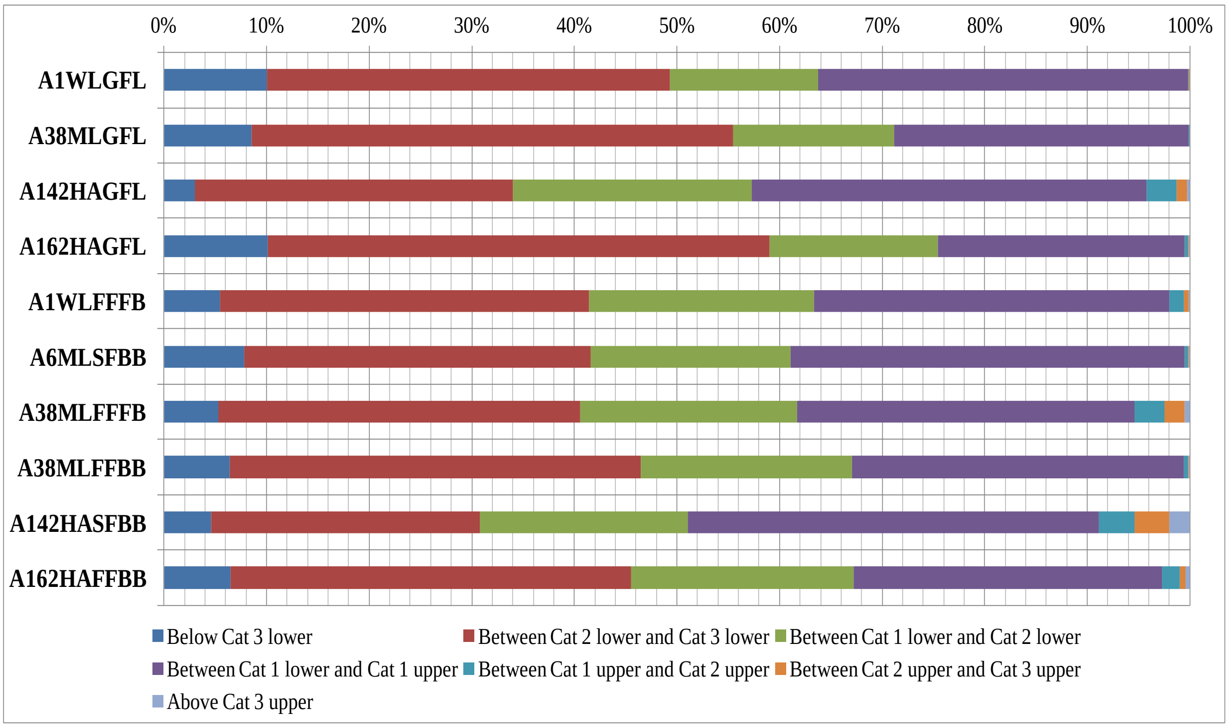

Figure 7.22: Percentage of hours of calculated temperatures within the internal spaces of the houses simulated at Oxley Woods using London Islington TRY that fall between different BSEN15251 thermal comfort thresholds (The summer period - May to September. Total number of hours- 3672).

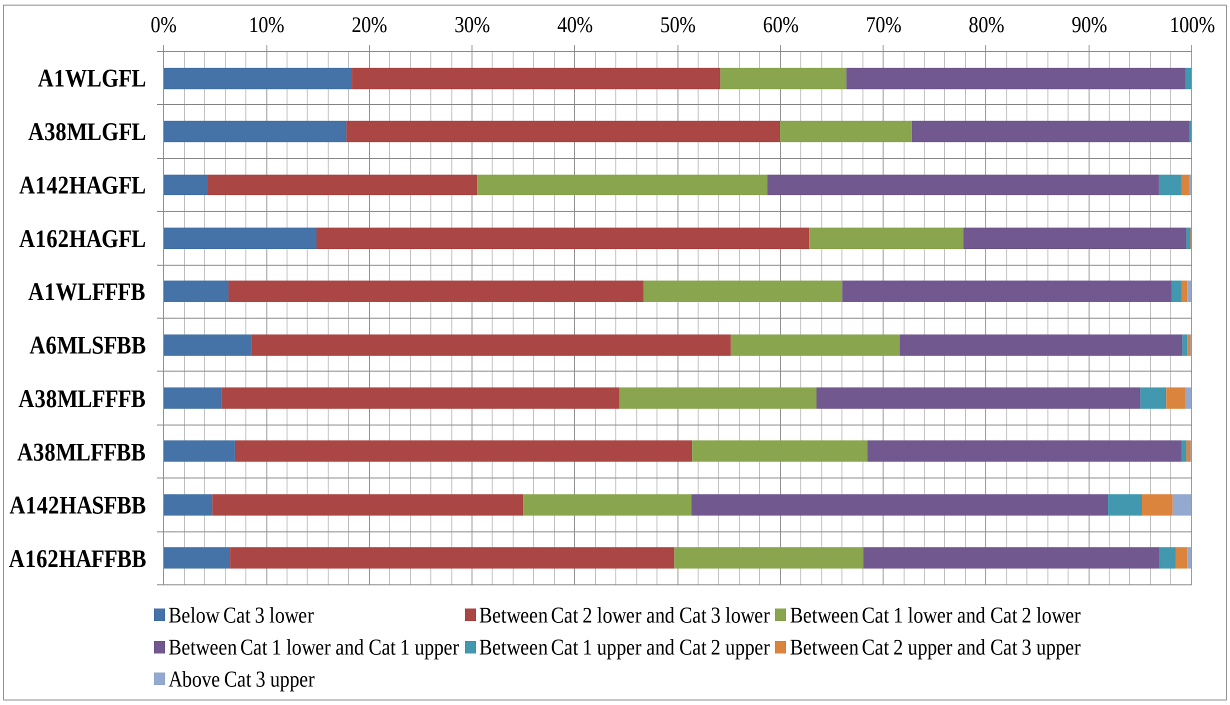

Figure 7.23: Percentage of hours of calculated temperatures within the internal spaces of the houses simulated at Oxley Woods using St Albans TRY that fall between different BSEN15251 thermal comfort thresholds (The summer period - May to September. Total number of hours- 3672).

Furthermore, the predicted indoor temperatures in the houses at Oxley Woods were also considered using the BSEN15251 thermal comfort thresholds. The results suggest A142HA (west facing facade with most of the internal spaces facing southeast orientaion) appears to be much warmer than other houses at Oxley Woods for London Islington and St Albans (Figure 7.24 and 7.25). The results also indicate cold discomfort above 5% in all the houses simulated at Oxley Woods in the summer.

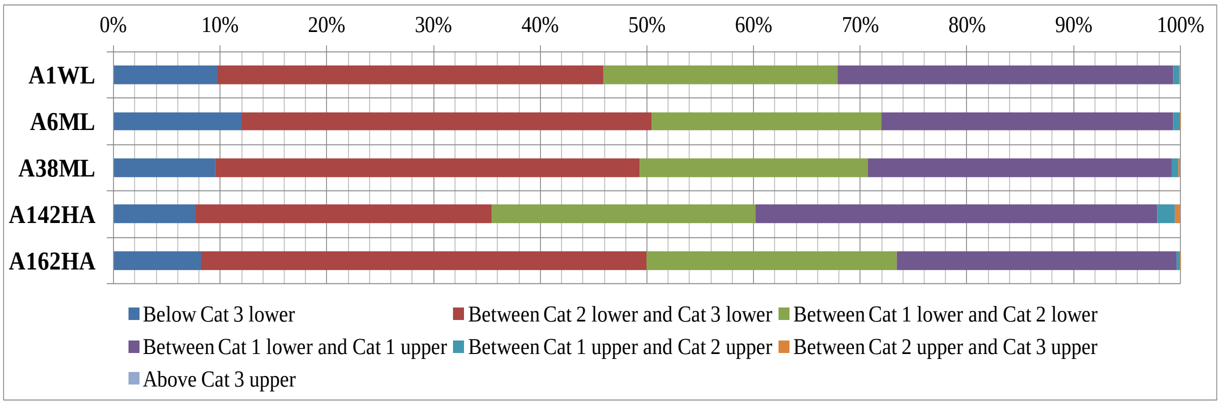

Figure 7.24: Percentage of hours of calculated internal temperatures of the houses simulated at Oxley Woods using London Islington TRY that fall between different BSEN15251 thermal comfort thresholds (The summer period - May to September. Total number of hours- 3672).

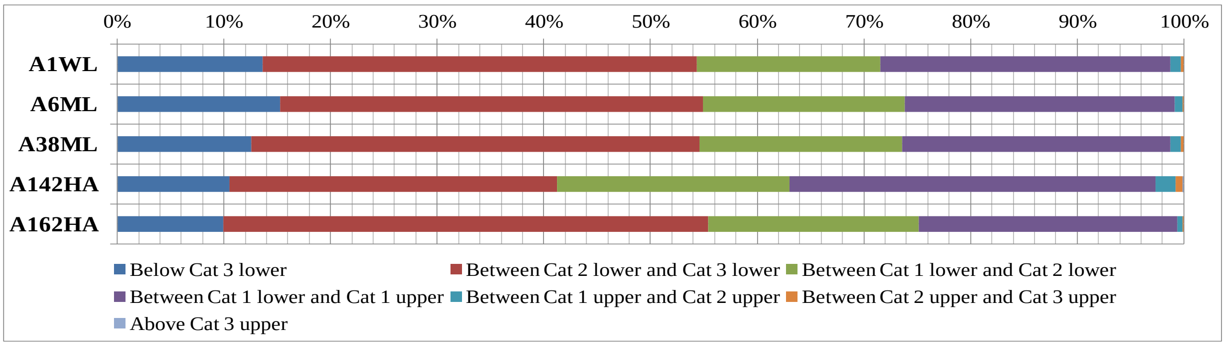

Figure 7.25: Percentage of hours of calculated internal temperatures of the houses simulated at Oxley Woods using St Albans TRY that fall between different BSEN15251 thermal comfort thresholds (The summer period - May to September. Total number of hours- 3672).

All the three case studies were further anlaysed. The bar charts (Figures 7.26 and 7.27) show percentage of hours that fall between the different categories of BSEN15251 thermal comfort. The results indicate cold discomfort with potential for warm discomfort at Oxley Woods and Stadthaus when the external temperature rises. Also, well above 50% of the spaces at Oxley Woods and Stadthaus are above the Category II lower indicator for most of the time when considering weather conditions for London Islington and St Albans.

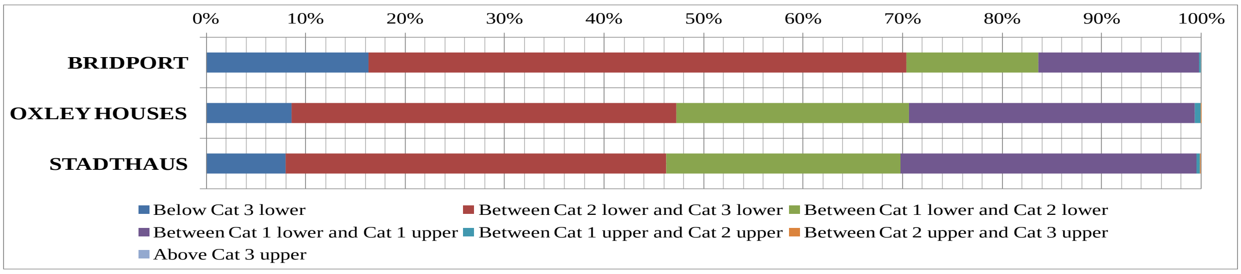

Figure 7.26: Percentage of hours of calculated internal temperatures at Bridport, Oxley Woods and Stadthaus using London Islington TRY that fall between different BSEN15251 thermal comfort thresholds (The summer period - May to September. Total number of hours- 3672).

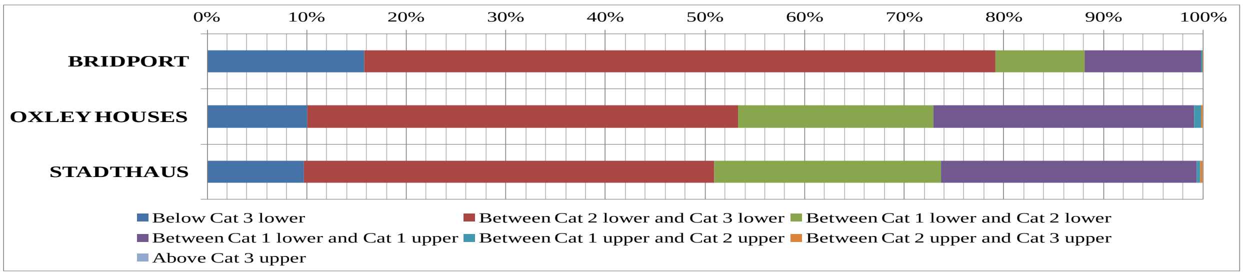

Figure 7.27: Percentage of hours of calculated internal temperatures at Bridport, Oxley Woods and Stadthaus using St Albans TRY that fall between different BSEN15251 thermal comfort thresholds (The summer period - May to September. Total number of hours- 3672).

Tables 7.2 and 7.3 below summarise the predicted internal temperatures in the living areas and the bedrooms considered at Bridport and Oxley Woods from May-September (that is, 153 days for summer period) for London Islington and St Albans. The day-time hour between 08:00-22:00 is used for the living areas (2295 hours) while the night-time hour from 23:00-07:00 is considered for the bedrooms (1377 hours). The total hours for dynamic thermal simulations is 3672 hours. The analysis suggests the maximum temperature in the spaces at Oxley Woods is slightly higher than Bridport. The predicted mean day-time in the living areas and anticipated mean night-time temperatures in the bedrooms are moderately higher at Oxley Woods than Bridport. As earlier discussed fom findings in Chapter 6, the simulated results further show that the internal spaces at Oxley Woods are warmer than the spaces at Bridport.

Table 7.2: Summary of the predicted indoor temperatures in the living rooms simulated at Oxley Woods and Bridport for the current summer period (May-September).

Name of space	**Max. temp (ºC)**	**Min. temp. (ºC)**	**Mean day-time temp (ºC)**	**Mean temp (ºC)**	**CIBSE: Total hours above 28ºC**	**CIBSE: Day time hours above 25ºC**	**BSEN15251: Total hours above Cat 1 upper marker**	**BSEN15251: Total hours above Cat 2 upper marker**	**Max. temp (ºC)**	**Min. temp. (ºC)**	**Mean day-time temp (ºC)**	**Mean temp (ºC)**	**CIBSE: Total hours above 28ºC**	**CIBSE: Day time hours above 25ºC**	**BSEN15251: Total hours above Cat 1 upper marker**	**BSEN15251: Total hours above Cat 2 upper marker**
Oxley Woods- London Islington TRY									**Oxley Woods- St Albans TRY**							
A1WLGFL	27.1	14.9	20.8	20.5	0	155	8	4	25.7	15.0	20.0	19.7	0	138	23	0
A38MLGFL	27.3	15.0	20.6	20.2	0	75	3	0	25.9	15.1	19.8	19.4	0	61	6	0
A142HAGFL	29.8	19.5	22.7	22.0	28	394	154	48	28.6	19.4	22.1	21.4	8	266	113	34
A162HAGFL	28.2	15.1	21.0	20.6	1	152	12	2	27.0	15.4	20.3	19.8	0	121	17	1
Bridport- London Islington TRY									**Bridport- St Albans TRY**							
FL1GFL	26.8	14.8	20.1	18.6	0	92	3	0	26.7	15.3	19.8	20.6	0	83	4	0
FL35SFL	28.3	12.9	20.3	19.2	5	118	22	6	28.4	13.3	20.0	17.8	2	92	37	8

Table 7.3: Summary of the predicted indoor temperatures in the bedrooms simulated at Oxley Woods and Bridport for the current summer period (May-September).

Name of space	Max. temp (ºC)	Min. temp. (ºC)	Mean night time temp (ºC)	Mean temp (ºC)	CIBSE: Total hours above 28ºC	CIBSE: Night time hours above 24ºC	CIBSE: Night time hours above 26ºC	BSEN15251: Total hours above Cat 2 upper marker	Max. temp (ºC)	Min. temp. (ºC)	Mean night time temp (ºC)	Mean temp (ºC)	CIBSE: Total hours above 28ºC	CIBSE: Night time hours above 24ºC	CIBSE: Night time hours above 26ºC	BSEN15251: Total hours above Cat 2 upper marker
Oxley Woods- London Islington TRY									**Oxley Woods- St Albans TRY**							
A1WLFFFB	29.8	16.0	21.3	21.5	20	129	0	18	29.6	15.0	20.5	20.8	18	69	0	36
A6MLSFBB	28.7	16.7	20.3	20.8	6	29	0	6	28.4	15.6	19.6	20.1	2	12	0	12
A38MLFFFB	30.6	16.3	21.0	21.8	68	100	0	93	30.4	15.2	20.3	21.1	54	56	0	91
A38MLFFBB	28.9	16.1	20.8	20.9	7	66	0	6	28.5	15.0	20.1	20.2	3	40	0	13
A142HASFBB	31.4	17.2	20.6	22.2	172	47	0	197	31.1	16.1	19.9	21.6	127	26	0	173
A162HAFFBB	29.6	16.3	21.1	21.4	30	108	0	37	29.3	15.1	20.4	20.8	14	61	0	53
Bridport- London Islington TRY									**Bridport- St Albans TRY**							
FL1FFB	30.4	18.7	20.8	21.8	19	2	0	38	28.9	17.7	20.5	21.4	13	0	0	48
FL7FFFB	27.5	20.1	21.0	21.6	0	4	0	0	27.3	19.4	20.7	21.3	0	0	0	3

In addition, the predicted indoor temperature at Bridport, Oxley Woods and Stadthaus were considered and tabulated below (Table 7.4). The analysis shows Bridport has the lowest temperatures in terms of minimum temperature, mean night-time and mean temperatures across the three case studies. Considering the results for London Islington and St Albans suggest Bridport is much cooler than Stadthaus and Oxley Woods. Also, the size of the openings contribute to the ability of the spaces at Bridport to be naturally ventilated under free-running conditions than Oxley Woods and Stadthaus. The results also show the internal temperature were below 26ºC throughout the period as the internal temperatures dropped rapidly at night when the external temperatures decreased.

Table 7.4: Summary of the predicted indoor temperatures at Bridport, Oxley Woods and Stadthaus for the current summer period (May-September).

Name of case study	Max. temp (ºC)	Min. temp. (ºC)	Mean night time temp (ºC)	Mean temp (ºC)	CIBSE: Total hours above 28ºC	CIBSE: Night time hours above 26ºC	BSEN15251: Total hours above Cat 1 upper marker	BSEN15251: Total hours above Cat 2 upper marker	Max. temp (ºC)	Min. temp. (ºC)	Mean night time temp (ºC)	Mean temp (ºC)	CIBSE: Total hours above 28ºC	CIBSE: Night time hours above 26ºC	BSEN15251: Total hours above Cat 1 upper marker	BSEN15251: Total hours above Cat 2 upper marker
London Islington TRY									**St Albans TRY**							
BRIDPORT	27.3	13.3	18.9	20.1	0	0	6	0	27.3	12.8	17.7	19.0	0	0	7	1
OXLEY	27.9	16.9	20.7	21.2	0	0	23	3	27.8	16.3	19.9	20.5	0	0	31	9
STADTHAUS	27.6	16.3	20.2	21.3	0	0	18	2	27.7	15.9	19.4	20.6	0	0	22	7

7.6 Comparative Analysis of Findings from this Study with Findings from the Previous Studies on Dynamic Thermal Simulations

In previous studies, summertime overheating is predicted in lightweight dwellings due to lack of thermal mass (Orme *et al.,* 2003; Kendrick *et al.,* 2012). Naturally ventilated dwellings built with heavyweight materials are predicted to perform better than lightweight dwellings in different seasons due to high thermal mass as they regulate temperature swing within indoor spaces (Pereira & Ghisi, 2011). The findings from this study through dynamic thermal simulations suggest overheating is likely to occur in the buildings although the results did not suggest extreme summertime overheating when considering the present weather conditions (TRY). Extreme summertime overheating is predicted in lightweight dwellings for the warmer future weather scenarios (Kendrick *et al.,* 2012). Thermal mass is considered as the most effective strategy for improving night-time cooling thereby reducing overheating in lightweight dwellings (Orme *et al.,* 2003). Comparing the results from this study with previous studies show that houses built with prefabricated structural timber panels are predicted to perform better than timber-framed houses. However, dynamic thermal simulations considering future warmer weather scenarios will be required for further comparison.

Also, overheating is predicted to occur not often within indoor spaces during occupied hours by a small percentage in lightweight dwellings when compared to heavyweight dwellings (Kendrick *et al.,* 2012). While a combination of good ventilation strategy and thermal mass reduces summertime overheating in lightweight houses (Pereira & Ghisi, 2011; Kendrick *et al.*, 2012). The findings show that for overheating to be properly addressed in prefabricated timber dwellings, design interventions considering good ventilation strategy and thermal mass should be considered. The findings from this study suggest that overheating is predicted to occur more often at Oxley Woods and Stadthaus than Bridport. Considering the designs of the buildings investigated in this study, Bridport has a wider area of openings, higher floor-to-ceiling height, higher floor area and volume with high thermal mass material (brick) used for cladding of the building which improve the thermal performance of the building when compared to Oxley Woods and Stadthaus.

7.7 Discussion and Comparative Analysis of Findings from the Surveys and Dynamic Thermal Simulations

The findings from dynamic thermal simulations of the case studies are compared with the findings from post-occupancy surveys, environmental monitoring and comfort surveys to understand the performance of the houses during summertime high temperatures.

Comparing the average running mean temperature for London Islington TRY (15.6ºC) and St Albans TRY (14.1ºC) with the average running mean temperature during environmental monitoring at Bridport (17.5ºC) and Oxley Woods (16.8ºC) suggests that the summer period from the two weather files (TRYs) was considerable cooler when compared to the average running mean temperature at Bridport and Oxley Woods in the summer. Table 7.5 below describes the simulated and monitored outdoor weather data used for this study.

Table 7.5: Description of the simulated and the monitored outdoor weather data used for dynamic thermal simulation and environmental monitoring

Outdoor weather	**Hours above 25ºC**	**Hours above 28ºC**	**Maximum temp. (ºC)**	**Minimum temp. (ºC)**	**Average running mean temp. (ºC)**	**Maximum running mean (ºC)**	**Minimum running mean (ºC)**
London Islington TRY	62	4	28.4	2.5	15.6	20.4	8.7
St Albans TRY	84	2	28.3	1.0	14.1	18.4	6.7
London City Airport for Bridport (monitored)	0	0	23.5	11.0	17.5	19.0	15.4
Luton Airport for Oxley Woods (monitored)	25	0	27.5	8.0	16.8	19.0	14.6

[*] The simulated period for London Islington and St Albans is from 1st May to 30th September. For London City Airport, outdoor weather data from 29th June to 12th July, 2012 was considered. For Luton Airport, outdoor weather data from 20th to 31st July was taken into consideration.

Taking into account the anticipated mean temperature across the three case studies suggests Bridport is to a large extent cooler with over 1.0ºC than Oxley Woods and Stadthaus for London Islington and St Albans in the summer. Likewise during the monitoring period in the summer, Oxley Woods is found to be 1.3ºC warmer than Bridport. Regarding the predicted average internal temperature at Bridport and Oxley Woods indicates that the bedrooms are much warmer than the living areas when considering the two weather data files (London Islington and St Albans) with a minimum of 0.6ºC across the two case studies. On the contrary, the measured mean internal temperature during environmental monitoring suggests the living areas are warmer than the bedrooms at Bridport while the bedrooms are warmer than the living rooms at Oxley Woods in the summer. The hottest living area and the bedroom were found to be FL35SFL and FL1FFB at Bridport while A142HAGFL and A142HASFBB were the hottest living room and the bedroom at Oxley Woods for thermal simulations. However during the monitoring period in the summer, the hottest living area at Oxley Woods was A1WLGFL while the hottest bedroom was A162HAFFBB. The hottest living area and the bedroom remain the same at Bridport for the monitoring period. Comparing the results of the simulated hottest living area and the bedrooms at Oxley Woods indicate external temperatures were cooler for simulations (London TRY and St Albans TRY) which are likely to reduce the frequent occurrence of summertime high internal temperature within the spaces. For instance, the results from the state logger discussed in Chapter 6 indicate the residents in A142HASFBB were opening the windows for most of the time (above 80%) throughout the monitoring period in the summer. Table 7.6 summarises the measured and the predicted temperatures in the internal spaces at Bridport and Oxley Woods suggesting A1WLGFL as the hottest space during the monitoring period in the summer while the simulated results show A142HASFBB as the warmest space. The table further shows that the occupants of some of the spaces such as A142HAGFL, A1WLFFFB that are prone to extreme summertime overheating when simulated are taking further adaptive actions in the real world setting to adjust the overall thermal conditions of the internal spaces.

Table 7.6: Comparison between the monitored and the calculated internal temperatures in the spaces investigated at Bridport and Oxley Woods for the summer period.

Year	Monitored (Summer 2012)					London Islington TRY					St Albans TRY				
Name of space	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 28°C**	**Hours above BSEN15251 Cat II upper**	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 28°C**	**Hours above BSEN15251 Cat II upper**	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 28°C**	**Hours above BSEN15251 Cat II upper**
A1WLGFL	30.0	19.8	23.5	15	15	27.1	14.9	20.5	0	4	25.7	15.0	19.7	0	0
A38MLGFL	28.1	18.2	22.6	4	3	27.3	15.0	20.2	0	0	25.9	15.1	19.4	0	0
A142HAGFL	28.0	18.3	22.4	3	6	29.8	19.5	22.0	28	48	28.6	19.4	21.4	8	34
A162HAGFL	27.3	18.6	23.7	0	2	28.2	15.1	20.6	1	2	27.0	15.4	19.8	0	1
FL1GFL	24.6	21.7	22.9	0	0	26.8	14.8	18.6	0	0	26.7	15.3	20.6	0	0
FL35SFL	25.0	22.7	23.7	0	0	28.3	12.9	19.2	5	6	28.4	13.3	17.8	2	8
Name of space	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 26°C**	**Hours above BSEN15251 Cat II upper**	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 26°C**	**Hours above BSEN15251 Cat II upper**	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 26°C**	**Hours above BSEN15251 Cat II upper**
A1WLFFFB	28.7	19.4	23.9	2	18	29.8	16.0	21.5	0	18	29.6	15.0	20.8	0	36
A6MLSFBB	29.2	21.0	24.7	6	33	28.7	16.7	20.8	0	6	28.4	15.6	20.1	0	12
A38MLFFFB	29.5	20.0	24.5	9	34	30.6	16.3	21.8	0	93	30.4	15.2	21.1	0	91
A38MLFFBB	29.1	20.8	24.3	12	16	28.6	16.1	20.9	0	6	28.5	15.0	20.2	0	13
A142HASFBB	29.8	18.0	23.2	2	18	31.4	17.2	22.2	0	197	31.1	16.1	21.6	0	173
A162HAFFBB	30.5	20.8	25.7	10	37	29.6	16.3	21.4	0	37	29.3	15.1	20.8	0	53
FL1FFB	24.7	21.3	22.8	0	0	30.4	18.7	21.8	0	38	28.9	17.7	21.4	0	48
FL7FFFB	23.8	21.2	22.3	0	0	27.5	20.1	21.6	0	0	27.3	19.4	21.3	0	3

The calculated indoor temperatures at Oxley Woods and Stadthaus are expected to be within the comfort range for most of the time when the external temperature is not more than 24ºC while at Bridport, the internal temperature is within the comfort range when the external temperature is 22ºC with over 1.5ºC between the expected internal temperature of the case studies.

Concerning the static CIBSE criteria, overheating is expected to be more frequent at Oxley Woods than Bridport as previously found out in Chapter 6. The results suggest the predicted internal temperatures between 08:00-22:00 in the living rooms rose above 25ºC for 75% and above 28ºC for 25% at Oxley Woods, while at Bridport exceeded 25ºC for 33% and none above 28ºC. The findings indicate the internal temperature at Bridport was well above 25ºC for more than 2% from 08:00-22:00 while the anticipated internal temperature at Oxley Woods and Stadthaus exceeded 25ºC for over 4% despite the external temperature was considerably lower when compared to the external temperature observed during environmental monitoring in the summer.

For the period between 08:00-22:00 and 23:00-07:00 in the bedrooms considered for the simulations, the findings show 13% of the bedrooms rose more than 5% of hours above the Category II upper threshold. Comparing the results with the results from environmental monitoring shows the risk of overheating at the case studies despite the internal conditions were predicted to be cooler during thermal simulations when compared to the monitoring period (Table 7.7). The results from the table suggest overheating is more frequent in the living areas and the bedrooms at Oxley Woods than Bridport. However, the expected internal temperatures of the houses are likely to be much warmer with possibility of extreme overheating in the future.

Table 7.7: Comparison between the average monitored and the average calculated internal temperatures in the living areas and the bedrooms at Bridport and Oxley Woods for the summer period.

Year	**Monitored (summer 2012)**					**London Islington TRY**					**St Albans TRY**				
Case study	**Living areas- % of temp above 25ºC (08:00-22:00)**	**Living areas- % of temp above 25ºC (18:00-22:00)**	**Bedrooms- % of temp above 24ºC (23:00-07:00)**	**Living areas % of temp above Cat. 2 upper (08:00-22:00)**	**Bedrooms- % of temp above Cat. 2 upper (23:00-07:00)**	**Living areas- % of temp above 25ºC (08:00-22:00)**	**Living areas- % of temp above 25ºC (18:00-22:00)**	**Bedrooms- % of temp above 24ºC (23:00-07:00)**	**Living areas % of temp above Cat. 2 upper (08:00-22:00)**	**Bedrooms- % of temp above Cat. 2 upper (23:00-07:00)**	**Living areas- % of temp above 25ºC (08:00-22:00)**	**Living areas- % of temp above 25ºC (18:00-22:00)**	**Bedrooms- % of temp above 24ºC (23:00-07:00)**	**Living areas % of temp above Cat. 2 upper (08:00-22:00)**	**Bedrooms- % of temp above Cat. 2 upper (23:00-07:00)**
Bridport	0%	0%	0%	0%	0%	33%	33%	0%	0%	0%	0%	0%	0%	0%	0%
Oxley Woods	100%	100%	83%	25%	100%	75%	75%	67%	0%	17%	75%	75%	17%	0%	17%

Looking at the houses at Oxley Woods, A412HA appears to be the warmest house out of the five houses simulated (Table 7.8). Across the case studies, the overheating analysis suggests Oxley Woods is the warmest case study. Comparing the results with the findings from the field surveys consistently show Bridport is much cooler than Oxley Woods during summertime high temperature and the potential risk of overheating is much higher at Oxley Woods than Bridport (Table 7.9). The findings suggest that the smaller internal spaces at Oxley Woods and Stadthaus are constantly getting warmer faster than the internal spaces at Bridport due to the difference in the floor area and floor-to-ceiling height which indicates a significant difference between the overall volumes of the internal spaces at the case studies. However, the occupants at Oxley Woods are more comfortable with the thermal environment in the summer which further suggests possibility of taking some adaptive actions to improve the thermal conditions in the real world situation. The results from table 7.9 also suggest brick cladding at Bridport may likely provide additional thermal capacity for the building's fabric to regulate temperatures swing than Stadthaus and Oxley Woods. However, further investigation will be required to examine the influence of cladding materials used in regulating temperature swing in the building. Considering the performance of the buildings' fabrics, it appears CLT panels used for Bridport and Stadthaus perform better than SIP used for Oxley Woods. Nonetheless, further study that considers dynamic thermal simulations of the three buildings using CLT and SIP for the fabrics will be required for comparison.

Table 7.8: Comparison between the calculated average internal temperatures of the houses at Oxley Woods for the summer period (May-September)

	London Islington TRY					**St Albans TRY**				
Oxley house	**Max. temp ºC**	**Min. Temp ºC**	**Mean temp ºC**	**Hours above 28ºC**	**Hours above BSEN15251 Cat II upper**	**Max. temp ºC**	**Min. Temp ºC**	**Mean temp ºC**	**Hours above 28ºC**	**Hours above BSEN15251 Cat II upper**
A1WL	28.2	16.3	21.3	2	4	28.1	15.4	20.5	1	10
A6ML	27.6	16.7	21.1	0	2	27.6	16.3	20.4	0	5
A38ML	28.4	16.8	21.2	3	8	28.2	16.2	20.6	1	9
A142HA	28.5	17.1	21.7	4	18	28.7	16.8	21.1	2	28
A162HA	27.7	16.9	21.1	0	2	27.4	16.3	20.5	0	3

Table 7.9: Comparison between the average monitored and calculated internal temperatures at Bridport, Oxley Woods and Stadthaus for the summer periods

Year	**Monitored (Summer 2012)**					**London Islington TRY**					**St Albans TRY**				
Case Study	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 28°C**	**Hours above BSEN15251 Cat II upper**	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 28°C**	**Hours above BSEN15251 Cat II upper**	**Max. temp °C**	**Min. Temp °C**	**Mean temp °C**	**CIBSE: Hours above 28°C**	**Hours above BSEN15251 Cat II upper**
Bridport	24.2	21.7	22.6	0	0	27.3	13.3	20.1	0	0	27.3	12.8	19.0	0	1
Oxley Woods	28.5	19.5	23.9	3	10	27.9	16.9	21.2	0	3	27.8	16.3	20.5	0	9
Stadthaus	-	-	-	-	-	27.6	16.3	21.3	0	2	27.7	15.9	20.6	0	7

The results further suggest lack of thermal mass and high level of insulation in timber houses contribute to frequent high temperatures within the internal spaces of modern houses. Moreover, the results show that a shortfall in minimum space standards did not only reduce the size of the internal spaces in dwellings but also contributed to increasing internal temperatures as they tend to get warm very quickly than bigger spaces thus leading to indoor occupants' discomfort. The study shows that thermal comfort of indoor occupants in modern UK houses need to be well considered at the design stage and the existing minimum space standards need to be reviewed as internal spaces of UK houses are getting smaller and are considered as the smallest in the Western part of Europe as mentioned in RIBA (2011) which could reduce the potential of extreme overheating in UK houses in the future as outdoor temperature increases over the years in the UK due to an increase in global temperatures.

7.8 Summary

This chapter discussed the results from dynamic thermal simulations and compared the findings with the findings from environmental monitoring carried out in the summer which have been considered in Chapter 6. The scope and method used for the simulations were explained. The case studies were simulated as free-running with no heating and cooling required for the period considered (May-September). As a result of the free-running condition, the number of assumptions made for the models were limited for the simulations which could greatly affect the overall results. The anticipated temperatures gave representation of the internal temperatures at the case studies as some variables used for dynamic thermal simulation cannot be accurately measured in terms of quantity. For instance, it was difficult to measure occupancy character accurately for the simulations. However, the findings from the calibration suggest a great proportion of alignment between the monitored temperatures and the expected temperatures with the difference not exceeding 2.0ºC for most of the time. The calibration showed majority of the monitored temperatures and the simulated temperatures in all the internal spaces considered were aligned with a slight difference which suggests the reliability of the calibration done for this study.

The relationship between the expected internal temperatures and external temperature at the case studies were discussed. The findings from the analysis provided a better understanding of the anticipated internal temperature at which the occupants at the case studies will be comfortable when the external temperature rises above a certain threshold. It was discovered that Bridport which has bigger internal spaces appears to be cooler than Oxley Woods and Stadthaus with smaller internal spaces when looking at the predicted temperatures across the three case studies. Also, the differences between the internal temperatures tend to decrease as the external temperature increases but the difference is not significant between Oxley Woods and Stadthaus.

Evaluation of the overheating risk using the static criteria and the dynamic thermal comfort criteria was discussed. The results predicted the possibility of summertime high internal temperatures across the case studies with tendency for frequent internal high temperatures at Oxley Woods and Stadthaus than Bridport. The results also indicated that the bedrooms are much warmer than living rooms across the case studies which suggest overheating may affect the indoor occupants from sleeping very well during night-time. Also, frequent internal low temperatures were observed within the internal spaces when the external temperature decreases. The findings from this chapter further explains the dynamic thermal comfort (BSEN15251) criteria provide a wider zones of comfort at which indoor occupants find comfortable at various locations.

The use of charts to classify percentage of hours between the different thermal comfort categories in the approved BSEN15251 showed some of the spaces at Oxley Woods with warm discomfort. It was observed that A142HA appears to be the warmest house at Oxley Woods. Considering all the case studies, all the internal spaces at Oxley Woods and Stadthaus are expected to be experiencing warm discomfort in the current year with tendency for extreme internal conditions in the future. The comparative findings from all the surveys and thermal modelling considered in this chapter suggest that for evaluation of the overheating risk to be carried out in dwellings, further similar studies need to take into consideration the use of dynamic thermal simulation and environmental monitoring as part of the methodology. Finally, the results consistently suggest that the potential of summertime overheating in modern houses in the UK which may affect overall well-being of occupants.

Chapter 8 Conclusion

8.1 Introduction

This chapter provides a summary of the research development and summarises the results from the surveys and dynamic thermal modelling and simulations. It presents the conclusions on the research propositions. It suggests possible areas that are well linked to this study for further research and presents the conclusion of the research outcomes. Lastly, it suggests recommendations for future studies on thermal comfort in dwellings and possible design approaches to adopt for future development of prefabricated timber houses.

8.2 Summary of the Overall Development of the Research

The focus of the UK government is to minimise carbon emissions generated in dwellings which accounts for at least 26% of the total emissions by setting a target to make all modern dwellings to be energy efficient by 2016 which has been considered a challenging task. Also, a target to build additional low carbon emission dwellings over the next few decades has been set by the government while the UK housing sector has been facing challenges in recent years to build more quality houses with bigger internal spaces that support overall well-being of occupants. Moreover, there is an increasing demand for housing in the UK especially in urban centres due to increase in the population and standard of living. In order to meet the growing demand for more houses, prefabrication methods of construction have been considered for houses due to the limited time required to build large number of quality dwellings and quick return on investment.

Prefabrication method of construction have not only provided solutions to shortages of UK housing supply but also helped to address problems relating to shortages of skilled workers in the sector when considering the history of UK housing development from the 19th century to the present time. The use of prefabricated timber contributes to overall carbon footprint of the project, lock in carbon, easy to transport and it is more appealing in terms of visual appearance when compared to other materials such as concrete.

Past studies have indicated summertime overheating is likely to occur in UK lightweight dwellings in the next few decades due to low thermal mass while few investigations have mentioned that houses built to passive standards and located in other parts of Europe with extreme winter season than UK are likely to experience high internal temperatures in summer. Various investigations conducted on UK houses during summertime have suggested potential of high internal temperatures and mentioned summertime temperatures are likely to increase due to climate change.

The principal aim of the research was to investigate overheating potential in UK timber houses. The general objective was to evaluate the thermal performance of prefabricated timber houses in the UK. In order to achieve the aims and objectives of the research, this study was conducted in seven different phases.

Review of relevant literature on thermal comfort in dwellings was carried out in the first phase of this study. The previous studies considered were carefully evaluated to discuss parameters that are relevant to the focus of the research. A thorough consideration of the review provided an in-depth understanding of how to develop the research methodology as well as formulate experimental plan for the research. The relevant literature considered helped to identify parameters to consider during the development of the questionnaires and criteria to use for evaluation of the risk of overheating in the buildings. An insight into the performance of various houses investigated in summertime in the UK and other part of Europe was gathered during the review. Factors influencing thermal comfort of occupants and an understanding of overall thermal comfort in dwellings were also gathered from the review conducted in the first phase.

Various UK minimum space standards were evaluated in the second phase and the review gave a better understanding of a shortfall in minimum space requirements. In addition, the review helped to understand sizes of UK dwellings are assessed by number of rooms while total internal floor areas are used to evaluate sizes of dwellings in other European countries.

The third phase of the research development considered the data protocol and analysis techniques. The experimental plans for the field studies in particular post-occupancy evaluation, environmental monitoring and comfort surveys were presented. Dynamic thermal modelling and simulation were also considered as a method to gather more data from the buildings that can be compared to meet the research goals.

The fourth phase of the investigation examined the case studies selected for the research. The minimum space standards reviewed suggest the use of GLA space standards (exceeded the Parker Morris standards plus additional 10%) for Bridport, the English Partnerships/ Affordable Homes standards for Oxley Woods and the Developer standards for Stadthaus. The reviews on environmental sustainability of the materials used for the buildings suggest they are airtight with a good potential for sound insulation and fire resistance.

The fifth phase of the research considered the field studies by carrying out post-occupancy surveys, environmental monitoring and comfort surveys at the three case studies. Environmental monitoring was conducted at Bridport and Oxley Woods in the summer of 2012 concurrently with comfort surveys while the surveys were carried out at Oxley Woods in the winter of 2013.

The sixth phase considered analysis of the data collected during post-occupancy surveys, environmental monitoring and comfort surveys. Analysis of the risk of overheating was carried out using the static thermal comfort criteria and the dynamic adaptive thermal comfort model. Comparisons of the results from various surveys in the summer and the winter were provided.

The seventh phase focused on dynamic thermal modelling and simulation of the three buildings investigated. The buildings were simulated under the same external weather conditions for the current year (London Islington TRY and St Albans TRY) using computer simulation software DesignBuilder by EnergyPlus. The simulated period for the buildings was from May 1st to September 30th (153 days) representing summer months in a year. The simulated data was calibrated using the monitored data by plotting the results on the same charts. The outcomes indicated a greater degree of alignment with the same pattern of charts. The difference between the monitored data and the simulated data was within 2ºC for most of the time. The simulated data was further analysed using the static and the dynamic thermal comfort criteria to evaluate the risk of overheating in the buildings. The results were compared and provided diversity of the outcomes which cannot probably be achieved using one or two methods.

8.3 Conclusion

The results from the surveys have been discussed in Chapters 6 and 7. Since four different methods were considered for the research, the outcomes have been provided using all the methods and comparison of the results has been presented. The main aim of the research was to identify the potential of overheating in prefabricated timber houses and this has been achieved based on the findings. Also, the research proposed to understand through this investigation how the occupants that are thermally dissatisfied adjust the thermal conditions of the houses and to understand if a shortfall in UK minimum space standards contributes to high internal temperatures in dwellings. The results suggest that all the research goals have been achieved.

8.3.1 Conclusion on the Field Studies (Post-occupancy Surveys, Environmental Monitoring and Comfort Surveys)

The results from post-occupancy surveys showed the occupants feel warmer within the internal spaces of the buildings in the summer with 81% responses at Bridport and Oxley Woods and 70% at Stadthaus while comfort surveys indicated 75% and 38% responses feel ‘warm’ at Bridport and Oxley Woods respectively in the summer. The respondents indicated high level of control with at least 50% of the occupants indicating satisfaction for control. Above 88% of the occupants accept the thermal environment at the buildings in the summer. From the post-occupancy surveys, at least 92% of the occupants indicated use of control to improve the thermal environment of the houses; however, the findings from comfort surveys suggest 77% of the occupants use control(s) regularly. The results showed there is a difference between what the respondents think they do and the actual actions they take to improve the thermal conditions of the buildings. More than 69% of the respondents perceived the bedrooms as the warmest space but the monitored results indicated the living areas were warmer than the bedrooms at Bridport with higher internal temperatures recorded during environmental monitoring in the summer. The design of Bridport showed higher floor-to-ceiling height, bigger internal floor area and volume of the bedrooms at Bridport than Oxley Woods and Stadthaus which may influence the occupants’ thermal sensation in the summer. Moreover, the bedrooms at Oxley Woods are located on the upper floors of the houses and hot air is likely to rise at a faster rate to the spaces on the upper floors; thereby influencing thermal sensation of the occupants in the summer. At least 57% of the occupants indicated pleasant experience at the buildings. The respondents that owned the houses indicated higher level of control to carry out various activities (r=0.416) while the occupants with longer duration of occupancy understand how to adjust the thermal environment of their house using control, in particular shading device (r=0.390).

Environmental monitoring results showed that the outdoor weather data collected did not indicate high summertime external temperatures at Bridport (from 11ºC to a peak of 23.5ºC) which could lead to regular occurrence of high internal temperatures in the houses monitored as the weather conditions were considered mild and wet. However, higher external temperatures were observed at Oxley Woods (from 8ºC to a peak of 27.5ºC) for a short period in the summer. Also, the average external temperatures observed in London (23ºC) and Luton (22.5ºC) during the hottest month (August) in 2012 was higher than the mean external temperatures recorded at Bridport (16.7ºC) and Oxley Woods (16.8ºC) during the monitoring periods in the summer.

The mean internal temperatures for the spaces monitored at Bridport (22.6ºC) and Oxley Woods (23.9ºC) during the summer surveys were within the comfort range (22-25ºC). The results showed the mean temperature was higher by 1.3ºC at Oxley Woods than Bridport in the summer and higher internal temperatures were observed in the houses monitored at Oxley Woods. The internal temperatures of the houses were within the comfort range in the winter. The relative humidity was between 40-60% for most of the time.

The results from the comfort surveys indicated that the occupants feel warmer at Bridport than Oxley Woods despite relatively mild summer weather conditions observed at Bridport. The occupants at Oxley Woods appear to have a better understanding of how to adjust the thermal environment of the houses. Linking the results from comfort surveys to environmental monitoring, the neutral temperatures were found to be 1.4ºC higher in the bedrooms monitored at Oxley Woods than Bridport as shown in Table 6.13. Comfort is within a wide range of temperatures for the living areas monitored at Bridport. However, the average neutral temperature for all the living areas monitored at Oxley Woods during the summer indicated 20.2ºC. Also, neutrality was found to be 0.8ºC higher at Oxley Woods than Bridport for all the spaces monitored indicating higher adaptation to the thermal environment at Oxley Woods. On the contrary, the preferred temperature was higher at Bridport by 1.8ºC than Oxley Woods suggesting the occupants at Oxley Woods could adapt to the thermal environment over a wide range. At Oxley Woods, mean internal temperature was higher by 1.3ºC than Bridport in the summer. The results further suggest higher internal temperature at Oxley Woods than Bridport with higher neutral temperature but lower preferred temperature.

In addition, the findings from the comfort surveys, the results showed that over 50% responses preferred to be cooler in the summer at Bridport despite wet and mild weather conditions. More than 88% of the respondents accept the thermal internal conditions of the houses in the summer suggesting higher thermal acceptability despite higher internal temperatures recorded at the buildings, in particular at Oxley Woods. The occupants feel warmer in the upper floor spaces than the lower floor spaces (r=0.423). The respondents feel less warm in the summer at Bridport and Oxley Woods when they frequently use windows to improve the thermal conditions of the spaces (r=0.328). More frequent use of doors for ventilation was noticed at Oxley Woods in the summer (r=0.367). Fans were used more often at night in the upper floors as a result of higher internal temperatures (r=0.362). Higher adaptability of the female occupants to higher internal temperatures was observed in the summer as they feel less warm than the male occupants (r=0.215).

Using the CIBSE ‘static’ criteria for evaluation of the risk of overheating, the results showed at least 67% of the bedrooms monitored at Bridport and Oxley Woods were above 1%/26ºC threshold indicating extreme overheating. For the living areas, 43% exceeded 1%/28ºC marker. Also, 50% of the living areas rose above 5%/25ºC while 56% of the bedrooms exceeded 5%/24ºC thresholds which suggest summertime overheating occurs in the buildings. The findings from evaluation of the risk of overheating using the dynamic adaptive comfort (BSEN15251) criteria indicate that 25% of the living area and 100% of the bedrooms monitored at Oxley Woods were above the Cat II upper threshold for more than 5% mark in the summer. However, none of the spaces monitored at Bridport suggested warm discomfort above the Category II upper threshold due to mild and wet weather conditions during the monitoring period in the summer. Combining all the spaces monitored at Bridport and Oxley Woods, 17% of the living area, and 75% of the bedrooms exceeded 5% of hours above the Category II upper indicator suggesting warm discomfort in the summer. The risk of overheating analysis using the adaptive comfort model suggests warm discomfort in 70% of the spaces monitored at Oxley Woods in the summer while warm discomfort was indicated in 50% of the spaces monitored at Bridport and Oxley Woods. The results revealed that Oxley Woods is warmer than Bridport with up to 5% of the monitoring period above the Category II upper indicator.

8.3.2 Conclusion on the Dynamic Thermal Modelling and Simulations

The simulated results showed Bridport with bigger internal spaces was cooler by at least 1ºC than Oxley Woods and Stadthaus with smaller internal spaces when considering the predicted average internal temperatures. Also, the differences between the internal temperatures tend to decrease as the external temperature increases but the difference is not significant between Oxley Woods and Stadthaus.

The outcomes from evaluation of the overheating risk using the static criteria and the dynamic thermal comfort criteria indicated the possibility of summertime high internal temperatures at the buildings with tendency for frequent internal high temperatures at Oxley Woods and Stadthaus. The bedrooms were warmer than the living rooms at Bridport and Oxley Woods by at least 0.6ºC which suggest overheating can possibly affect the indoor occupants from sleeping very well during the night-time. Also, frequent internal low temperatures were observed within the internal spaces when the external temperature decreases indicating the thermal behaviour of the fabrics are strongly connected with the external weather conditions. The designs of the buildings showed that low thermal mass of timber can be detrimental to the occupants' comfort within the spaces when the external temperatures reduce or rise. The findings revealed that low thermal mass in the case study buildings contributes to high indoor temperatures observed in all the spaces monitored in the summer. The results showed that the dynamic thermal comfort (BSEN15251) model provides a wider range of zones of comfort at which occupants find comfortable at different locations.

The classification of percentage of hours between the various thermal comfort categories in the approved BSEN15251 using bar charts showed that A142HA is the warmest house at Oxley Woods due to the orientation of the house as most of the internal spaces are located along the south-east orientation. The findings showed that orientation is an important factor in design as the houses along south-east and south-west orientations are at risk of summertime overheating when compared to the houses at north orientation. The results from dynamic thermal simulations and the field surveys consistently show

Bridport is much cooler than Oxley Woods during summertime high temperature and the potential for risk of overheating is higher at Oxley Woods than Bridport. The smaller internal spaces at Oxley Woods and Stadthaus are constantly getting warmer faster than the internal spaces at Bridport as a result of the difference in design (for instance, internal floor area, floor-to-ceiling heights) which indicates a significant difference between the overall volumes of the internal spaces. Nonetheless, the residents at Oxley Woods are more comfortable with the thermal conditions of the houses in the summer which suggests wider potential of adaptation to improve the thermal environments in the real world situation.

The outcomes of the work showed that overheating occurs in UK timber houses. The study further indicated through dynamic thermal simulations that low thermal mass and high level of insulation in timber houses contribute to frequent high temperatures within the internal spaces of modern houses. The shortfall in UK minimum space standards did not only contribute to construction of smaller dwellings but also contributes to increasing internal temperatures as smaller spaces tend to get warm faster than bigger spaces thus increasing occupants' discomfort and dissatisfaction. The existing minimum space standards need to be reviewed as internal spaces of UK houses are getting smaller which could reduce the potential of extreme overheating in UK houses in the future as outdoor temperatures are likely to increase in future in the UK due to the increase in global temperatures.

In summary, the research outcomes strongly supported the first and third propositions set out at the beginning of this study. However, the outcomes of the research regarding the second proposition suggest the occupants are thermally satisfied with the thermal environment of the buildings despite higher internal temperatures recorded in the summer.

8.4 Recommendations and Further Research

Though the research has been completed and the results support the research aim and met the objectives outlined for this study, there are few challenges encountered during the investigation which need to be outlined for recommendation and future research to take into consideration especially the study that relates to field studies of thermal comfort in dwellings.

(a) Extensive study on residential buildings built with prefabricated timber to examine performance of the buildings in order to gather wider samples for comparison is suggested for further study. Since limited studies have been carried out on prefabricated timber buildings, the study will help to further understand the thermal behaviours of different buildings built with timber and diversity of the users to adjust the thermal conditions of the internal spaces.

(b) A study on integration of passive cooling strategies to improve the thermal conditions of prefabricated timber houses during summertime for the current and the future years is suggested for further research.

(c) Another area to consider for further study is housing space standards which can be further explored as an in-depth study on the trend especially between urban and suburban dwellings. The study should consider the trend over the last few decades. Also, a thorough study on various methods of construction used in the last few centuries and the impact on thermal behaviour of building fabrics can be considered.

(d) In addition, further investigations needs to be carried out on prefabricated timber houses of different types built with different materials as the research found out that low thermal mass contributes to frequency of high internal temperatures in timber houses during summertime.

(e) Extensive surveys that include post-occupancy surveys, environmental monitoring, comfort surveys and dynamic thermal simulations should be considered in different housing built across the centuries (from the 19th century till the present) for future study. The study will help to understand a change in trend of the environmental conditions and thermal behaviour of UK housing over the last two centuries. Also, the indoor air quality of internal spaces of the houses along with sound and lighting levels within the indoor spaces are suggested for further research.

(f) Other possible area for future work is to investigate the parameters that influence change in the thermal conditions of the houses due to change in arrangement of internal spaces of the houses built in the last few centuries. The study will consider houses built with different materials. Also, further study on structural components, shapes, methods of construction of buildings in relation to the thermal environments of internal spaces will be considered.

(g) Due to climate change scenarios, further investigation on the performance of timber houses using dynamic thermal simulation taking into consideration future weather data files (the 2050s, the 2080s) is suggested for further study.

Regarding recommendations on how to improve the performance of timber houses in future, various professionals in the built environment should work closely during the design stages of houses to actualise a well-thought-through design. The design development should consider appropriate use of materials, proper analysis of the thermal environment of the spaces, thermal behaviours of fabrics and integration of controls that can be operated manually and user friendly. These approaches would enhance the overall well-being of occupants rather than only the application of high levels of insulation which can possibly increase the internal temperatures and methods of construction that can cause defects.

The outcomes of the research showed frequent high internal temperatures were observed in UK timber houses. The results revealed that overheating occurs due to smaller internal spaces and high level of insulation of the building fabric. The findings showed that design of houses with smaller internal spaces contributes to frequent indoor temperatures in dwellings. The performances of prefabricated timber envelopes depend mainly on design, the overall volume of the spaces, external weather conditions and the occupants' actions to take further adaptive measures to improve the thermal conditions of the spaces during summertime. Improvement has to be made regarding thermal mass of timber which can help the mitigation of overheating and regulate temperature swing within the internal environments in summertime. Additional effort need to be made on design when timber is used for buildings. The overall urban form of timber housing needs to be taken into consideration at the design stage as heat cannot be dissipated easily in the mid-terraced dwellings in the summer while the end-terraced dwellings tend to get warm quickly due to the low thermal mass of timber.

Orientation of spaces should be carefully considered in the design of newly built houses. Indoor spaces should be provided with adequate size of openings that will enhance natural ventilation of spaces in summertime. Construction of houses should be built in accordance with the minimum setback standards set in the planning guide to reduce overshadowing observed between houses in urban areas. The minimum setback standards will also improve air quality between different houses. In addition, the minimum setback standards will improve the rate of fresh air that gets into indoor spaces which can possibly reduce the impact of summertime overheating in dwellings. The existing minimum setback standards should be reviewed to promote healthy and sustainable environment in dwellings. As observed in houses built in the early 20th century (that is, the Edwardian period), the minimum setback should form part of the overall landscape in dwellings to provide cooling effect during hot summer days which can possibly reduce summertime overheating in dwellings.

The policy that promotes use of prefabricated timber for housing development should be put in place by the government for various housing providers including local authorities, housing developers, investors and intending home owners. More publicly and privately financed prefabricated timber housing developments should be encouraged to improve the UK timber housing stock which is currently less than 10% of the total housing stock to promote the overall concept of sustainable housing in the UK. Efforts should be made by the government to encourage people to use prefabricated timber products for construction of dwellings by investing in the sector. More investors should be encouraged to invest in the UK timber housing sector to promote locally produced structural timber panels which are currently manufactured and transported to the UK from other part of Europe. The various initiatives will help the cost of prefabricated engineered timber products to be more affordable for people to build. Also, the building regulations guiding the different local councils in the UK should set a minimum percentage of houses that must be constructed with prefabricated timber per year to encourage the use of timber for housing developments. The development will change the general perception of people about timber housing which has a long history in the UK as a way of providing temporary dwellings in the period of housing shortage. The design of houses built with prefabricated timber should take into consideration spaces that promote the overall well-being of people and the internal conditions must be comfortable for occupants in different seasons.

The existing minimum space standards should be reviewed. Sizes of UK dwellings should not be assessed by number of rooms provided but by the total floor areas as being done in other European nations that are more densely populated than the UK who build bigger houses to provide internal spaces that improve overall well-being of occupants. The overall research outcomes showed that newly constructed UK houses are getting smaller and overheating occurs frequently in modern houses. Therefore, efforts should be made to address a shortfall in minimum space standards to enhance occupants' comfort and overall well-being as external temperatures are expected to be increasing as global temperature increase in future.

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Appendix 1

This appendix presents overview of UK housing in the 19th century. Overview of UK housing in the recent historical period (that is, the 1980s and the 1990s) had been discussed in Chapter 3.

A1.0 19th Century UK Houses- Design, Materials, Construction and Environmental Sustainability

The 19th century marked the beginning of UK mass housing development. The development started in the 1880s with construction of more ambitious publicly and privately financed mass housing developments. The development focused on replacing poor houses with social housing due to rapid industrialisation in many UK urban centres. The improvement gave the local councils a leading role based on the powers granted to them to improve the hygienic situation of houses in urban centres (Woodman & Greeves, 2008). This led to the displacement of many families with a shift in focus of construction from workhouses, schools, churches to mainly housing projects such as the Peabody Square Estate, London[35]: a privately financed housing development comprising blocks of apartments for various social classes with different typologies such as one-bedroom and two-bedroom flats (Figures A1.1 and A1.2). The estate was built in accordance with minimum space requirements recommended by the Housing of the Working Classes Act of 1880 which stated the need for healthy houses in urban and suburban areas. The internal spaces at the Peabody Estate were planned by placing bedrooms next to living rooms providing occupants to walk through living room to bedroom. The estate was built mainly with traditional materials (bricks, slates) using traditional methods of construction with no insulation (in contrast, timber-framed houses have either infill panels or insulation in the cavities) which may likely improve internal conditions of the flats in summer due to high thermal mass of bricks. However, further investigation needs to be carried out to examine the performance of the 19th century houses in different seasons; while this study focuses on the performance of prefabricated timber houses built in the last decade and the results had been discussed in Chapters 6 and 7.

At the Peabody Estate, there was a provision for fireplace in the living room of each apartment and coal was used for heating in winter. The bedrooms were not heated as occupants were expected to spend longer hours in the living rooms unlike modern houses

[35] The Peabody Estate comprised of blocks of flats for middle-class (mansion flats) and working-class (tenement flats). The developments of Peabody Estate stirred up need for the local authorities to provide social housing for people such as the London City Council that developed many LCC estates from 1889.

with heating systems provided in all habitable spaces. In summer, the internal spaces were expected to be naturally ventilated with provision for large size windows in all the habitable spaces. The bedrooms were not ensuite as occupants had to walk through the corridors to access the washrooms allocated to two or more apartments. In addition, the bathrooms were 'common' to all flats in any given storey as shown in Figure A1.1. The storage spaces (cupboards) were not provided inside the apartments but located next to the washrooms as shared facilities for occupants of different apartments. Also, kitchen facilities were shared between residents of different apartments on each floor. The stair hall was centrally placed at the core area of the building for residents to access their apartments. Gardens and open green spaces were provided for residents to relax and recreate which added to the overall urban environment of the development and possibly minimise frequency of extreme high temperature in summertime (Figure A1.2).

Another example of housing development built in the 1870s was Shaftesbury Park Estate in Battersea, London[36] (Booth, 2012). The architectural style of the houses built in the 1870s and the 1880s is 'Neo Renaissance'.[37] From 1870 to the end of the century, terraced dwellings were commonly built in the UK (Campbell, 2008; Woodman & Greeves, 2008); while other types of houses were built in suburban areas and the bye-laws specified at least 14m² open spaces at the back of the dwellings for various purposes like gardening and relaxation. For floor-to-ceiling height, at least 2.4m was recommended and arrangement of the internal spaces were planned to avoid having too deep rooms and the concept of one habitable space with a cloister was introduced (Moran, 2004; Campbell, 2008; Coolen & Meesters, 2012). This was done to improve the internal condition of dwellings (Moran, 2004; Whitehead, 2007; Clune *et al.*, 2012). The century

[36] Shaftesbury Park Estate in Battersea, London (1873-1877). The Estate is a privately financed housing development, also a good example of philanthropic housing and comprised of at least 1,200 two-storey dwellings of different typologies such as two-bed and three-bed houses. The dwellings were built for various social classes with provision for bathrooms only in the houses for the highest class and the typologies were ranked by number of bedrooms. All the other typologies for middle-class and working-class have shared bathrooms. The houses were built with well decorated red bricks and the pitch roofs were covered with slates material. The typologies have different facades that enhanced overall urban view of the estate. The houses were provided with gardens and trees planted along the streets which add to the overall landscape design of the development. All the living rooms were provided with fireplaces. The spaces were naturally ventilated in summer. The housing was built using the Classical Victorian style.

[37] Neo-Renaissance, also known as Renaissance Revival is an architectural style used for houses in the 19th century that does not suggest Gothic Revival style (a revival style from medieval period that features pointed arch windows and doors with asymmetrical layout designs) or Greek Revival style but indicates a combination of previous styles (renaissance architecture) before the century with features of various classic Italian styles such as large size of windows, decorated cornice.

was known for the introduction and development of terraced housing in Britain with a focus on internal arrangement of spaces and emphasis was laid on avoiding deep plan internal spaces and the need for corridors to enhance circulation.[38]

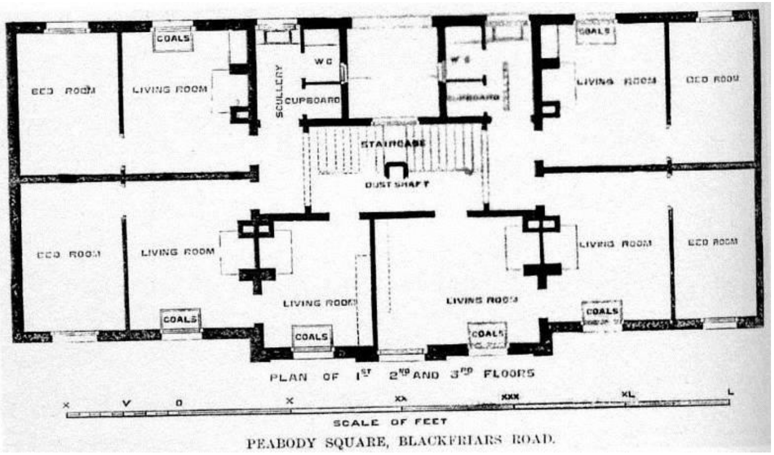

Figure A1.1: Floor plan of the Peabody Square housing, London (1880s) showing non-deep internal spaces with fireplace in the living rooms to accommodate coal used for heating and arrangement of corridor near the spaces and the stair hall for access and circulation, lack of internal circulation within the flats (that is, walk through living room to bedroom) and shared washroom and storage for different flats (Campbell, 2008)

Figure A1.2: External view of the Peabody Square housing development in London (1880s), a good example of philanthropic housing provision showing decorative cornice along the facade clad in bricks, large openings for natural ventilation and lighting and hip-gable roof with projecting chimney used for heating (Campbell, 2008).

[38] Terraced housing is a combination of dwellings in a row arrangement and often identical in terms of floor plans, elevations with common partitions between the dwellings. The privately financed houses were built as speculative and the bye-laws recommended development of terraced housing as a possible means of addressing shortage of housing supply as it saved additional costs of building external walls for each dwelling unit.

From the 1880s, Mock-Tudor houses were also built in urban and suburban areas to imitate external features of traditional Tudor timber-framed houses constructed between the 15th and the 17th centuries. Some of the features of traditional Tudor timber-framed houses include: wattle and daub infill panels, mullion windows, stone or brick base, timber-framed, gable roofs, eaves, ridge tiles, sill plates and chimneys for fireplaces. Considering Mock-Tudor houses built from the 1880s, they were well-designed, properly constructed, stylish, durable and well-decorated facades with timber. The architectural style of Mock-Tudor houses was greatly influenced by Art Nouveau and the Arts and Crafts movement. Since the 19th century marked the beginning of industrialisation and mass production of various prefabricated components, timber components used for decoration of facades of Mock-Tudor houses were mass produced. Moreover, different prototypes such as two-bedroom and three-bedroom were provided in Mock-Tudor houses. The internal spaces in traditional Tudor timber-framed houses were smaller than Mock-Tudor houses built with bricks and decorated with timber during the 19th century due to limited span of timber used mainly for traditional Tudor timber-framed houses. The fireplaces in Mock-Tudor houses were located in living areas along the outer walls using coal with no heating provided in bedrooms. Sash and casement windows were installed in spaces. Kitchens in Mock-Tudor houses were bigger in size than kitchens in traditional Tudor timber-framed houses and reduced storage spaces in Mock-Timber houses were provided underneath the stair hall leading to upper floors. Additional spaces for a piano and drink cabinet were created which made internal spaces to be reduced in size. The gable roofs were covered with slates material. Mock-Tudor houses in suburban areas were provided with private gardens which can possibly influence the overall performance of the houses.

Most houses built during the 19th century were for the upper- and middle-class with steady growth of the sector and high demand for houses with a focus on good living conditions compared to many modern housing developments that focused mainly on number of dwelling units. The 19th century houses were largely financed and owned by philanthropic organisations such as the Peabody Trust and occupants were mainly tenants with provision for residents with higher income to buy the apartments. In suburban areas, houses built during the century were owned by wealthy individuals as country houses with a provision for additional internal spaces to accommodate large numbers of family members and servants. Also, suburban housing developments were provided with additional facilities such as private gardens and landscape parks. The facilities were not provided in housing built in urban areas due to a growing demand for more plots of land for additional housing developments. In terms of design, the 19th century houses were considered to be distinctive with no repetition of floor plans (Moran, 2004; Campbell, 2008). For maisonette flats, the designs have between two and three floors with variations in arrangement of internal spaces and treatment of facade. Also, arrangement of internal spaces into different sections (zoning) within a house was introduced to improve living conditions of people. Living areas were expected to be warmer due to provision for heating and occupants were expected to spend longer hours in living rooms which may not possibly be the same in modern houses and had been examined in Chapters 6 and 7. The 19th century houses were mainly low-density in terms of occupants' number per total floor area of dwellings with generous internal space and higher floor-to-ceiling heights for natural ventilation and lighting.

A2.0 20th Century UK Houses- Design, Materials, Construction and Environmental Sustainability

The 20th century saw the growth of timber housing developments in the UK at different periods in the century (1910-1930 and in the 1940s) and towards the end of the century (that is, the 1990s). The century also marked the growth of UK mixed-use housing developments. During the Edwardian period (1900-1914), mixed-use housing developments with private outdoor spaces initiated by Henrietta Barnett[39] for various classes were considered in many UK cities especially in London (Woodman & Greeves, 2008). Barnett's original proposal was to construct mixed-use developments with different facilities like shops, post office and schools but could not be built due to financial constraints.[40] Apart from the introduction of mixed-use developments, many municipal housing estates were built between the 1910s and 1920s in the UK such as the Becontree Estate in East London (1921-1935). The Becontree Estate is a publicly financed housing with a total area of $10km^2$. It accommodates well over 90,000 people

[39] Henrietta Barnett (1851-1936) was a prominent social reformer in England. She worked on the development of social housing projects for various social classes such as the model for Hampstead Garden Suburb, London.

[40] Mixed-use developments can be in terms of space usage where dwellings and other communal facilities such as shops, post-offices are provided for people. They can also be described in terms of development of housing for various social classes such as provision of smaller apartments for working-class and bigger apartments for middle-class (professionals).

and is the largest housing estate in Europe. The working and middle-class houses were built in accordance with minimum space standards highlighted in the Housing Act of 1919. Different typologies of dwellings such as two-bed and three-bed houses were provided for occupants. In total, up to 26,000 dwellings were built and they have two floors with living rooms, kitchens located in the ground floors and bedrooms in the upper floors. The dwellings have smaller windows when compared to houses built in the 19th century but larger than those of modern houses. The houses were provided with fireplaces.

The Becontree Estate was built with bricks using traditional methods of construction with no insulation. The kitchens, bathrooms have hot and cold water supply. The heating system in all the houses used coal or gas compared to the 19th century houses that were mainly heated with coal. Storage facilities were provided for occupants at the ground floor. Toilets were provided in the dwellings with no need for shared bathrooms as observed in the 19th century houses. Also, the houses have private gardens which are not commonly found in modern prefabricated timber houses built in urban areas but can be observed in modern timber houses and Mock-Tudor houses[41] located in suburban areas (Figure A1.33). Open green areas were also provided in the estate as part of the overall urban environment for residents to relax. For all houses built during the Edwardian period and the post-Edwardian period, the Housing Act 1919 set the minimum setback standard of 21m between houses in suburban streets to reduce overshadowing which is no longer taken into consideration in many modern houses. The minimum setback standard improves air quality and speed of fresh air that gets into indoor spaces of houses in suburban streets which can possibly reduce the impact of summertime temperatures (Figure A1.4). Also, the minimum setback areas were considered as part of the landscape in suburban streets to provide cooling effect during summertime which is no longer considered in many modern houses. Examples of dwellings built during the Edwardian period include the ‘Byker’ flats and suburban housing with ground and first floor flats in terraced housing built across the UK (Figure A1.5).

[41] Mock-Tudor houses were built from the 1880s to the late 1930s. Mock-Tudor houses were decorated with timber painted black to imitate traditional Tudor timber-framed houses and external walls painted white. The black timber was preserved using oil. Timber used was locally sourced and in some cases brought from Scandinavian nations such as Sweden and Denmark.

Figure A1.3: View of a Mock-Tudor manor house located at the banks of the River Mersey in Liverpool built in the 19th century showing the ornamented facade with a unique black and white timber materials suggesting a blend of Victorian architecture with features of traditional Tudor timber-framed construction and crafts covered with slates material laid on striking gable roof (National Trust, 2013).

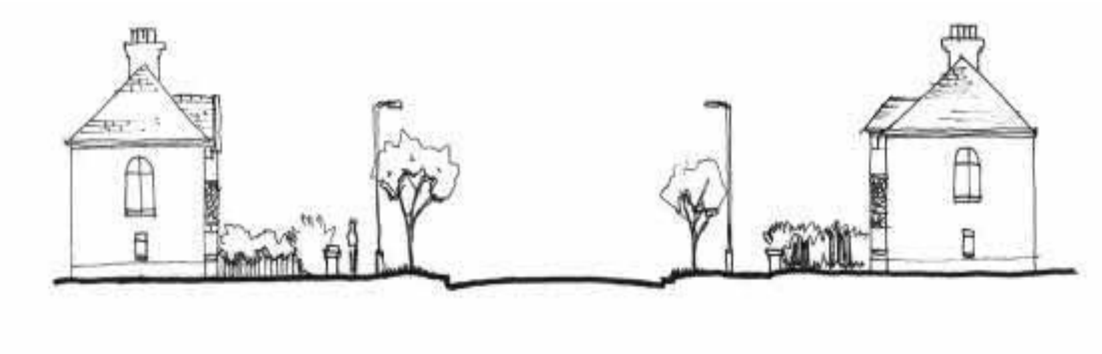

Figure A1.4: Street view of suburban housing developed in Maidenhead during the Edwardian period showing uniform building line and rhythm along the street with the minimum setback standard of 21m to reduce overshadowing, improve air quality and rate of fresh air into internal spaces which are no longer considered in many newly built houses (The Royal Borough of Windsor and Maidenhead, 2010).

Figure A1.5: External view of 'Byker' flats in terraced housing in one of UK cities (Newcastle- left) and Edwardian suburban housing in Maidenhead (right) with centrally positioned openings over decorated entrance areas with left entrance leading directly to the first floor flat while the right entrance leads to the ground floor flats.

The interwar period (1920s-1930s) saw development of innovative mass housing as many of the modernist architects like Berthold Lubetkin, Walter Gropius, Erno Goldfinger and Erich Mendelssohn came to the UK in the 1930s (Woodman & Greeves, 2008). During the period, continental Modernism was being taken up (though not by all architects) and certain lessons (aesthetics, constructional, environmental and typological) applied to municipal and private housing. The period also saw construction of privately financed blocks of apartments such as Highpoint at North Hill in Highgate, London designed by Berthold Lubetkin and financed by an entrepreneur named Sigmund Gestetner. Construction of Highpoint blocks of apartments contributed to the overall growth of social housing sector during the period with provision of 64 apartments in Highpoint-1 for people and additional apartments in Highpoint-2. The housing developments built during the period were provided with private spaces and shared facilities like integrated nursery schools and gardens. The design considered spacious living areas and small bedrooms as some modernist British architects like Maxwell Fry indicated that bedrooms should be small. Maxwell Fry mentioned that *'people don't live in bedrooms all day'* and living areas should be generous for people to enjoy mealtime and relax (Campbell, 2008; Coolen & Meesters, 2012). Also, the sizes of kitchens provided in many dwellings were considerably reduced with limited space for people to carryout different tasks (Moran 2004; Campbell, 2008). For instance, Kensal House in Ladbroke Grove, London built in 1936 and designed by Maxwell Fry with internal floor area of $17.2m^2$ for living room, the balcony ($3.7m^2$), one of the three bedrooms ($11.6m^2$), while the kitchen ($9m^2$) which only allow the residents for cooking and other activities need to be done in other spaces.[42]

Kensal House is a grade II listed building owned by the Royal Borough of Kensington and Chelsea. It comprises two noticeable modernist blocks of apartments painted white and built for working-class in accordance with the Greenwood Act of 1930[43] that focused on proper planning of internal spaces in dwellings, clearing of slum and rehousing of people. The Greenwood Act of 1930 did not specify the minimum setback standard between houses in suburban streets and minimum space requirements as earlier considered in the Housing Act of 1919. The Greenwood Act stated need for construction

[42] Most of the interwar houses in urban centres were predominantly flat roofed blocks of flats but other types of houses such as Mock-Tudor terraced dwellings were built in suburban areas.

[43] The Act made provision for higher percentage of subsidies on landed properties that were on the high side in terms of cost. It also made provision for variations in rent as approved by the local authorities.

of quality housing for people. Kensal House was built with simple and unornamented concrete and covered with a flat roof also made with concrete. The housing development has a range of on-site facilities such as a community centre and a crèche. The overall concept of the development was to have a modern urban village where residents can feel safe, healthy and happy with their living conditions. In total, Kensal House has 68 apartments with different prototypes ranging from two-bedroom to three-bedroom apartments. The living room and the bedrooms were placed on the outer part of the blocks along north and south orientations to maximise natural lighting and ventilation as well as reducing energy required for running the two blocks of apartments. Also, the arrangement of the internal spaces provided a natural way of cooling the internal spaces during hot summer days which has been the major concern of this study which is to examine the potential of summertime high internal temperatures in prefabricated timber houses. Cupboards were provided in the kitchens for storage. The apartments were provided with central heating systems that used gas for heating. Since concrete is a high thermal mass material, internal environment of Kensal House is likely to be comfortable for occupants in summer but further investigation will be required to examine the actual performance of the house which will not be considered in this study. Each apartment was provided with kitchen, bathroom and corridor to access living room and bedrooms. Considering the overall urban environment of Kensal House, there were no provisions for private gardens which can possibly help in reducing the impact of summertime temperatures within the environment.

Apart from flat roofed social housing developments expressing Art Deco that were constructed in urban areas during the interwar period, Mock-Tudor houses observed from the 1880s and the Edwardian period were also developed in the UK due to housing boom as over 4 million dwellings were provided. The type of houses built from the 1920s varied from terraced to semi-detached depending on the financier of the project. Most Mock-Tudor houses built in the 1930s have different geometric shapes such as round bay in front views, striking gable roofs and semi-circular porch set into external walls (Figure A1.6). In addition, cottage-style timber-framed houses were developed in suburban areas between the 1920s and the 1930s. The living rooms of the 1930s houses were provided with fireplaces for heating with no heating provided in the bedrooms and central heating systems were installed in many of the houses after decades. Floors and walls of the interwar houses were insulated to reduce heat loss. The internal spaces were expected to be moderately warm in summer but further investigation on the actual performance of the 1930s houses need to be considered due to the rising external temperatures in the last few decades caused by global warming. The windows were originally installed as bay and wooden casement windows suggesting the possibility for heat loss in winter. However, the original windows of many houses have been replaced with double glazed windows to improve the overall performance. Storage spaces were provided next to kitchens. The houses were mostly built in suburban areas and were provided with private gardens and green open spaces.

Figure A1.6: Mock-Tudor housing development built during the interwar period in Ham, Surrey showing a typical arrangement of houses with replicated style and decorative timber, striking gable and the houses are clad with less stylish timber and provision for minimum setback as specified in the space standards and rear private gardens (Alamy, 2014).

The later part of the 1940s saw rapid development of prefabricated timber-framed houses in the UK to solve problems associated with housing shortages, lack of trained workers and rising demand for housing after the Second World War. The period saw a shift from construction of Mock-Tudor houses to timber-framed houses. The post-war timber houses were built in accordance with the Dudley minimum space standards of 1944 (space standards considered in Section 3.3.1). The government provided the general guidelines on the design but various developers were permitted to come up with their designs, methods of assembly the prefabricated timber components and the heating systems (Gilbert, 2011). The houses were built with features of modernism architecture such as flat roof, large windows, unornamented prefabricated components as observed in the interwar houses and other post-war modernist houses. Examples of timber houses built in the 1940s include the Excalibur Estate in Catford, London (Figure A1.7) and the Arcon

Estate in Newport, Gwent (Vale, 1995, p.2). The major typologies of dwelling units built were two-bed and three-bed bungalows. The internal spaces were arranged in an open plan layout with provision for fireplaces for heating in living areas using gas compared to the 19th century houses and the Edwardian houses that used coal for heating. Bedrooms were not provided with heating and living areas were expected to be considerably warmer than bedrooms. Separate storage spaces were not provided but included in fully fitted kitchens as small-sized cupboards. Bathrooms were also provided for the houses. Large size glazed windows as opposed to regular size windows were placed at the corner of living areas for natural lighting, ventilation and viewing the immediate environment. Internal spaces were expected to be naturally ventilated in summer. The cavities (50mm width) within the walls were insulated using wool to reduce heat loss and energy consumption in winter with a potential for summertime high internal temperatures which is the main concern of this study. The overall urban environment for the houses was not thoroughly considered as they can be assembled in any vacant plot of land. However, general layout was planned for evaluating the number of dwellings a plot of land can take which was not observed in other houses built with heavyweight materials. This may be due to the general view of people that timber houses are temporary structures and the houses were built to last for only a few decades.

Figure A1.7: Views of the Excalibur Estate in London, a timber-framed post-war speculative mass-produced housing development showing timber flat roofs, corner windows and panelled plywood doors (Prefab Museum 2014).

Also, open plan design with no clear demarcation between living area and kitchen was considered for blocks of apartments built in the 1950s (Adler, 2008; Campbell, 2008). Moreover, the idea of ‘housing clusters’ design that has been showcased at Keeling House in Bethnal Green, London designed by architect Denys Lasdun in the early 1950s and completed in 1959 was developed (Figure A1.8). Other examples of housing developments built during the period include Sulkin House, Usk Street in Bethnal Green, London completed in 1952 and Cranbrook Estate opened in 1963. Most of the housing developments were provided with a minimum of 4.5m floor-to-ceiling height in living areas to improve the thermal conditions of the spaces. A minimum of 4.5m floor-to-ceiling height in living areas was introduced to enhance natural way of cooling the spaces in summer as hot air rises at a faster rate when fresh air comes into the spaces. Alton West in Roehampton designed by Peter Carter, Alan Colspon and Colin St John Wilson is provided with double-height living areas. The housing developments constructed in the 1950s were built in accordance with the Housing Manuals of 1949 and the space standards had been discussed in Section 3.3.1. The period between the 1950s and the 1960s also saw a change in the minimum setback standard of 21m observed between houses in suburban streets during the Edwardian period (Figure A1.9).

Figure A1.8: External views of Keeling House, Claredale Street in Bethnal Green, London showing clustered arrangement of apartments with centrally placed water body in the foyer at the ground floor which can possibly improve the thermal conditions of the building in summertime.

Figure A1.9: Street view of suburban housing developed in Maidenhead between the 1950s and the 1960s showing building line and rhythm along the street with a move from the minimum setback standard of 21m observed during the Edwardian period which can possibly lead to overshadowing as well as reduce indoor air quality and rate of fresh air into internal spaces and increase the impact of summertime temperatures when compared to houses built during the Edwardian period (The Royal Borough of Windsor and Maidenhead, 2010).

In the late 1960s and early 1970s, most high-rise housing developments were built using prefabricated methods of construction. The use of prefabricated methods of construction was employed to build houses in order to save time, cost and enhance mass produced houses on a large scale. In 1968, well over 420,000 new dwellings were built in the UK (Campbell, 2008; Maliene & Malys, 2009) and the Parker Morris minimum space standards also came into operation (which had been discussed under Section 3.3.2). Also, the late 1960s saw the people's indication of growing frustration and dissatisfaction regarding the poor living conditions in houses which had affected their well-being with a request for funding to clear slums, carry out refurbishment of the houses and various action groups such as the Walkley Action Group in Walkley, Sheffield, Manchester and Salford Housing Action Group were formed by a few tenants in different cities to call for the redevelopment of housing in the areas. Many high-rise housing developments such as Sivill House in Bethnal Green, London and the iconic Red Road Estate in Glasgow were also built in the 1960s.

The period between the 1960s and the 1970s also saw construction of timber-framed self-build housing developments in the UK pioneered by Walter Segal (1907-1985), a German emigrant architect. Segal developed a system known as the "Segal Method" that moved away from conventional methods of construction by focusing on development of a modular, timber-framed construction methods that can be built in any location (Homebuilding, 2014) as shown in Figure A1.10. The system is cost-effective in terms of construction, labour required, materials, time and maintenance. The houses were built with modernist features such as flat roof, simple geometrical shapes, unornamented facade and the roofs were covered with multiple layers of felt to avoid leakage. The houses were built in different prototypes such as 2-bed, 3-bed with limited internal partitions to reduce overall cost of the dwellings. The cavities in the external wall were well insulated and the internal walls were clad with plasterboard. The development of housing built using the "Segal Method" has been considered as eco-friendly strategy to construction of dwellings due to use of timber for construction. Examples of timber-framed self-build housing developments built by Segal include Segal Close housing and Walter Way housing in Southeast, London.

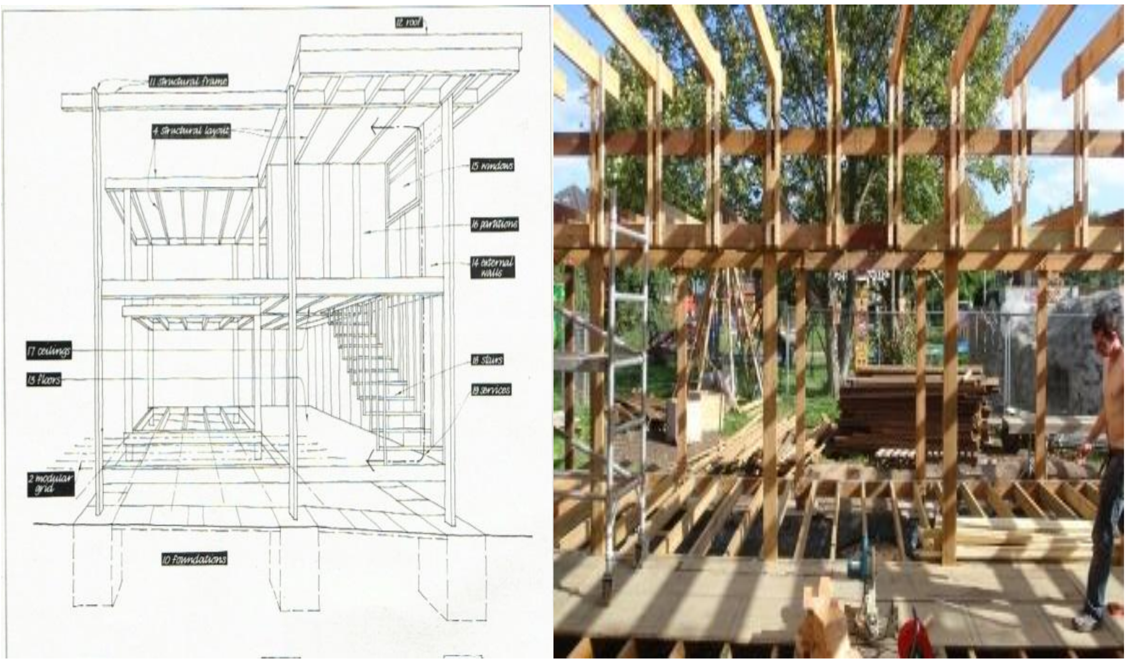

Figure A1.10: The Segal Method showing assembly of various prefabricated components of building such as walls, roof using timber-framed construction methods that can be built in different locations (Architects Journal, 2012).

Prefabrication methods of construction were also used for construction of housing in the late 1960s. Mixed-use development such as the Brunswick Centre in Bloomsbury, London designed by architect Patrick Hodgkinson in 1967 and completed in 1972 was developed. It was built in accordance with space standards specified in the Housing Manual of 1949. The Brunswick Centre was provided for people with communal facilities and components used for construction which were mass produced. It has 16 dwelling prototypes such as penthouse, one-bed, two-bed and three-bed apartments. It was built with concrete using prefabricated methods of construction. In total, about 400 dwelling units were provided in the development and up to 100 units are privately owned. The dwelling units were arranged in two rows in the upper floors, shops were located in the lower floors and the two basement floors were provided for parking. The floor areas of two-bed apartments range from $75m^2$ to $80m^2$. Storage facilities (cupboards) were provided near the kitchens in one-bed apartments while separate storage spaces were provided in two-bed and three-bed apartments. Central heating systems were provided in the apartments for heating during cold season.

The internal spaces at the Brunswick Centre are provided with single-sided ventilation. However, potential of frequent high internal temperatures can possibly be reduced in the spaces due to high thermal mass of concrete used for the envelopes when compared to lightweight houses with low thermal mass. Also, there is an indication of leakage in the building fabrics due to poor details and further investigation will be required to examine the fabrics which may affect the overall performance of the housing development and occupants' comfort. Outdoor open and green spaces were provided for residents and visitors to relax. Landscape design of the development with provision for water bodies around the building adds to overall urban environment of the Brunswick and can possibly enhance comfortable internal and external conditions for people during summertime. The architectural style for the housing development indicates New Brutalism[44] suggesting a change in trend of architectural style from modernist architecture used for the post-war houses in the mid-1940s to New Brutalism in the late 1960s. It is also a good example of a megastructure as mentioned by (Banham, 1969). So, a pincer movement was attacking prefabrication construction methods in concrete panel and timber-frame during the period.

From the beginning of the1970s and even in the 1980s, the number of new tower blocks of flats was considerably reduced due to the partial collapse of Ronan Point in Newhan, East London in 1968 caused by a gas explosion and Pruitt-Igoe in St Louis, US that was purposely demolished in the mid-1970s for being infamous as a place associated with various social problems. As a result, high-rise housing development was no longer considered as the solution to high density family housing due to problems like poor ventilation, overshadowing, lack of adequate space for parking, pedestrians and structural defects. Private developers were empowered to develop various housing projects with autonomy on design, specifications, materials, methods of construction and the period saw rapid development of private/speculative housing with conventional method of construction. The 1970s saw the rejection of timber-framed methods of construction for dwellings as a result of the World in Action documentary on BBC TV that exposed construction defects, poor details of the post-war timber houses (Anson *et al.*, 2002, p. 386; BRE, 2002). Also, there were other problems observed in timber houses regarding dampness, condensation, wet indoor conditions which can affect the overall well-being of

[44] New Brutalism is an architectural style that was expressed in many housing developments between the 1950s and the 1970s. The style draws its inspiration from modernist architecture that started during the interwar period with a focus on materials such as concrete, bricks that can be exposed when used for construction and expressed the buildings' facades.

occupants. The developments led to concerns on credibility and performance of timber as a good material to build houses and use of timber for construction of dwellings was discouraged. However, timber-framed methods of construction were not totally eliminated.

The introduction of the Housing Act of 1980 empowered council flat tenants and gave them the opportunity to buy their apartments at a discounted price when compared to the actual market price and more than 2.3million council dwellings were sold to tenants. The political change that occurred during the time also created an enabling environment for private developers to operate. The period saw decline of publicly financed housing development and private developers were supported with grants to construct speculative housing. Many private housing developments were constructed with numerous urban and suburban housing projects across the UK which led to a decrease in development of new council flats. London's Dockland housing development is one of the notable privately financed housing projects completed towards the end of the 20th century as well as privately owned luxury apartments like Horselydown Square in Bermondsey, London (Figure A1.11) and China Wharf in Shad Thames, London (Campbell, 2008). Also, some housing projects with features of Neo-vernacular British architecture such as privately financed terraced housing in Aldershot, Hampshire were built. The houses also known as 'Noddy' housing or 'boxes' are low standard, small in size, built on narrow plots with unusable roof space beneath pitched roofs (Figure A1.12). The 20th century also saw the development of housing projects featuring Georgian Revival and Victorian architecture with focus on space.[45] A good example is Jeremy Dixon housing in Maida Vale, London; a public/private partnership housing scheme built between 1981 and 1983.

[45] Many of revivalist schemes are built for occupants with smaller household sizes. The houses are built to be more appealing in terms of visual appearance with a focus on a neat facade details, decoration of cornice etc. The internal spaces are very small with projection for more number of dwellings to accommodate more people as well as promoting social community by providing a common access, stair hall for occupants.

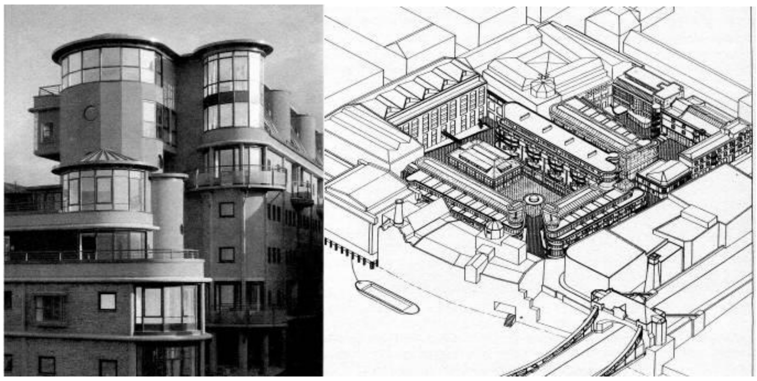

Figure A1.11: Views of Horselydown Square in Bermondsey London designed by Wickham & Associates in 1989, a luxury housing development with articulated facades that do not suggest it is a block of apartments (Architecture Today, 1991).

Figure A1.12: Privately financed housing in Aldershot, Hampshire with small internal spaces, narrow accessible road with uninhabitable internal space especially at the roof part of the development indicating waste of space (Independent Newspaper, 2012).

Jeremy Dixon housing is a terraced development which consists of 12 large houses (Figure A1.13). The floor-to-ceiling height and floor area of the internal spaces were considerably reduced compared to the houses built in the 19th century. Due to the decrease in floor area of the internal spaces, separate storage spaces were not provided within the house. The architectural style of the development moved away from post-modernism towards a reductive Victorian revivalism observed in other houses built in the 1970s but the features of the development such as simple and geometric facades with great attention to details as well as expression of a wide-ranging approach to style conforming to Victorian architecture. The development is built with bricks locally sourced using traditional methods of construction indicating the ability of the internal conditions to be comfortable in summer due to high thermal mass of bricks but further investigation will be required to examine the frequency of summertime high temperatures. The gable roof is covered with tiles different from flat roof used for the post-war mass produced houses. Each dwelling unit (flat or small house) is provided with either a modern garden located at the rear side of the development or a roof terrace for leisure and relaxation. Looking at the urban environment of the housing development shows a potential for noise pollution from traffic but it is easily accessible for occupants due to various transport networks.

Figure A1.13: View of Jeremy Dixon housing scheme in Lanark Road, Maida Vale, London (1981-83), a good example of public/private partnership located on a site owned by the London Borough of Kensington and Chelsea and part-funded by Michael Taylor Developer providing dwellings for small family sizes with a neat facade details showing the windows, arches decorations on top of the windows as well as paired walls between the buildings imitating the early Victorian architecture (Alan Powers, 2007; p.201).

A3.0 Criticism of Modernism in UK housing

The developments of high-rise blocks of flats mainly financed by local authorities and introduced by the architects working in the London County Council's department of architecture in the post-war period (from the mid 1940s) brought criticism against modernism in UK housing which were meant to address shortage of housing supply in the period (Moran, 2004; Woodman & Greeves, 2008; Campbell, 2008; Booth, 2012). The high-rise blocks of flats developed were designed by some leading British modernist architects such as Berthold Lubetkin, Denys Lasdun, Jane Drew, and Maxwell Fry with special interest in mass housing. The arrangements of internal spaces were different from traditional British house layouts with modernism approach that favoured open layouts with limited partitions and floor-to-ceiling height window. The designs from British modernist architects were criticised due to the similarity in appearance in different locations across the UK with reinforced concrete or steel-framed elements used for the high-rise blocks of flats and the external walls clad using infilling or pre-manufactured components. Also, there were criticisms about the modernist architects and planners for having too much influence on housing policy in the UK to encourage the government to build high-rise social housing which they considered alien to British traditional housing design. However, the efforts of the modernist architects in contributing to the overall development of mass housing in the UK must be commended.

The performance of high-rise social housing built in the post-war period was also criticised. Some crucial services like heating, cooling, electricity and even plumbing were installed using centrally placed service runs in the structure to conceal all the services (Dutton, *et al*., 2002, p.138; Moran, 2004). Many of the bathrooms and toilets were considered small with no access to natural lighting. The heating systems were centrally controlled with minimum intervention by occupants in each space to adjust the controls to suit the thermal conditions of the internal spaces. The size of the lift was considered very small for the number of residents living in most of the housing developments. The internal floor areas as well as height of high-rise social housing make it difficult for residents to carry out their everyday activities.

UK modern housing developments have also been built with modernist approach especially in terms of design, and construction method. Chapter 5 will focus on the case studies to understand the current trend. Chapters 6 and 7 had considered the performance of the structures and influence of housing parameters such as size and floor-to-ceiling heights. In order to understand different housing parameters used for various UK houses built in the 20th century and for the houses built in the 21st century which had been considered in Chapter 5.

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Appendix 2

This appendix presents a letter of invitation to participate in a survey as discussed in Chapter 4.

Invitation to Participate in a Survey

Dear Resident,

We write to formally introduce and invite you to participate in a survey on Thermal Performance of Prefabricated Timber Housing in the UK.

This study is being conducted by Timothy Adekunle, a research (PhD) student of Centre for Architecture and Sustainable Environment (CASE), Kent School of Architecture at the University of Kent in order to have a better understanding of indoor environments of low-carbon prefabricated housing in the UK. This research will help the investigator to better understand occupants' thermal adaptation to the internal conditions of modern houses. At the end of this study, the investigator will provide feedback of this study that focus on the thermal conditions in low-carbon prefabricated timber housing based on the data provided by the survey respondents.

The University would greatly appreciate if you can spare some time in completing the questionnaire(s) that will be administered over the next few weeks. Since the validity of the results depend on obtaining a high response rate, your participation is crucial to the success of this study. The questionnaire will focus on assessment of the thermal environment, and it will take few minutes to complete.

Administration of questionnaire indicates your consent to participate in this study. Please be assured that your responses will be held in the strictest confidence, as there is no name or personal details required. Every respondent will be treated anonymously. As soon as the investigator receives your completed survey and data collected all questionnaires will be kept by the University and later destroyed. If the results of this study were to be written for publication, no identifying information will be used.

The potential benefits to you from participating in the study include gaining a better understanding of the thermal conditions of low-carbon prefabricated timber housing in the UK. The study will also be helpful to increase your understanding on how to improve the level of comfort in houses. Should you require, you will have the opportunity to receive feedback regarding the study's result.

If you have any questions about this study, you can contact the person(s) below:

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I hope that you will be able to participate in this study.

Regards,

Timothy Adekunle

This study has been reviewed and approved by The University of Kent, Canterbury. If you have questions or concerns regarding this study please contact the Investigator or Supervisors.

Appendix 3

This appendix presents structure of the post-occupancy questionnaire discussed in Chapter 4. The results of the data gathered from the survey were presented in Chapter 6.

Kent School of Architecture | Centre for Architecture & Sustainable Environment (CASE)

UNIVERSITY OF KENT, CANTERBURY

POST-OCCUPANCY QUESTIONNAIRE FOR EVALUATION OF INDOOR ENVIRONMENT OF LOW-CARBON PREFABRICATED TIMBER HOUSING

This survey is part of a study to evaluate the thermal conditions of low-carbon prefabricated homes in the UK. We appreciate your feedback in this evaluation.

A. General Information

Building name: ....

Date: .... Time: .... Floor/Flat number: …………………………………........

1. Age (i) Under 18 (please state..........) ☐ (ii) 18-30 ☐ (iii) 30-45 ☐ (iv) 46-55 ☐ (v) 56 and above ☐

2. Sex (i) Male ☐ (ii) Female ☐

3. Employment status. (i) Retired ☐ (ii) Full-time ☐ (iii) Part-time ☐ (iv) Currently not in employment ☐

3b. Please state type of occupancy. (i) Rented ☐ (ii) Owned ☐

4. How long have you lived in the building? Years.............................. Months................................

5. On the average, how many hours per day do you spend in the building? ....

6. How many people live in your flat? (i) 1-2 ☐ (ii) 3-4 ☐ (iii) 4 and above ☐

7. What are the factors that influence your decision to live in the building? Please tick as many that apply (i) Cost ☐ (ii) Building type ☐ (iii) Materials ☐ (iv) Location ☐ (v) Others (please state).......................

B. Thermal Comfort

8a. How would you describe the thermal conditions in your flat in **summer** season?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

8b. How would you describe the thermal conditions in your flat in **winter** season?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

9a. How do you rate the overall thermal comfort of your flat in **summer** season based on the following scale? (Please tick one)

Very Comfortable ☐☐☐☐☐☐☐ Very uncomfortable

9b. How do you rate the overall thermal comfort of your flat in **winter** season based on the following scale? (Please tick one)

Very Comfortable ☐☐☐☐☐☐☐ Very uncomfortable

C. Satisfaction

10a. How do you rate the overall thermal environment of your flat in **summer** season based on the following scale?

Very satisfied | | | | | | | | Very dissatisfied

10b. How do you rate the overall thermal environment of your flat in **winter** season based on the following scale?

Very satisfied | | | | | | | | Very dissatisfied

D. Control

11. Please tick any item listed below you use to improve thermal environment of your indoor spaces?

Door open	Window open	Blind/curtain open	Light on	Central heating on	Fan on	Portable heater on	Others (specify)

12. Do you use any of the items listed in question 11 to improve thermal conditions of your flat often?
(i) Yes ☐ (ii) No ☐

13. Do you use any shading device to reduce sunlight into your flat? (i) Yes ☐ (ii) No ☐

14. How much control do you feel you have over the thermal environment of your indoor space?
High Control | | | | | | | | No control

15. How satisfied are you with this level of control?
Very satisfied | | | | | | | | Very dissatisfied

16. In general, how often do you use any of the controls provided in the building to adjust the thermal environment at your indoor space?
Regularly | | | | | | | | Never

17. How does your thermal comfort in your indoor space enhance or interfere with your ability to carry out activities?
Enhances | | | | | | | | Interferes

E. Others

18a. Please state the space you spent most of your time within your flat. (i) Lounge ☐ (ii) bedroom ☐

(iii) Dining/Kitchen ☐ (iv) Others (please specify)………………………….

18b. Is there any space in your apartment you consider to be much warmer than the other spaces? ....

19. How would you describe your experience as an occupant of the building you are living at this moment?
Pleasant | | | | | | | | Unpleasant

20. Is there any aspect of the indoor environment of the modern house you would like to comment on?...
....
....

Appendix 4

This appendix presents structure of the comfort survey questionnaire discussed in Chapter 4. The results of the data gathered from the survey were presented in Chapter 6.

Kent School of Architecture | Centre for Architecture & Sustainable Environment (CASE)

UNIVERSITY OF KENT, CANTERBURY

COMFORT SURVEY QUESTIONNAIRE FOR EVALUATION OF LOW-CARBON PREFABRICATED TIMBER HOUSING

This survey is part of a study to evaluate the thermal conditions of low-carbon prefabricated homes in the UK. Please tick or select as appropriate. We appreciate your feedback in this evaluation. Thank you for your participation

A. General Information

Date: .... Building name: ....

1. Age (please tick) (i) Under 18 (please state........) ☐ (ii) 18-30 ☐ (iii) 30-45 ☐

(iv) 46-55 ☐ (v) 56 and above ☐

2. Sex (please tick) (i) Male ☐ (ii) Female ☐

3. Location of apartment in the building (floor/ flat number/ orientation): ....

Time: Morning……………………………. Afternoon…………………………..

Evening…………………………………

4. **Feeling-** At present I feel

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

5. **Preference-** I would prefer to be

Much cooler	Cooler	No change	Warmer	Much warmer

6. Is the thermal environment within your flat at this moment acceptable to you? (i) Yes ☐ (ii) No ☐

7. Have you used any of the options below in the last half hour?

Door open	Window open	Blind/curtain open	Light on	Central heating on	Fan on	Portable heater on	Others (specify)

8. Which items of clothing below are you currently wearing?

Short sleeve shirt/blouse	Long sleeve shirt/blouse	Trousers/ Long skirt	Shorts/ Short skirt	Dress	Pullover	Jacket	Long socks
Short socks	Tights	Tie	Slippers	Sandals	Shoes	Boots	Others (specify)

9. At this moment are you wearing more clothing than you prefer? (i) Yes ☐ (ii) No ☐

10. What has been your activity in the last 15 minutes?

Sitting (passive work)	Sitting (active work)	Standing relaxed	Standing working	Walking indoors	Walking outdoors	Others (specify)

11. Have you consumed any of the following items within the last 10mins? (i) Hot drink ☐ (ii) Cold drink ☐

B. Response on Thermal Comfort Parameters

12. I would like higher air movement into my present space. (i) Yes ☐ (ii) No ☐

13. Have you experienced any overheating in your flat today? (i) Yes ☐ (ii) No ☐

14. Do you like to add anything? ....

Appendix 5

This appendix presents a letter received from one of the representatives of Oxley Woods' residents after the surveys to complain about frequent high internal temperatures observed in the houses in summer.

Oxley Woods temperature data

Chris [redacted]@googlemail.com]
Sent:31 March 2014 21:36
To: T.O.Adekunle
Cc: B SWANN [redacted]@btinternet.com]

Hi Timothy,

Hope you are well.

Residents of Oxley Woods have been having a think about options that might improve our homes, and one of the topics has been the relatively high temperatures experienced in summer.

Do you have any data on this that you would be able to share with us? It would be great to have some details of how the houses perform, including the peak temperatures experienced.

I'd be happy to discuss if you have any queries. I'll be working from home during Tuesday so reachable on [redacted] or via this email address.

Best regards,

Chris