Energy reduction in domestic homes using smart control systems

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by

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Abstract

The aim this work was to investigate the effect smart heating control systems have on the energy performance in domestic homes in the UK.

An experimental investigation was conducted of three case study buildings which were selected with different constructions and occupancy patterns to represent a cross section of the typical UK housing stock. Temperature data loggers were deployed in each home from 1 February until 31 April 2014 and these logged the internal temperature of the living room, kitchen and master bedroom at 5 minute intervals. A numerical analysis using IES VE (Integrated Environmental Systems Virtual Environment) dynamic thermal modelling software was undertaken of these three case study buildings with the results from the experimental investigation used to provide validation that the thermal performance of the dynamic thermal models was the same as the case study buildings, within experimental tolerances.

The thermal performance for each case study building was compared to the CIBSE (Chartered Institute of Building Service Engineers) recommended guidelines for internal thermal comfort temperatures and consistent underheating in each case study building was identified. One dynamic thermal model was selected and taken forward for modifications to be made to the heating control system, with the single zone thermostatic control system being replaced by a 2 zone thermostatic control system and finally a multi zone thermostatic control system.

Three thermostat schedules were investigated for the zoned control systems, the first being a 9-5 working schedule assuming the occupants are out of the house between those hours, an always occupied schedule assuming some level of occupation through the day and a nightshift schedule assuming a shift workers pattern not following a traditional Monday to Friday 9 – 5 working week.

The study found that increasing the zoning of the control systems did not yield energy savings in every case but did increase the comfort conditions for the occupants and the degree of control the occupants had in their building. The occupancy pattern was found to affect the performance of the zonal heating strategy.

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Nomenclature

λ	Thermal Conductivity (W/mK)
d	Thickness (mm)
R_{int}	Internal surface resistance (m^2K/W)
R_{ext}	External surface resistance (m^2K/W)
R_n	Thermal resistance of layer n (m^2K/W)
U	Thermal transmittance (W/m^2K)
$T_{(x,y,z,t)}$	Temperature in the solid at position (x,y,z) at time t (°C)
$\underline{W}_{(x,y,z,t)}$	Heat flux vector at position (x,y,z) at time t (W/m^2)
ρ	Density (kg/m^3)
c	Specific heat capacity (J/kgK)
Q	Energy (W)
c_p	Specific heat capacity of air at constant pressure (J/kgK)
ρ_a	Density of air (kg/m^3)
V	Volume (m^3)
T_a	Bulk Air Temperature (°C)
T_n	Temperature at node n (°C)
δ_n	Local node spacing (m)
Δ	Simulation time step (s)
W	Heat flow (W)
T_1	Temperature at surface 1
T_2	Temperature at surface 2
R_{com}	Combined radiative and convective resistance of the air gap (m^2K/W)
T_s	Mean surface temperature (°C)
K	Coefficient
N	Coefficient
h_c	Convective heat transfer coefficient
v	Wind speed (m/s)
T_i	Supply temperature air (°C)
$\dot{m}$	Air mass flow rate (kg/s)
ε	Surface emissivity (W/m^2)
σ	Stefan-Boltzmann constant (W/m^2K^4)
Θ	Absolute temperature of the surface (K)
$d\omega$	Element of solid angle
θ	Direction angle measured from the surface normal
T_s	Surface temperature (°C)
T_{mrt}	Mean radiant temperature of the enclosure (°C)
h_r	Surface heat transfer coefficient for exchange with the MRT node.
β	Surface inclination (°)
$L^*(\beta)$	Net long wave radiation gain (W/m^2)
ε_e	Emissivity of the external surface
$L_{sky}(\beta)$	Long wave radiation received directly from the sky (W/m^2)
$L_g(\beta)$	Long wave radiation received from the ground (W/m^2)

Θ_e	Absolute temperature of the external surface (K)
Θ_a	External absolute air temperature (K)
p_w	External air water vapour pressure (hP)
c_{cloud}	Cloud cover
ρ_g	Short wave ground reflectance (albedo)
I_{glob}	Total solar flux on the horizontal plane (W/m^2)
f_{shd}	Diffuse sky shading factor for the surface
I_{dir}	Direct solar flux incident on the surface (W/m2)
I_{beam}	Solar flux measured perpendicular to the beam (W/m^2)
θ_i	Angle of incidence
I_{sdiff}	Diffuse sky solar flux incident on the surface (W/m^2)
I_{hdiff}	Diffuse sky solar flux on the horizontal plane (W/m^2)
β	Inclination of the surface
I_{gdiff}	Diffuse ground solar flux incident on the surface (W/m^2)
α	Solar altitude
F	Fourier Number
dW	Radiation flux (W/m^2)
dA	Element of surface area (m^2)
T_e	External air temperature (°C)
Φ_m	Metabolic rate(W)
Φ_w	Rate of performance of external work (W)
Φ_{rc}	Convection in respiratory tract (W)
Φ_{re}	Evaporation in respiratory tract (W)
Φ_k	Conduction from surface of a clothed body (W)
Φ_r	Radiation from surface of a clothed body (W)
Φ_c	Convection from surface of a clothed body (W)
Φ_e	Evaporation from the skin (W)
Φ_s	Body heat storage (W)
M	Metabolic rate of body surface (Wm^{-2})
W	External work of body surface (Wm^{-2})
f_{cl}	Ratio of clothed to unclothed area of human body
θ_{ai}	Average air temperature surrounding the body (°C)
θ_c	Operative temperature (°C)
p_s	Partial water vapour pressure in the air surrounding the body (Pa)
h_c	Convective heat transfer coefficient at the body surface (Wm^{-2}K^{-1})
θ_{cl}	Surface temperature of clothing (°C)

Chapter 1 Introduction

UK government policy statement, *Building a Greener Future* in 2007 (UKGov, 2007), sets out the ambitious target of all new domestic properties to be zero carbon by 2016. However this does not set any targets for homes already built and as such the requirement to retrofit technology to reduce carbon and consequently, energy consumption.

Statistics compiled by Palmer and Cooper (2011) indicate domestic housing is the single largest consumer of fuel in the UK and so a prime area to target in the field of energy reduction. Energy used in UK homes accounts for more than a quarter of the total energy use and carbon dioxide emissions in the UK, see Figure 1.1.

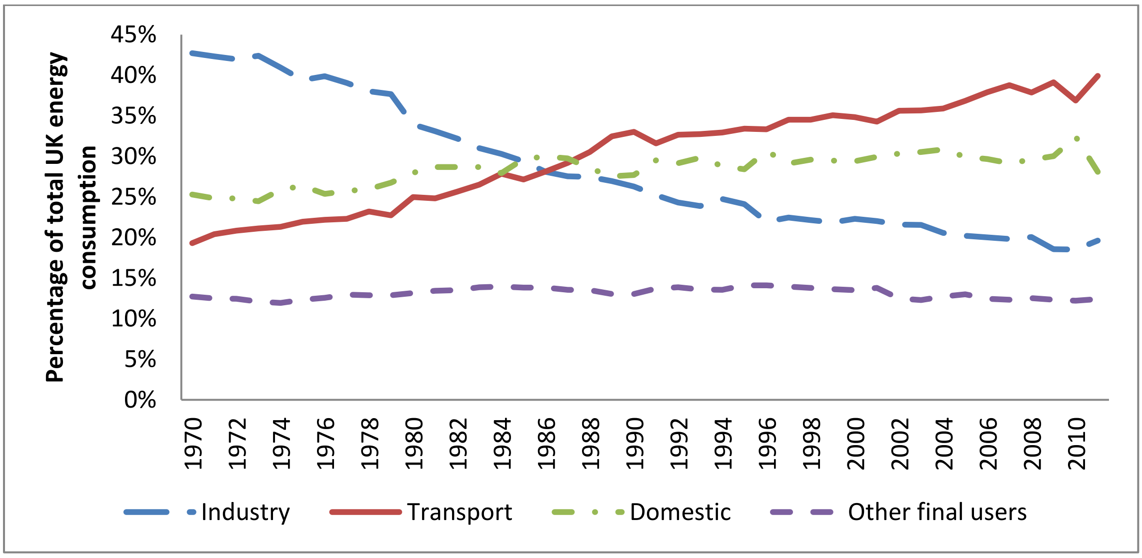

Figure 1.1 UK Energy consumption 1970 – 2010 (Figure adapted from DECC, 2012).

Figure 1.1 indicates that since 1970, the proportion of total UK energy consumption related to transport has increased significantly with a smaller increase in domestic energy consumption. However, more energy is used in housing (28% of final energy consumption) than either road transport (27%) or industry (17%), and therefore housing represents a major opportunity to reduce energy use and CO_2 emissions as well as alleviating the effects of fuel poverty (which is discussed later in this section), which was estimated at 18.4% in the UK in 2010 (DECC, 2012b), by reducing the amount of energy households use and thus lowering the cost to the consumer.

The way energy is used in homes today is very different to the beginning of the recording of the statistics in 1970 where housing made up 25% of the final energy consumption with industry contributing 43% and transport (total) 19% (DECC, 2012). With the UK importing many manufactured goods such as textiles, cars and electronics, this is a major reason for the reduction in the industrial energy consumption and thus a proportional increase in domestic and transport fuel consumption. The transport sector energy consumption has increased more rapidly than domestic due to the proliferation of air travel and consumers owning personal motor vehicles.

As previously mentioned, in 2010 18.4% of the UK were in fuel poverty with a further 15.6% being vulnerable to fuel poverty, which, when combined make up over one third of UK households. A household is defined as in fuel poverty when they spend over 10% of their annual income on maintaining an adequate level of warmth in their home (21°C in main living area, 18°C in all other occupied rooms). These statistics are quite significant when one takes into account the single largest energy use within any home is space heating. A full breakdown of domestic energy end use can be seen in Figure 1.2.

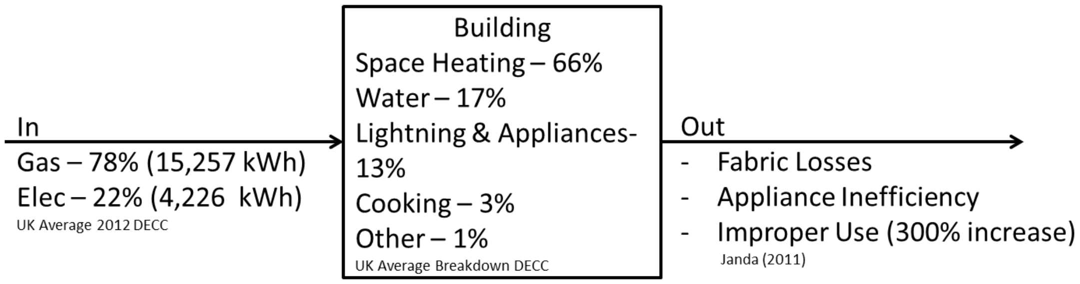

Figure 1.2 Domestic energy use.

Figure 1.2 provides the current breakdown of energy use in a domestic house provided by the Department of Energy and Climate Change. Gas is the predominant energy use making up on average 78% of fuel used in a typical domestic setting with the majority of this gas being used in space heating and water applications (83% of total energy consumption).

The occupants behaviour has been identified as a major factor in the energy performance of domestic dwellings and it has detrimentally affected the consumption by up to 2 or 3 times as discussed by Zhang *et al*. (2011). These findings indicate that addressing user behaviour provides the potential to address the government target of carbon neutrality by 2016 (UKGov, 2007).

As identified previously, the new targets to ensure all new buildings by 2016 are zero carbon does not address the current UK building stock which provides an opportunity for large energy savings to be made.

1.1 Smart heating control systems

Smart homes are identified one way to achieve an energy reduction in UK housing stock. A smart home is described by De Silva *et al.* (2013) as an approach to computerise them by using sensors to gather data regarding the residents and utility consumption and the use and analyse this data to identify required reactions from the building by controlling mechanisms within it. Within this larger smart home concept is the sub-category of smart heating control systems.

Smart control systems for domestic heating control exist on a sliding scale from simple concepts such as the Evohome smart multizone control systems using centralised wireless radiator control to remotely control the heating in each zone in a domestic home (Honeywell 2014). The PreHeat investigated by Scott *et al*. (2011) uses occupancy prediction to control the space heating and an automatic system proposed by Boait and Rylatt (2010) derives the heating time setting from measured electricity and water consumption.

There is one feature which connects all the concepts above which is that of feedback and actuation. A non-smart heating controller will only react to human input or non intelligent actions such as a switch to turn the heating on and off or a timeclock which is set to one specific time. A smart controller will react to a monitorable input such as occupancy, electricity consumption or room temperature and control the heating without the need to human intervention.

1.2 Problem Definition and Methodology

This thesis investigates the implementation of a smart home as a method to reduce energy, where a smart home is a home which maintains comfort levels with minimum energy consumption.. In turn, these reductions in energy consumption will result in a cost reduction for homeowners paying energy bills acting as a potential means of alleviating fuel poverty.

A general overarching control methodology can be described pictorially as shown in Figure 1.3. A building has both an energy input and an energy output (energy use). Both aspects of energy within the building are governed by control systems. As previously mentioned, current control systems present a large area for investigation due to their current misuse by home owners and the basic nature with which they provide control.

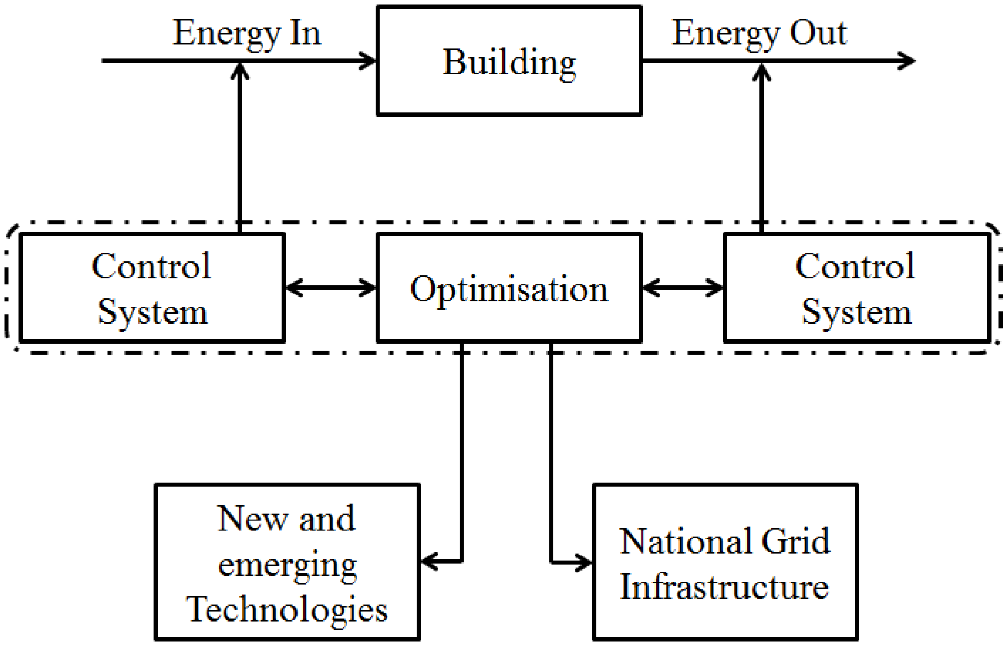

Figure 1.3 A typical domestic heating control system overview.

Figure 1.3 illustrates that optimisation occurs between both sides of the control system for the home, both the regulation of the energy that the home consumes (energy in) and the way the energy is used (energy out). The optimisation which occurs between these control systems can be seen as one control system as indicated by the dashed box. This interconnection is key to the holistic building control as a modification in the Energy Out can result in a change to the Energy In.

Of particular interest in this thesis is the performance of older domestic properties as these tend to have the most basic and outdated control systems, along with poor building envelopes as opposed to modern buildings which are built to higher building regulations and have more advanced control systems installed.

The methodology, described in Figure 1.4, will be used to form the basis for experimental investigation. Figure 1.4 highlights the main elements for investigation within this thesis as the effect on building temperature and energy performance with the implementation of zone based heating control

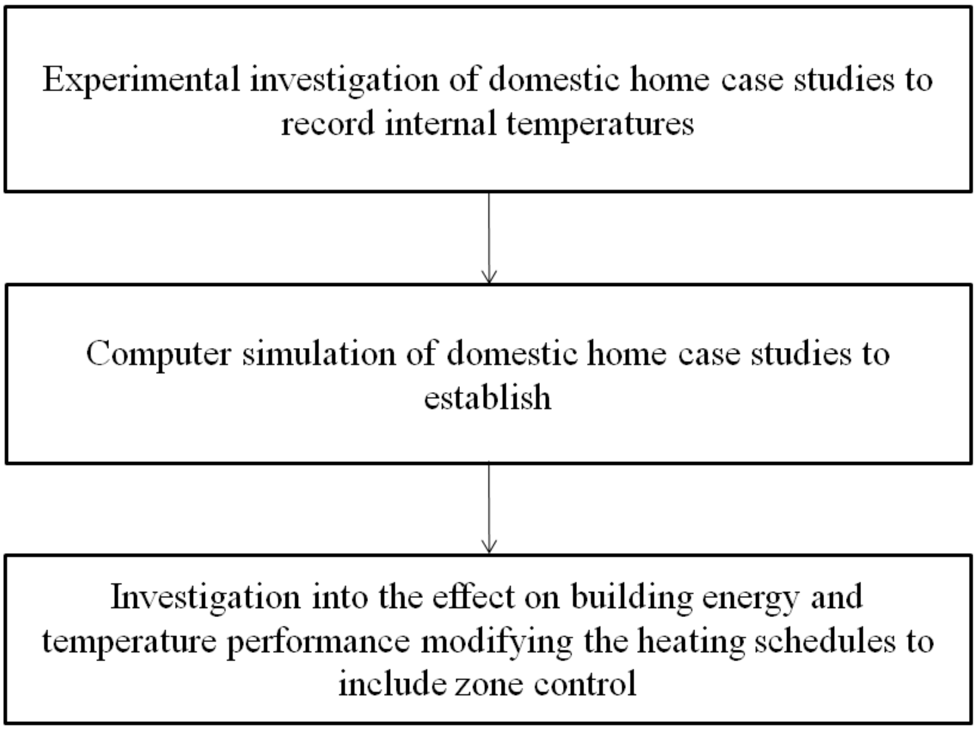

Figure 1.4 The investigation methodology.

1.3 Aims and objectives

The research has the following main aim.

Investigate the effect on domestic heating energy consumption resulting from the installation of a smart home heating control system.

Within this aim there are a number of objectives which will be addressed in turn:

1. Establish current heating benchmarks for domestic homes using experimental observation and three case study homes.
2. Compare experimental results from case study homes to numerical results from dynamic thermal modelling to establish validity of the numerical models.
3. Compare experimental performance to recommended CIBSE guidelines for thermal comfort in UK domestic homes.
4. Implement a two zone control system in the dynamic thermal model to establish the energy implications this has on the case studies
5. Implement a multi zone control system in the dynamic thermal model to establish the energy implications this has on the case studies

1.4 Structure

The thesis is divided into 7 chapters which will guide the reader through the thesis to the conclusions detailed in chapter 7.

Chapter 1 is the introduction which outlines the background to the study and details the methodology and aims for the study.

Chapter 2 contains the literature review which is a critical review of past research in this area to establish the research gap and suitable methodologies to use in this study.

Chapter 3 Establishes the three case study buildings including their geometry, construction, internal schedules and location. This is used to build the dynamic thermal models used in the results section.

Chapter 4 contains the computational research methodology which details the construction of the dynamic thermal models including the parameters used for the simulations and the geometry of the dynamic thermal models.

Chapter 5 is the experimental research methodology which details the experimental observation which was undertaken in the case study buildings including the equipment, methodology and sensor deployment.

Chapter 6 contains the results and discussion of the study including the validation of the experimental observation and subsequent modification of the heating system to draw conclusions on the implementation of multi zone heating systems.

Chapter 7 outlines conclusions drawn from the study and recommendations for future work which has resulted from this investigation.

Chapter 2 Literature Review

2.1 Introduction

Domestic space heating control provides a large potential for energy savings in the domestic market to address the fuel poverty and rising CO_2 emissions identified in the government building a greener future policy statement.

The purpose of this chapter is to provide a comprehensive review of recent research into smart and energy efficient buildings. From this comprehensive study, conclusions are drawn identifying a lack of investigations into retrofitting control systems onto existing domestic building stock, lack of focus on holistic control of a domestic home and a lack of investigation into a smart control system specifically tailored for retrofit. These inform the research methods and gaps to be investigated in this study, furthermore the gaps identified are used to define the aims and objectives of the thesis.

Chapter 2 consists of the following sections. Section 2.2 defines the different factors which drive domestic energy consumption including thermal comfort, legislation and market forces. Section 2.3 establishes the demand side management as a method of controlling domestic energy consumption, Section 2.4 reviews innovative technologies and control theories which could be put into practice in the domestic environment. Section 2.5 details operational techniques from single zone to multi zone domestic heating and how these different systems affect the overall energy consumption. The chapter concludes with Section 2.8 identifying gaps in current research for energy reduction in domestic home heating systems through smart control systems and Section 2.9 provides a summary of the chapter.

2.2 Domestic Energy Consumption for space heating

Domestic energy consumption in the UK is reported annually in the UK housing energy factfile (Palmer and Cooper, 2014). The historical trend for domestic energy consumption is shown in Figure 2.1.

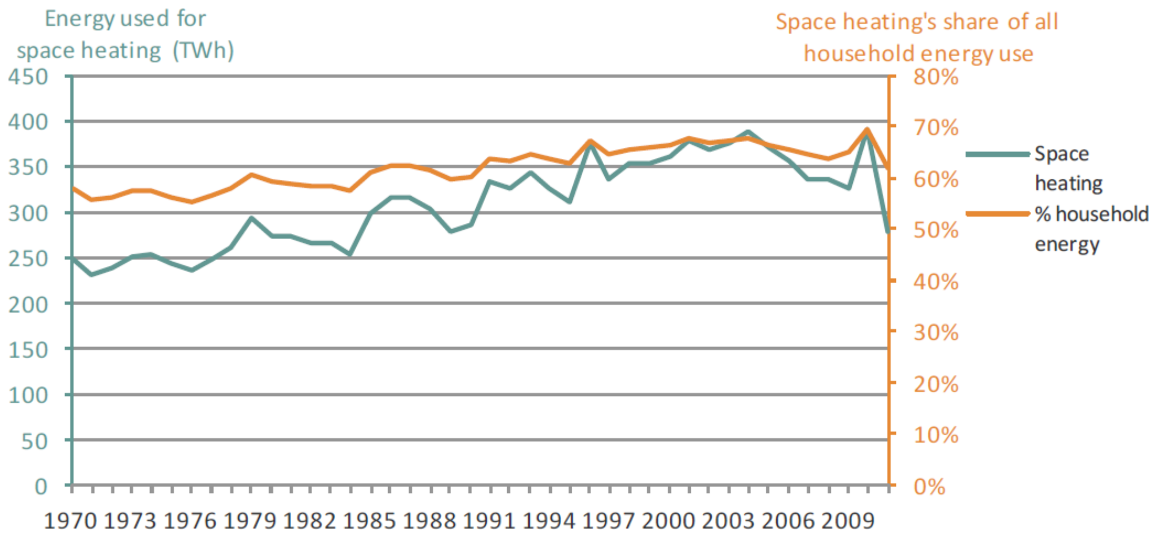

Figure 2.1 Final energy use for housing and all sectors in the UK (Palmer and Cooper, 2014)

The energy consumption used for heating in domestic homes has risen from the beginning of the recording period in 1970 until 2004 where it peaks with an annual consumption of 387.9 TWh per year, an increase of 140.2 kWh since 1970. This then fell from 2004 until 2009 with energy saving measures beginning to be put into place in homes. After 2009 there are erratic and steep increases and decreases in domestic energy used which is attributed to alternating cold and mild winters where vastly differing degrees of heating are required. The erratic nature of this period shows clearly what a dramatic effect the external climate can have on the energy consumption of a home.

The driving forces behind current savings already realised are primarily through improving building heating systems and the building fabric (insulation). These savings are illustrated in Figure 2.2.

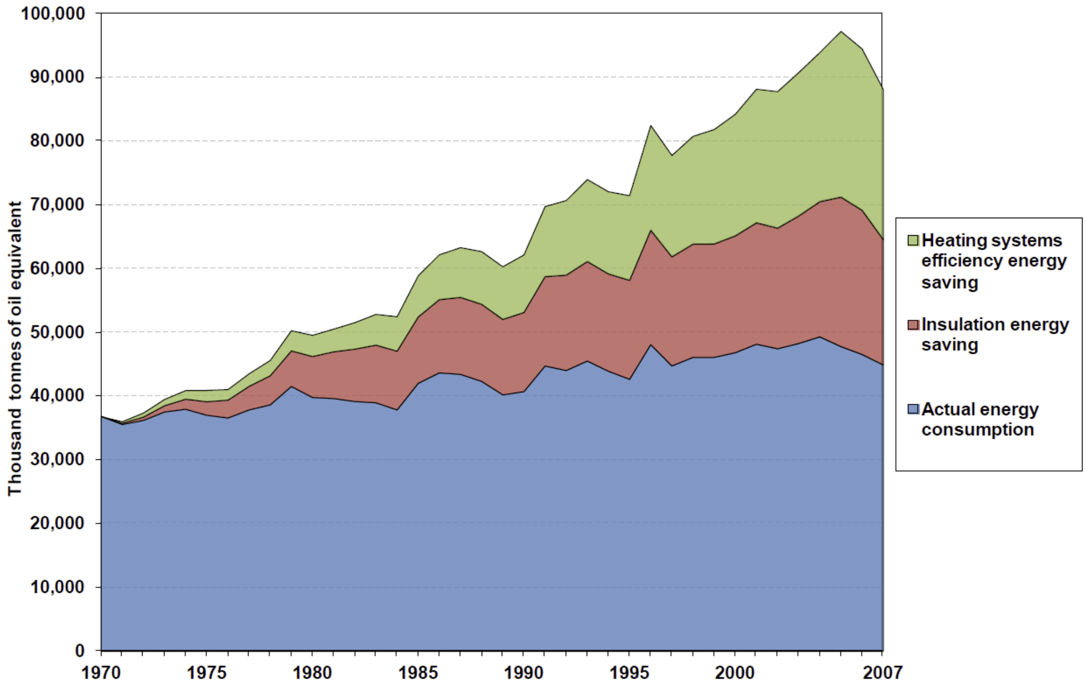

Figure 2.2 Heating energy savings from 1970 - 2007 in UK domestic homes (DECC 2012)

Between 1970 and 2000 improving the building fabric of domestic homes has been the driver behind reducing domestic energy consumption for space heating, however after 2000 the heating systems themselves became a larger driving force in lowering domestic heating energy consumption.

The reports highlighted clearly show a suitable area for study with building heating controls playing the largest part in reducing domestic heating demand in the UK.

2.2.1 Domestic heating control systems

There are multiple drivers behind domestic energy consumption which include the installed control systems, thermal comfort, legislation and market forces. Each will be discussed in turn starting with a study into current practices in heating system control.

Peeters *et al.* (2008) conducted a two part study into the current practice in control of heating systems in Belgium. The initial survey consisted of 10 installers of heating systems and 56 households to establish what the current central heating systems consist of. The current systems were then modelled in dynamic thermal simulation software to establish system shortfalls and potential for improvements. The study concluded that when current best practice control systems are used with gas boilers and radiators to provide space heating, they have been shown in Europe to have overall efficiencies as low as 30%.

Boait and Rylatt (2010) conducted a study into the human interface of home heating systems as poor thermostat design was attributed to impaired comfort and poor heating system efficiency.

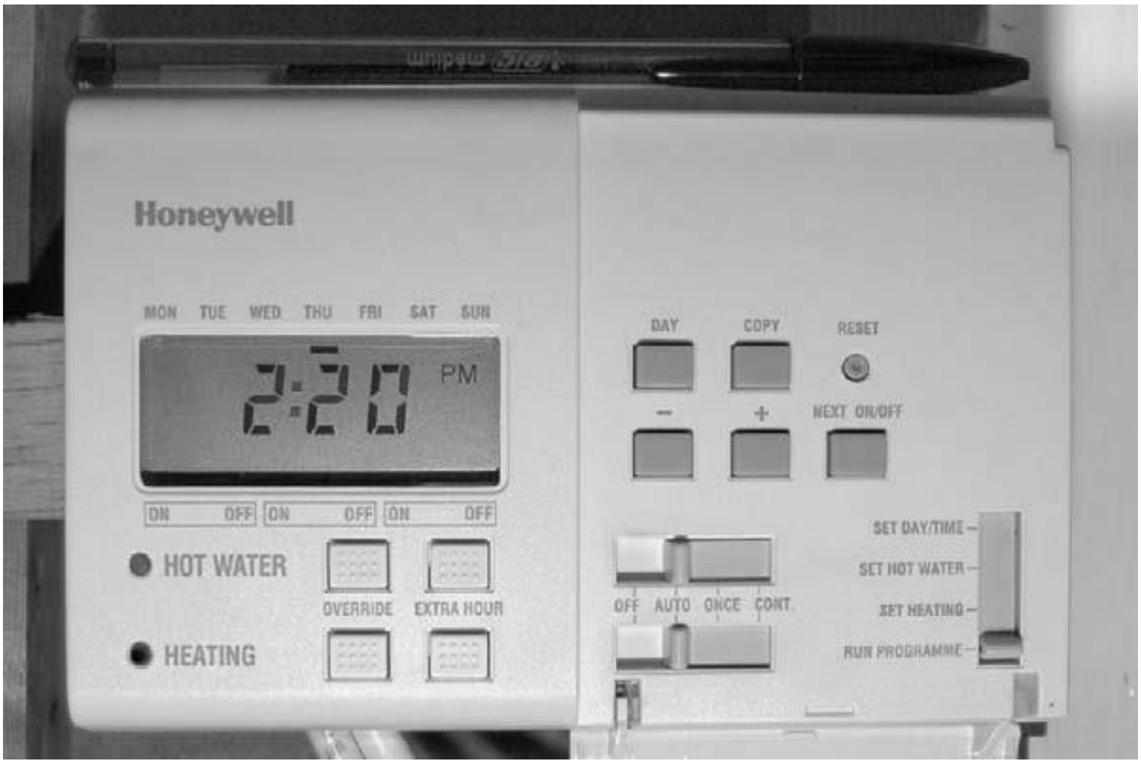

Figure 2.3 A typical programmable thermostat often misused by occupants resulting in poor heating system efficiency (Boait and Rylatt, 2010).

Figure 2.3 depicts a typical programmable thermostat which, when misused, results in poor heating system performance. The study by Boait and Rylatt (2010) consisted of prototyping a new heating control device where thermostat timing is derived from electricity and hot water use. The study found that the new system produced useful energy savings of approximately 14.1% over a traditional system. The study identified that usually boilers are controlled by a programmer which can be set to determine the periods during which there is a requirement for space heating, and separately where there is a storage cylinder present for hot water. The operating temperature of the space heating is usually controlled by a single thermostat, ideally in a central location, but the temperature may be regulated in individual rooms if thermostatic radiator valves are fitted. A typical programmer requires 28 steps to enter all the heating times which are often identical for each day of the week and this can be quite complex for the average person and this may lead to the manual switching on/off of the heating system which will result in energy wastage when heating is inadvertently left on.

Peffer *et al.* (2011) undertook a comprehensive review on the current state of thermostats, evaluating their effectiveness in providing sufficient occupant thermal comfort and optimal control of heating systems. The study investigated user perceptions relating to thermostats, concluding that over almost half of the users studied do not use any programming features, with them being hesitant to alter any setting for fear of using more energy. The users also found the operational literature very cumbersome and difficult to understand which further led to incorrect use as user manuals were not understood correctly.

Zhang *et al.* (2011) investigated occupant behaviour and concludes that this plays a pivotal role in the energy performance of a building, including electrical consumption due to leaving appliances switched on. A review of previous behavioural research studies was undertaken and concluded that the occupants energy use behaviour can significantly influence the household energy consumption with the energy consumption of houses of similar construction varying by a factor of up to 3.

Janda (2011) conducted a review of current work into building users and how they play a critical role in the built environment relating to the thermal and energy performance of the buildings which they inhabit. Four factors were identified which influence a building energy use of which occupants are one.

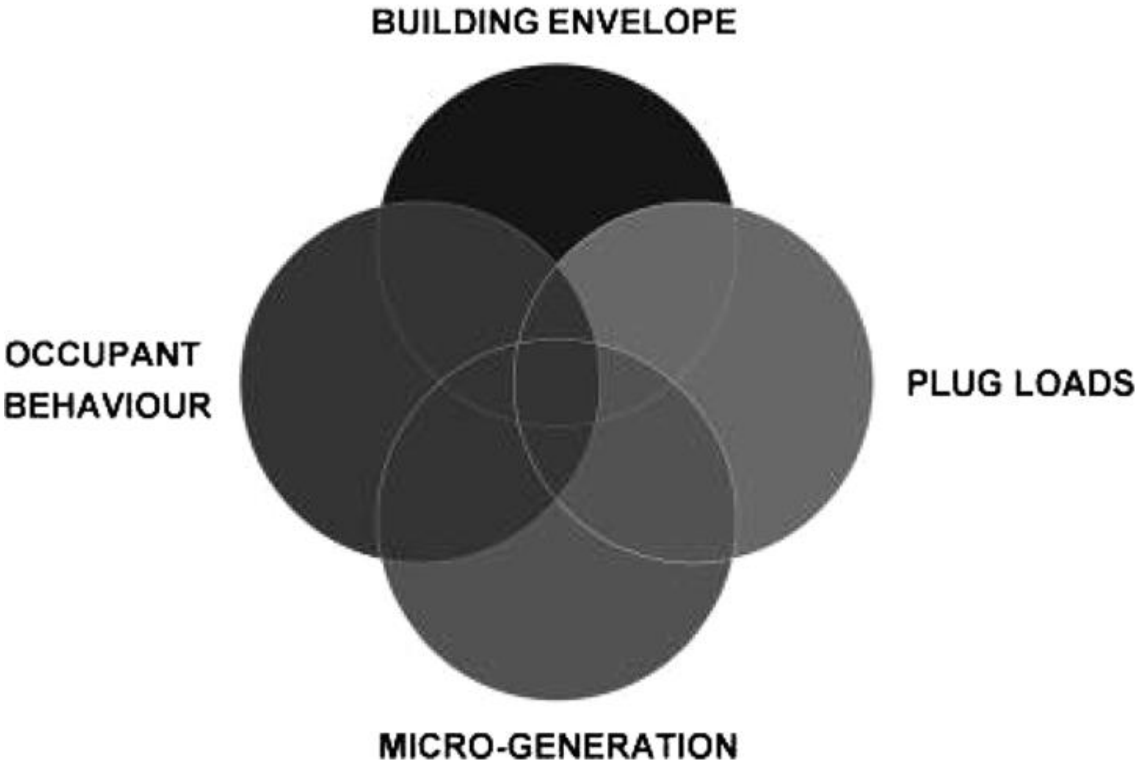

Figure 2.4 Influence map of interconnected domestic energy use drivers (Killip, 2009).

The overlapping areas of the influences shown in Figure 2.4 indicate that none of these operate exclusively, but they all affect one another to drive the building energy usage. The study concludes that during building design, user involvement in building performance needs to be more heavily recognised and taken into consideration, concluding that architects are in the best position to drive this user driven area of building design. Also the study highlights that occupants behave in more complex ways than designers take into account and this can produce large variations (up to 300%) in the energy consumption.

2.2.2 Thermal Comfort

Thermal comfort of the building occupants has a large impact on domestic energy consumption. This section defines the comfort conditions people require with the associated thermostat settings and how these drive domestic energy consumption.

Vine (1986) conducted a survey of self reported winter and summer thermostat settings of over 250 homes in the US. A wide range of hypothesis on factors which effect thermostat settings were tested which included age, education, income, race, home ownership, dwelling type, dwelling size, dwelling age, heating fuel, air conditioner type, energy audit, climate, year and time of day. The study reported higher thermostat settings for younger people, and lower thermostat settings within large multi family homes over single family homes.

Andersen *et al.* (2009) conducted surveys (933 in summer and 636 in winter) on occupant control of indoor environments in Danish homes. The study sample was representative of a wide range of dwelling sizes, ages, ownership, location and heating systems. The study found that the proportion of dwellings with the heating turned on was strongly related to the outdoor temperature. Solar radiation, dwelling ownership and perception of the indoor environment were also strong factors.

Huebner *et al.* (2013) conducted a 6 month study of 55 social housing households and surveyed 220 university staff participants. The social housing data was gathered using interviews, surveys and monthly energy meter readings whilst the data for the university staff was gathered using an online survey. A breakdown in the findings can be seen in Figure 2.5.

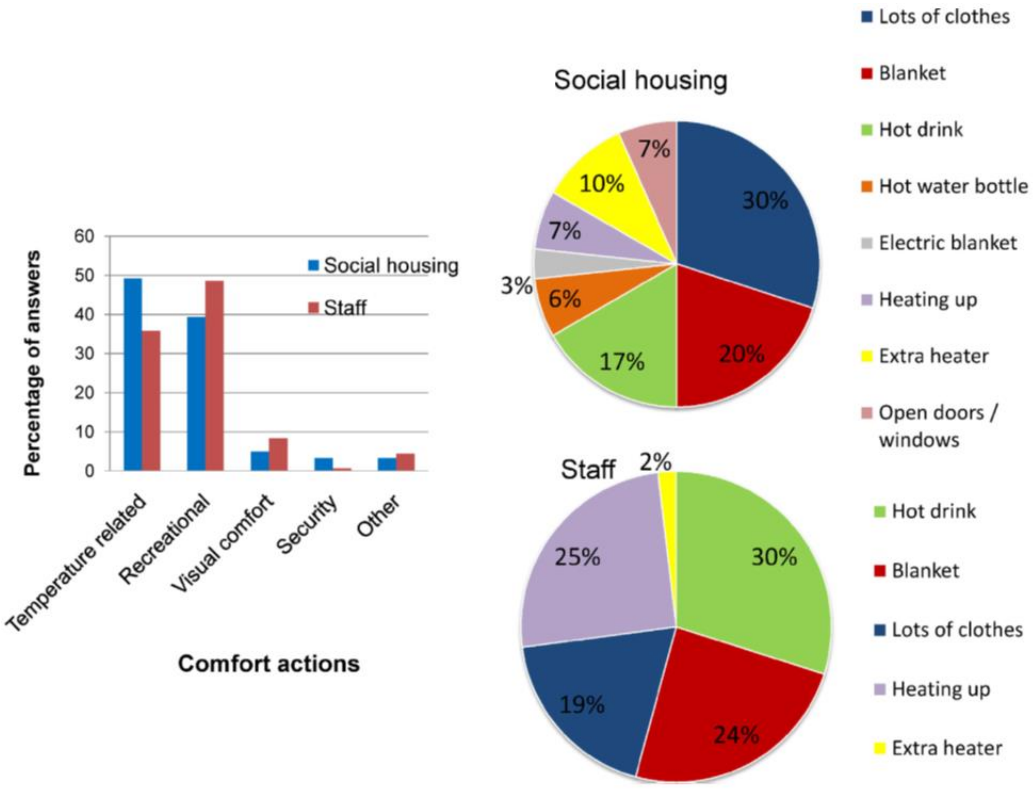

Figure 2.5 Illustrative charts of comfort actions by occupants in a residential setting used to maintain thermal comfort and drivers for modification of the heating schedule (Huebner *et al.*, 2013).

Figure 2.5 shows that the largest driver for comfort actions in social housing are temperature related whilst in staff housing recreational is the largest driver. Social housing tenants are also more likely to take non energy related actions when feeling thermal discomfort compared with staff who are more likely to take energy related actions. The study identified that comfort is commonly defined by people as the warmth they experience in their home, however the temperatures are gradually increasing which is resulting in an increase of energy usage.

Palmer and Cooper (2014) report that since 1970 the average internal winter time temperature has risen by approximately 4 °C and this is the same trend for both centrally heated and non-centrally heated homes. The study used data from Digest of UK Energy Statistics from the Department of Energy and Climate Change This shows that the temperature increase is not a direct consequence of improvements in heating systems, but trends in occupant comfort.

Kane *et al.* (2015) investigated heating patterns in UK homes as part of the 4M longitudinal study of 249 homes in Leicester, UK. The study used occupant surveys along with on-site temperature monitoring over a two month period to establish heating patterns covering a wide range of occupant age, occupation, building type and heating system. The study found that although internal temperatures are important, other factors, such as homeowner age and employment, are deciding factors in home energy usage, with the unemployed and elderly typically running their heating systems for longer periods and at higher settings.

2.2.3 Legislation

The UK government has set and agreed to multiple climate change targets. The climate change act of 2008 (UKGov, 2008) sets out the UK Governments targets to reduce carbon emissions by 80% of 1990 baseline levels before 2050. This section will discuss the legislative policies which are being enacted to reach this target starting with the use of Renewable Energy Sources.

Klessmann *et al.* (2011) use high quality data from Eurostat (statistical office of the European Union), Observ'ER and Green-X (European renewable energy council). The study investigates the use of Renewable Energy Sources (RES) to help achieve the 2020 renewable energy consumption targets. The study concludes that most member states that agreed to the target put less effort into renewable heating and cooling than into renewable electricity. Energy efficiency was identified, especially in the heating sector, to be of much importance to reduce the requirement for renewable energy and help hit the 2020 target.

Ekins *et al.* (2013) outlines the government plan for domestic heating provision to meet targets by 2050. This provision breakdown is highlighted in Figure 2.6.

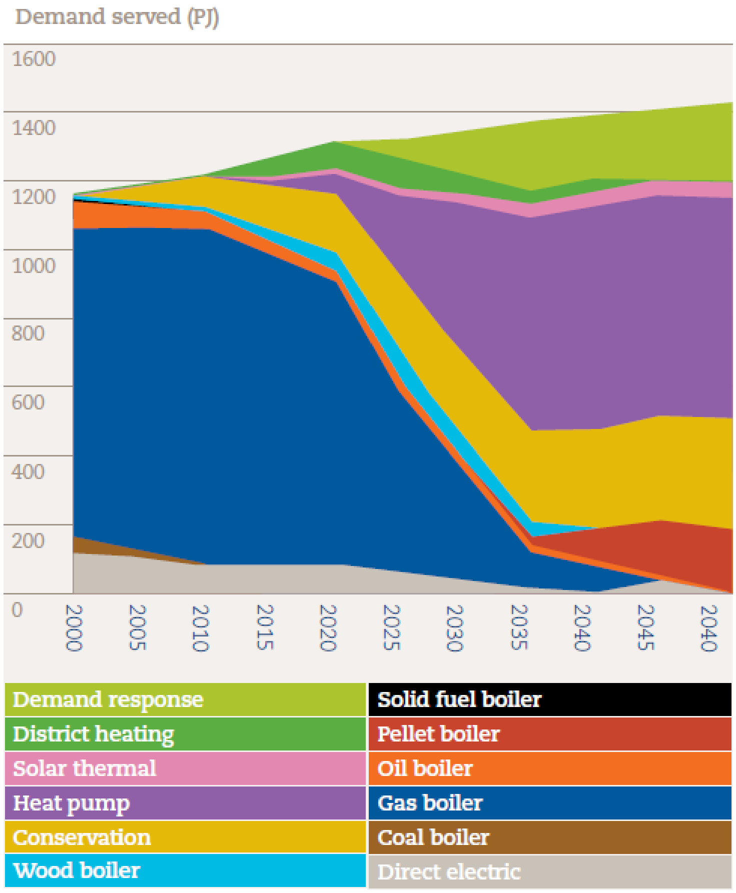

Figure 2.6 Chart and table detailing the provision of domestic heating by end use technology by 2050 (Hawkes, 2011).

Figure 2.6 highlights the current reliance on gas boilers. However, this is projected to fall significantly in 2020 onwards with the main heating provision being taken up by heat pumps. Two significant sources of reduction in carbon emissions that should be noted are demand response (reducing demand through proper use of heating controls) along with conservation (energy reduction through insulation, etc). It should be noted that by 2050 electricity production is projected to be largely carbon free and so the heat pumps driven by electricity will inherit this carbon reduction.

Roelfsema *et al.* (2014) performed a study based on quantification of government climate change policies by den Elzen *et al.* (2013) and Hof *et al.* (2013) with further bottom-up calculations and literature reviews to establish if countries were going to achieve their targets. The study notes that for the EU, the pledge to reduce GHG emissions by 20% by 2020 is on track with a current value of 19%. However it is not on track to meet the unconditional pledge of 30% without additional policies or actions.

2.2.4 Market Forces

Along with the thermal comfort and legislative actions, market forces also drive domestic energy consumption. In this context, the main market force is the cost of fuel which has been continually rising. The section begins with a study on the price elasticity of domestic fuel to establish how fuel cost affects our fuel usage.

Klein (1987) used data from country wide energy surveys administered by the US Department of Energy using samples of between 1000 and 6000 multistage stratified samples of all homes in the US. The study investigated the price elasticity of domestic fuel by running economic simulations on this primary data. The study observed that energy cost does indeed affect the use of domestic energy, with increasing costs causing a subsequent reduction in use, particularly in poorer households.

Henretty (2013) uses primary energy meter data from the office of national statistics to report on energy consumption between 2005 and 2011 using the total number of electricity meters to be the total consumers of energy in England and Wales. The study demonstrates that in England and Wales, during the period 2005-2011, average household energy consumption actually fell from 20.7 MWh in 2005 down to 16.1 MWh in 2011, a total reduction of 22.2%.

DECC (2013) used primary data from the English Housing Survey (EHS) which included 14,400 in the 2011 data set which comprises of an occupant interview and inspection of subsets of properties. The study provides evidence that a major cause of the income gap in fuel poor households is the high rise in fuel costs compared to the retail price index (RPI).

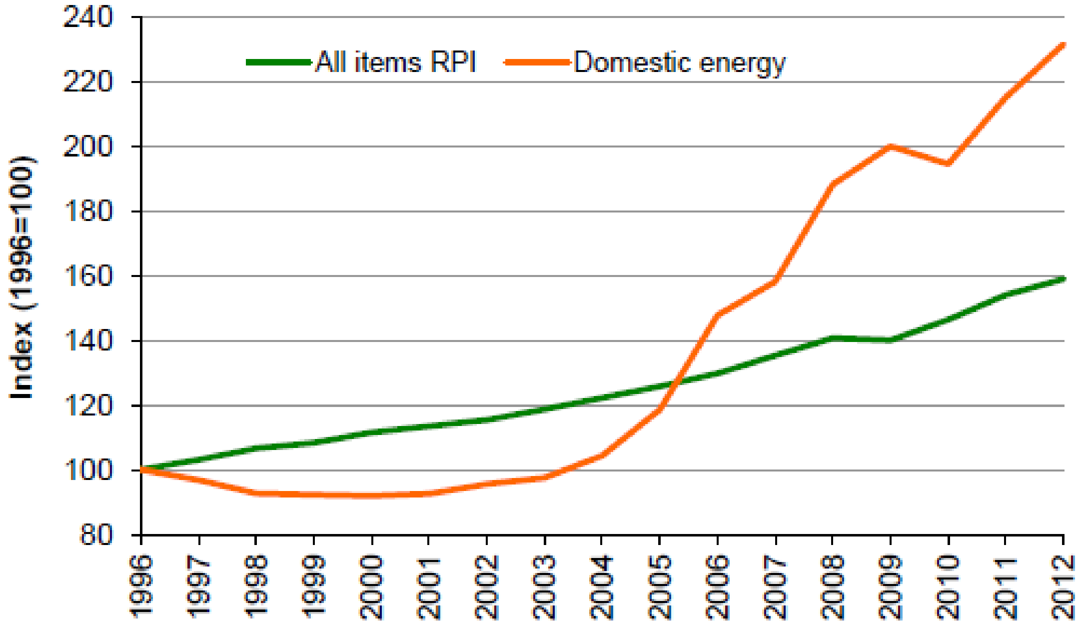

Figure 2.7 The rate of domestic energy price increase compared to inflation from 1996 until 2012. (DECC, 2013).

Figure 2.7 illustrates that in 2012 the retail price of energy has risen to over double the retail price of other typical goods which contributes to the average income gap in fuel poor households. This has risen in the period 2005 – 2011 from £319 - £448 (40% increase) with 15% of England being fuel poor in 2011.

Andreadis *et al.* (2013) used RoofRay software to identify the extent of domestic roof area in Dundee suitable for solar PV and Trnsys simulation software to perform an energy and cost simulation on the installation of solar panels in Dundee. The study investigates addressing fuel poverty through the provision of building integrated solar panels to reduce the dependency on grid supply which Middlemiss and Gillard (2015) identify as one factor which contributes to fuel poverty. It was reported that with government grants for purchase and installation, fuel poverty in Dundee could be significantly reduced along with providing a reduction in CO_2 emissions at an acceptable cost.

ONS (2014) uses the Living Costs and Food Survey (LCF) to report on the expenditure of households during 2005 – 2011. The LCF survey consists of face to face interviews with 5500 households, along with each participating household keeping a two week expenditure diary. The study finds that during the same period, an increase in average monthly electricity expenditure of 30%, an average monthly gas expenditure of 34% and an average monthly expenditure on other fuels by 53%.

Middlemiss and Gillard (2015) conducted 17 in-depth interviews of 15 households covering the participants use of energy over time, experience of fuel poverty and their experience with new government energy policies. Participants were selected by recommendation from the housing association and health workers who identified tenants who were currently living in fuel poverty. The study finds six key challenges which contribute to fuel poverty which are quality of dwelling fabric, tenancy relations, energy costs and supply, stability of household income, social relations in and out of the household and ill health.

Section 2.2 discussed the main elements which drive domestic energy consumption both externally and internally. In order to reduce energy consumption and consumer cost, modifications to current control practices should be implemented.

2.3 Demand Side Management

Demand Side Management aims to control the scheduling of domestic loads in order to reduce peak demand and also shift non time critical loads to offpeak hours resulting in a cost saving to the user. The section will then continue to discuss user behaviour and user awareness.

Infield *et al.* (2007) investigated the potential of using demand side management as a method for integration of renewable and micro generation for domestic electrical loads as this is becoming more popular in the UK. The study consisted of a review into current practice outside of the UK, along with computer simulations to find its potential impact on the UK energy grid. The study concluded that if domestic loads can be controlled in near real time, then this will contribute to making the energy supply grid a dynamically controlled system which then regulates the frequency of supply and maintains the supply reserve.

Hamidi *et al.* (2009) investigated the different tariffs available to domestic customers by identifying the ‘economy 7’ and ‘economy 10’ tariffs which encourage users to shift electricity usage to off peak times. Two different methods of demand response control were identified which, namely price–based demand such as the economy tariffs and incentive based demand where users are paid to alter their usage by the provider at certain times, such as times of grid instability. The study identifies only passive loads, such as domestic hot water generation, and 'cold appliances' which are more elastic and easy to control than loads such as lighting which has a direct effect on the users quality of life, which allows the passive loads to become more elastic and responsive. This indicates that the demand response control is heavily dependent on the appliances installed but potentially yields a controllable consumption profile.

Hamidi *et al.* (2009) studied responsive loads affected by the economy 7 electricity tariff. This was achieved by observing a residential region in the city of Bath, UK and analysing data obtained from the monitoring of these dwellings which mostly consisted of residential housing. With the non-restricted tariff there is a constant demand between approximately 55% and 28% of maximum demand all day, reaching up to 50% during peak expensive hours. This is in contrast to the economy 7 tariff which peaks up to 85% of maximum demand, but this is during off-peak cheaper hours and during peak expensive hours, the demand never rises above approximately 30%, thus saving money which demonstrates a demand side management system working.

Di Giorgio and Pimpinella (2012) expanded on this concept and used a smart home controller as a means to schedule domestic appliances taking into account energy tariffs and peak energy load times with an architecture, as indicated in Figure 2.8.

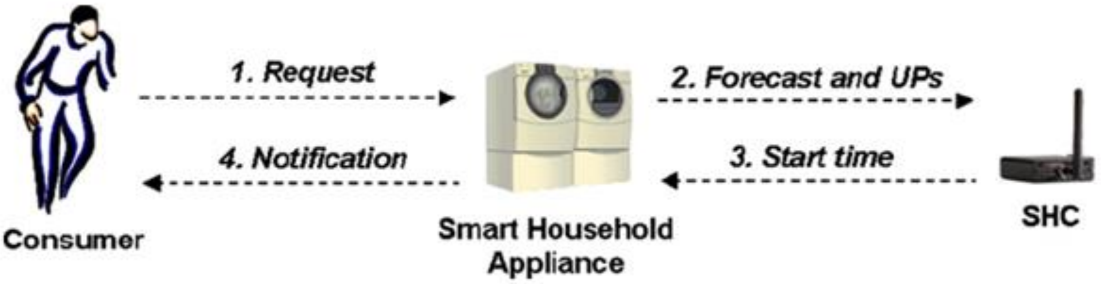

Figure 2.8. Schematic representation of information flow in a demand side management system (Di Giorgio and Pimpinella, 2012).

In the demand side management scenario described in Figure 2.8, the user indicates the user preferences (UPs) of when the appliances should run and then goes to the smart home controller (SHC). Using data from the smart meter, the SHC choses a start time that is most appropriate within the UPs to minimise the energy cost and notify the consumer.

The logic that the controller follows is an over-time approach, which is shown in Figure 2.9, where the user continually inputs preferences into the SHC to control the appliances. Then the demand side management (DSM) and smart meter (W) also input into the smart home controller which plans and schedules the control of appliances depending on the inputs to maximise energy reduction whilst still completing all the required actions.

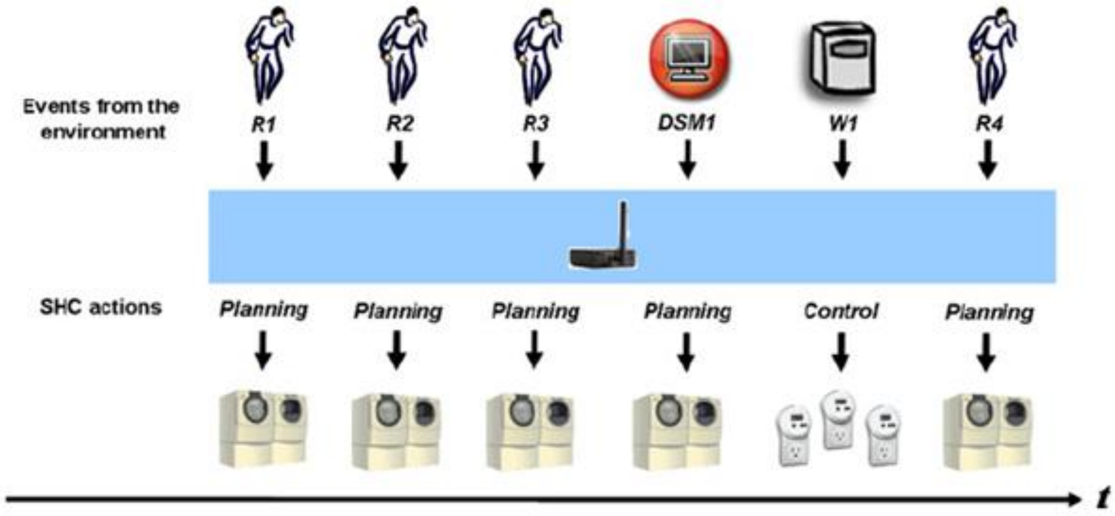

Figure 2.9. Schematic representation of work flow in a demand side management system (Di Giorgio and Pimpinella, 2012).

Di Giorgio and Pimpinella (2012) simulated, using primary data sources, a model of domestic energy usage and the savings made by controlling the domestic appliances and moving the energy consumption to offpeak energy times. The study demonstrates energy savings of up to 21% can be made using the demand side management of domestic appliance scheduling.

Rastegar *et al.* (2012) investigated demand side management, with the addition of a direct load control, where the utility controls aspects of the household devices in order to control the network burden, and in return the household receives a reduction in cost. This is modelled in numerical simulations to verify a reduction in cost. The investigation indicated that load commitment controlled by the user reduces the energy costs for the household. In order to maintain a peak load, the users should be subject to a maximum transfer limit of electricity, and therefore high usage appliances should be switched off during the day.

This section identified that user inputs and requirements are key within the demand side management control case, and indeed any control case. User behaviour and awareness of energy consumption will now be discussed with its impact on energy consumption established.

2.3.1 User Behaviour

User behaviour relating to the control of their heating system has been shown to be wasteful with programmable controls being underutilised. The section begins with a study into thermostat usage habits and to establish patterns in heating use.

Meier *et al.* (2011) conducted 87 occupant interviews and online surveys of thermostat usage habits and patterns. An additional 83 were then undertaken to include pictures of the thermostats which included 20 low income homes. This initial study was followed by laboratory tests to establish thermostat usability. Figure 2.10 illustrates the completion rate of setting a programmable thermostat in the laboratory tests.

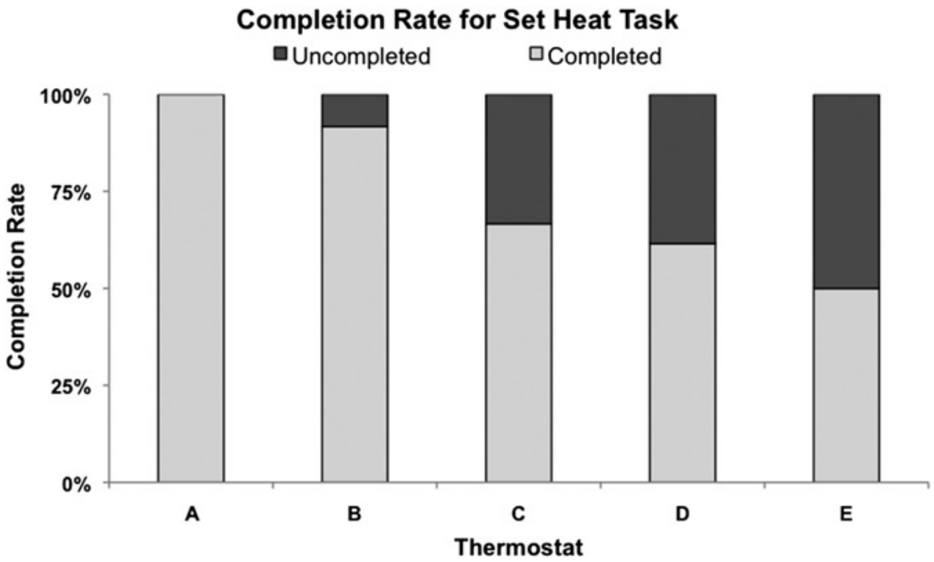

Figure 2.10 Completion rate for a range of different thermostats to correctly set a programmable thermostat (Meier *et al.*, 2011).

The success rate described in Figure 2.10 for the tests varied between thermostats, with thermostat E having a 50% success rate and the majority of thermostats being below a 75% success rate. The study highlighted that 90% of residents that were interviewed did not change their thermostat settings to set a weekend or weekday pattern. Further 50% of the occupants interviewed had the thermostats on long term hold, thus ignoring any automatic varying of the internal temperature.

Shipworth (2011) tested the hypothesis that thermostat settings have risen over time by undertaking a repeated cross-sectional social survey of home owners of centrally heated houses in the UK using data from 1987 (171 participants) and 2007 (427 participants). Findings from the survey comparisons indicate that no change in thermostat settings has occurred from 1984 until 2007. Instead the lack of reduction of home energy use is blamed upon energy reduction techniques not being as effective as originally thought. Dwelling area heated, duration of heating and window opening during the heating season may have increased over time, thus reducing the potential for any energy savings.

Huebner *et al.* (2013) conducted a 6 month study to gain a more in depth understanding of human behaviour relating to energy consumption in domestic housing. This was in the form of user surveys, interviews, monthly meter readings and finally that there is a deficit in instruction on how to use the home heating systems. Habit was seen as the largest barrier to behaviour change in relation to heating system operation and related to energy consumption activities, with cost being the largest motivator for behaviour change.

Wei *et al.* (2014) conducted a behavioural study to identify driving factors for space heating control in residential buildings. The study took the form of a comprehensive literature review the underlying drivers and building simulation. The study notes that although turning down or turning off heating in unoccupied room is a valuable way to save energy but the ability to do this is dependant on the occupancy of the dwelling. Many occupants opting to keep their heating on the highest setting when they are at home.

2.3.2 User preference on indoor thermal conditions

Coupled with user behaviour the perception of building occupants on their condition within the home is an important influence on the energy consumption of the home along with the operating temperatures

Hong *et al.* (2009) conducted a survey into thermal comfort in low-income dwelling before and after energy efficient refurbishments. The study surveyed 2500 homes with the thermal comfort and indoor temperature of the living room and master bedroom at 8am and 7pm every day for a period of 11 days over two winters in 2002/2003. An average temperature increase over this time from 17.1°C to 19°C saw the proportion of househoulds feel thermally comfortable rise from 36.4% to 78.7%. The temperature at which the residents felt thermally neutral was reported to be 18.9°C.

Oreszczyn *et al.* (2006) conducted a study in five urban areas in the UK consisting of half hourly living room and master bedroom temperature readings taken over a 2 to 4 week period. Each dwelling underwent a regression of indoor to outdoor temperature to obtain median standardised daytime living room temperatures and night time bedroom temperatures. The living room daytime temperature was reported to be 19.1°C with the bedroom night time temperature 17.1°C.

Huebner *et al.* (2013a) studied 248 dwellings with central heating over a period of 92 days from November 2007 to January 2008. The temperature measurements were translated into on/off heating profiles for each home. It was determined that contrary to common modelling assumptions, homes were heated outside normal periods with little difference between weekday and weekend heating patterns. The average temperature recorded during heating periods was 19.5°C. Variability between homes in demand temperature and hours of heating was seen as substantial and the study concludes the need to revisit some common assumptions on temperature made in building stock models.

Vadodaria *et al.* (2014) reviewed average winter and spring-time indoor temperatures in UK homes measured over the period 1969 – 2010. The current temperatures were based on hourly temperature measurements taken from February 2010 until April 2010 with the winter period 11 February 2010 until 24 February 2010 investigated in detail. The heating period for the living room showed underheating compared to World Health Organisation (WHO) recommendations of a minimum of 21°C as shown in Figure 2.11.

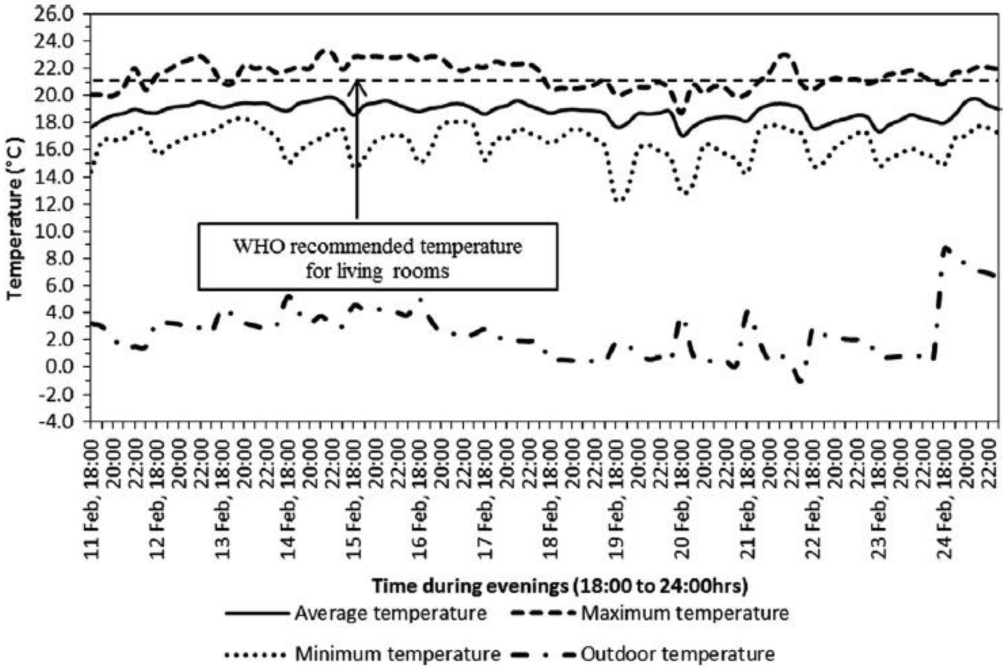

Figure 2.11 Living room temperature during heated periods from 11 February 2010 - 24 February 2010 (Vadodaria *et al*. 2014).

The WHO recommended temperature of 21ºC is shown with the average internal temperature falling below this line during the entire observation period. Figure 2.12 shows the proportion of time the rooms spend at the recommended temperature.

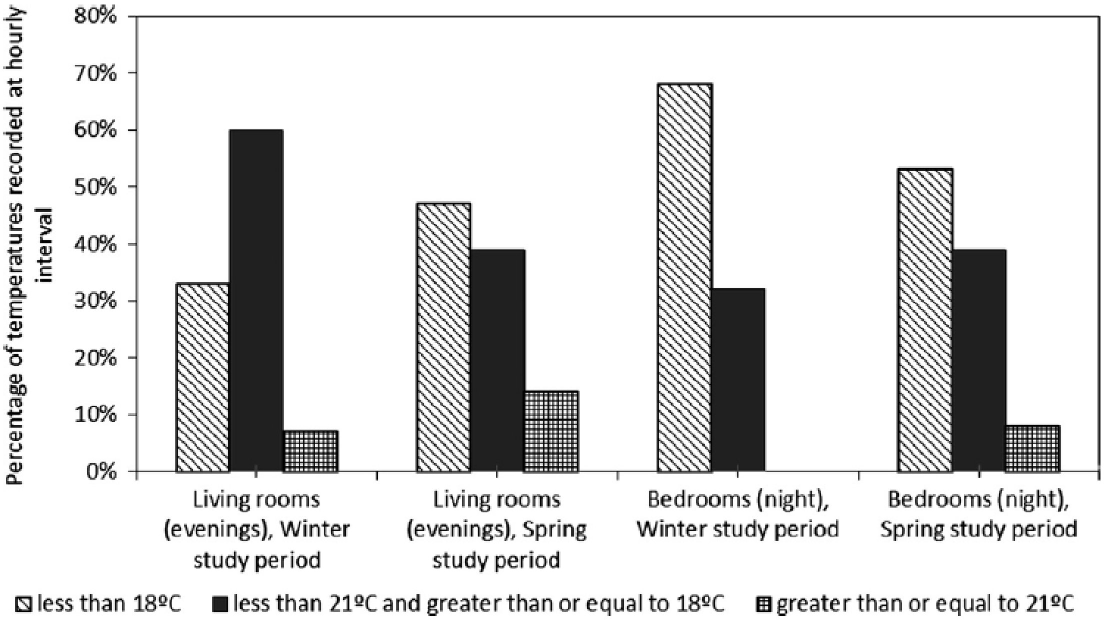

Figure 2.12 Percentage distribution of temperatures in living rooms and bedrooms (Vadodaria *et al*. 2014).

The rooms spend very little time at the recommended temperature with less than 10% in the living room during winter.

A qualitative survey was also undertaken to survey the occupants to establish their perceived thermal comfort. It concluded that a temperature of 20°C - 22°C may be required to achieve thermal comfort but stated more work would need to be carried out to verify this.

Shipworth (2011) investigated the change in thermostat settings in English houses between 1984 and 2007. The results of the CARB07 study show that depending on home age, the thermostat set points were between 18.7°C and 19.6°C.

2.3.3 User Awareness

In home displays and smart meters are becoming more common and provide the consumer with a higher degree of information on their energy consumption. This section begins with their effect on the energy consumption of the home by affecting the owners energy usage.

Olmos *et al.* (2011) investigated the potential change in consumption behaviour of energy in domestic homes with the use of a smart meter and demand response resulting from the implementation of actions designed to reduce the overall use of electricity, or to modify that pattern of electricity usage throughout the day. This was achieved by developing an analytical framework and methodology based on an extensive literature review, and applying this to data from Austria, using data from the German Power Exchange. The work highlights that engagement of the consumers is paramount in these schemes and for the success to be then realised, then information, along with economic incentives should be provided, such as energy saving tips and time varying tariffs. The time of use tariffs and critical peak pricing were found to produce a reduction in energy use in the short term.

Figure 2.13 shows a typical smart meter with an integrated information display showing real time energy usage to inform the user, the effectiveness of which is investigated by the authors below.

Figure 2.13. Pictorial example of an in home display connected to a smart meter showing current energy usage. (BritishGas, 2015).

Energy suppliers are responsible for replacing over 53 million gas and electricity meters in UK homes and businesses. The mass roll-out of smart meters is expected to start in 2014 and to be completed in 2019. However there is a degree of public misunderstanding relating to smart meters and them being mixed up with the functions provided by both in home displays and the demand side type fuel consumption.

Krishnamurti *et al.* (2012) have investigated the human perception and behaviour related to smart meters in order to further understand how they will impact on domestic life and the potential ability to create energy savings. The study consisted of user interviews regarding their preconceptions relating to the implementation of smart meters in domestic homes. This was achieved by a series of questionnaires and interviews with members of the public over a wide range of socioeconomic backgrounds, and where previously some had both been and not been exposed to smart meters. The results of the questionnaires demonstrate that there is a degree of ambiguity regarding smart meters and peoples understanding of the potential benefits and drawbacks with the public expecting instant cost savings and mistaking smart meters with intelligent in-home displays. The results show that there are perceived risks with less control, increased costs and violations of privacy.

Bonino *et al.* (2012) investigated home energy interfaces to establish if having this kind of feedback mechanism contributed to energy saving actions by the occupant of the home. The study consisted of an online survey of 992 residents which consisted of the user watching a short video and then answering goal setting questions followed by feedback type questions. The study indicated that the public, in general, would be willing to adopt an in home display and thus show a desire to save energy. The study indicates that good locations for the display would be in a kitchen where the majority of the energy is consumed, or in a transient location such as a hallway where the display is observed frequently.

Hargreaves *et al.* (2013) undertook an investigation into how UK householders interact with smart meters installed in their homes over a 12 month trial period which led to differing results. Similar to Krishnamurti *et al*. (2012), this was in the form of a survey and questionnaire based study and the findings extracted from follow-up qualitative interviews. The work suggests that the smart monitors gradually fade into the background of everyday life, and thus the location is less important. These monitors do increase knowledge and confidence in electricity consumption but beyond a certain level fail to motivate energy reduction.

A further form of building control is the use of smart meters coupled with demand side management schemes. Smart meters are electricity and gas meters which perform the traditional function of measuring energy consumption but also they offer a range of advanced functions, such as inform one how much energy is being used through a display in your home and it can communicate that directly to your energy supplier DECC (2015).

2.4 Intelligent Control Strategies

In this case, intelligent controls are control systems which make decisions based on external information either sensed or provided by the users. In contrast to typical thermostats which work on a fixed schedule and timeclock, intelligent control systems operate dynamically to maximise occupant comfort as well as maintain energy savings. This section details the technology required to implement these as well a detailed review of two Intelligent Control Strategies Multi Agent Systems (MAS) and Model Predictive Control (MPC).

2.4.1 Information Communication Technology

Information Communication Technology (ICT) is key to the deployment of smart homes and current equipment is investigated in this section starting with a review of application and feedback methods for saving energy in domestic homes.

Wood and Newborough (2003) performed a comprehensive literature review into the application of information feedback methods for saving energy in domestic homes and found individual appliances are not considered in these. A study was conducted of 44 homes, which monitored electricity used for cooking and provided feedback in three different ways, either a paper information pack, electronic consumption indicators or both. The study concluded that a visual energy cost indicator will reduce cooking energy by 10% to 23% as opposed to a simple information pack provided to the family which will reduce the energy consumption by about 10%. However the main driver for energy use is the size of the family.

Wood and Newborough (2007) built on their earlier paper Wood and Newborough (2003) and investigated a range of energy consumption displays for residential homes with a view to assessing them as a method for reducing the household energy consumption. The authors critically analysed previous work, comparing and analysing some studies and research papers to determine the strengths and weaknesses of different display mechanisms for energy consumption with a view to reducing the overall domestic consumption. They concluded that target setting is important to promote energy saving decisions, along with internal household competition and comparison to previous energy consumption rates. Monetary reward is also identified as important, whereas the social reward of external competition with similar households is not effective in promoting energy reduction.

Cook *et al.* (2009) performed a survey of technologies that form the core of ambient intelligence and applications that are affected by them, particularly technologies that are described as ‘intelligent’. The survey was in the form of a study of current literature and work in this field. The study concludes that the backbone of all building automation systems as the Information Communication Technology (ICT) which enables the data transfer and processing in order to automate the systems and with the shift in people, the computing power ratio towards computing, it is still of increasing importance.

Rathnayaka and Kuruppu (2011) have investigated differing wireless technologies related to home automation. The study comprised of primary research into the wireless technologies by evaluating and comparing the positive and negative attributes of each wireless technology. The authors pictorial representation of an embedded home automation system can be seen in Figure 2.14.

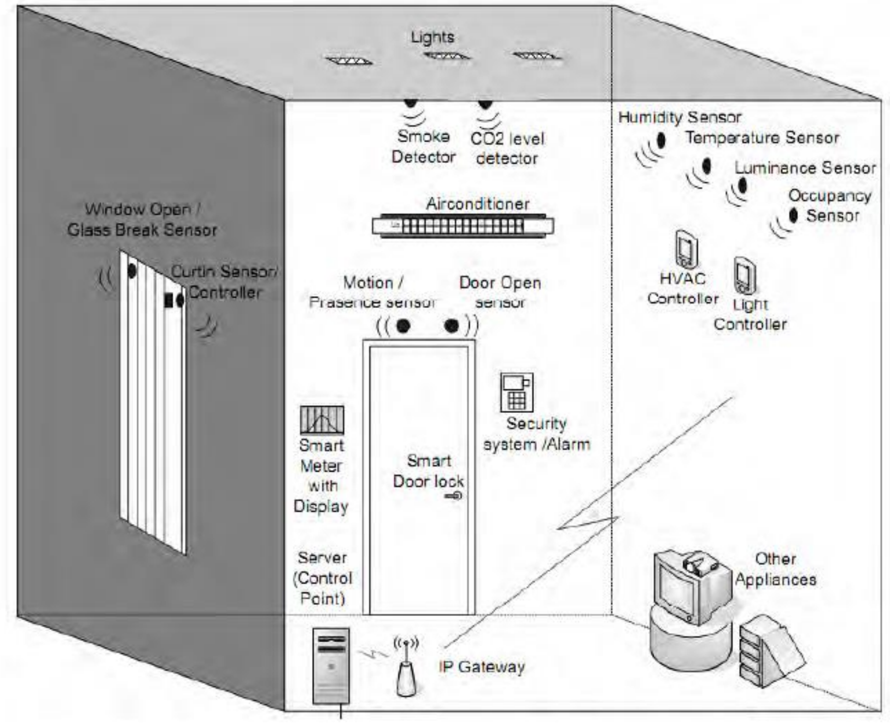

Figure 2.14 Range of sensors, controllers and feedback devices which could be used in smart home installations (Rathnayaka and Kuruppu, 2011).

Figure 2.14 illustrates all the smart home devices which could be included in a complete smart home control system for which the researcher is exploring wireless technologies to connect together. The research concludes that each wireless technology has individual benefits and drawbacks when used in different home automation system, thus each system should have a wireless technology chosen specifically for it. Sensors form an integral part of the smart home system, thus providing the information required for the system to intelligently make decisions and adjustments.

Ding *et al.* (2011) undertook a review and identified different sensor types that are suitable for deployment within a smart home environment, by evaluating their strengths and weaknesses. The study indicated that current research only evaluates sensors in terms of laboratory experiments and it is important that stakeholders are made the focus when evaluating their feasibility. One further way to potentially reduce energy in a smart home environment would be to provide the user with important energy related information to enable informed decisions to be made by the occupants regarding their own energy consumption.

Markovic *et al.* (2012) present an overview of the smart home concept and goes on to identify some of the challenges faced by ICT within this domain. This is done by providing an overview of a smart home system, identifying different components which make up the system and proceeding to discuss the different ICT challenges faced when trying to implement the system, such as the control systems ability to integrate further devices, cross platform compatibility, different needs due to differing demographics and a lack of existing infrastructure. The work concludes that the framework in which the smart home is implemented should be an event based infrastructure and work should be performed towards identifying a subscribed and published model to work with and moving towards a unified standardised method. In addition, Markovic *et al.* (2012) have explored the ICT hardware required to facilitate the networks that these control systems rely on.

2.4.2 Agent Based

Agent based control consists of a number of individual agents pertaining to different variables to be maximised (energy reduction, thermal comfort, etc.) which interact to solve a complex problem whilst attempting to maximise their own solutions. This section being with an review of such a system suitable to control a domestic smart home.

Khan and Matskin (2010) approached the engineering of multi agent systems as digital ecosystems (a digital version of a natural ecosystem) focusing on the dynamic and social behaviours of the agents by taking into account the cooperation, coordination, negotiation and management attributes of the system. Both streams of research concluded in the proposal of a framework which facilitates multi agent systems as a method of providing control in a domestic smart home scenario. Although the multi agent system part of the control package is central to successful operation, a comprehensive and structured knowledge base is also essential to manage all the information relating to the control system to enable intelligent decisions to be made.

Reinisch *et al.* (2010) developed a suitable knowledge base for a smart home application by using the web ontology language (OWL) standard, which incorporates information relating to energy use and production, user preference, building physics and tariff costs. They discussed this by outlining the ThinkHome case study as an example to describe the outcomes which can be derived from the OWL ontology knowledge base combined with the intelligence of the multi agent system, such as self-learning and context awareness. The conclusions indicate cost savings can be made from turning off the appliances that are in standby mode. Whilst the outcome of turning off standby appliances reduces the energy consumption, this may appear to be obvious, the study outlines a system which does this automatically and thus eliminating any aspect of human behaviour in forgetting or neglecting to turn the appliance off.

Wang *et al.* (2011) investigated a BEMS architecture in the form of a wireless multi agent control system for controlling HVAC, lighting and electrical devices, as indicated in Figure 2.15.

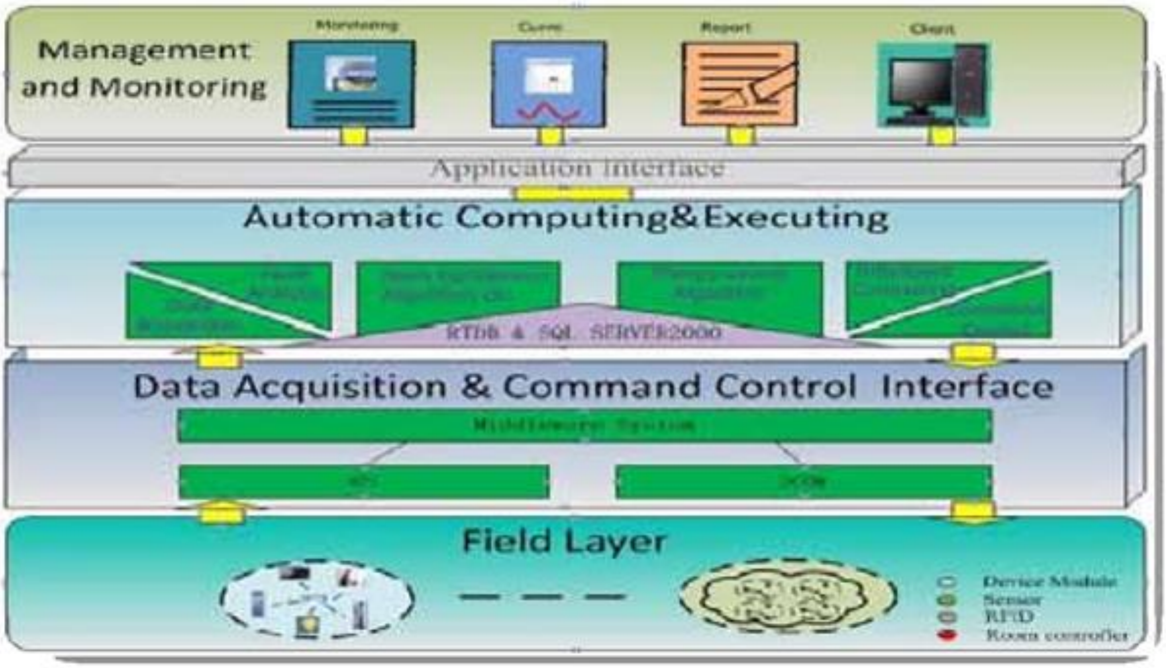

Figure 2.15. Data flow through a multi layer agent based system architecture (Wang *et al.*, 2011).

Figure 2.15 outlines a tiered architecture which monitors and controls the building HVAC, lighting and electrical devices. The user interacts with the Monitoring and Management layer of the system, reading outputs and inputting user defined requirements, such as the required climatic conditions.

The control, processing and intelligent system decisions take place in the automatic computing and execution section which acts on data provided by the data acquisition and command control interface. All the data is gained via the field layer which provides sensor inputs to the system providing the data required in real time, such as room temperature, room occupancy, time of day, etc. The research concludes that this system developed is viable for implementation and has applications in large buildings, such as in the research establishment where the work was conducted (Shandong Jianzhu University, China). Although the author identifies it as suitable for large buildings, a simplified version could be adapted for use within domestic homes with generic field devices, command and decision layers and a common user interface. However further work would need to be performed in order to identify the cost implications relating to developing an advanced control system for use within a domestic home setting.

Joumaa *et al.* (2011) have developed a BEMS architecture in the form of a multi agent system that is suitable for application to the smart home domain. The study investigated a 3 layer system consisting of a local layer, a reactive layer and an anticipative layer. The local layer provides the real time control to the space, using the data from both the reactive and anticipative layers. The reactive layer looks at the current conditions, for example the indoor and outdoor conditions, and attempts to modify the anticipative layer in order to produce the design thermal conditions inside the building whereas the anticipative layer with slow dynamic response, which incorporates a thermal energy model of the building, takes into account predictable events to remove as much use from the reactive layer as possible and this reduces the energy consumption as far as practicable with existing knowledge of current energy costs and probable building conditions.

The proposed system was tested and it was discovered that a distributed system, such as the one described with individual agents solving their own sub-problems such as ambient temperature (iterating until satisfaction is reached), did not yield as good energy savings as a centralised system which requires more computing power but solved the entire problem at once. However the distributed system has other benefits, such as openness, scalability and the ability to manage diversity.

A multi agent system is a collection of intelligent agents that interact within an environment to solve complex problems. Figure 2.16 depicts a typical multi agent system where the agent system houses each intelligent agent and controls the interaction between them.

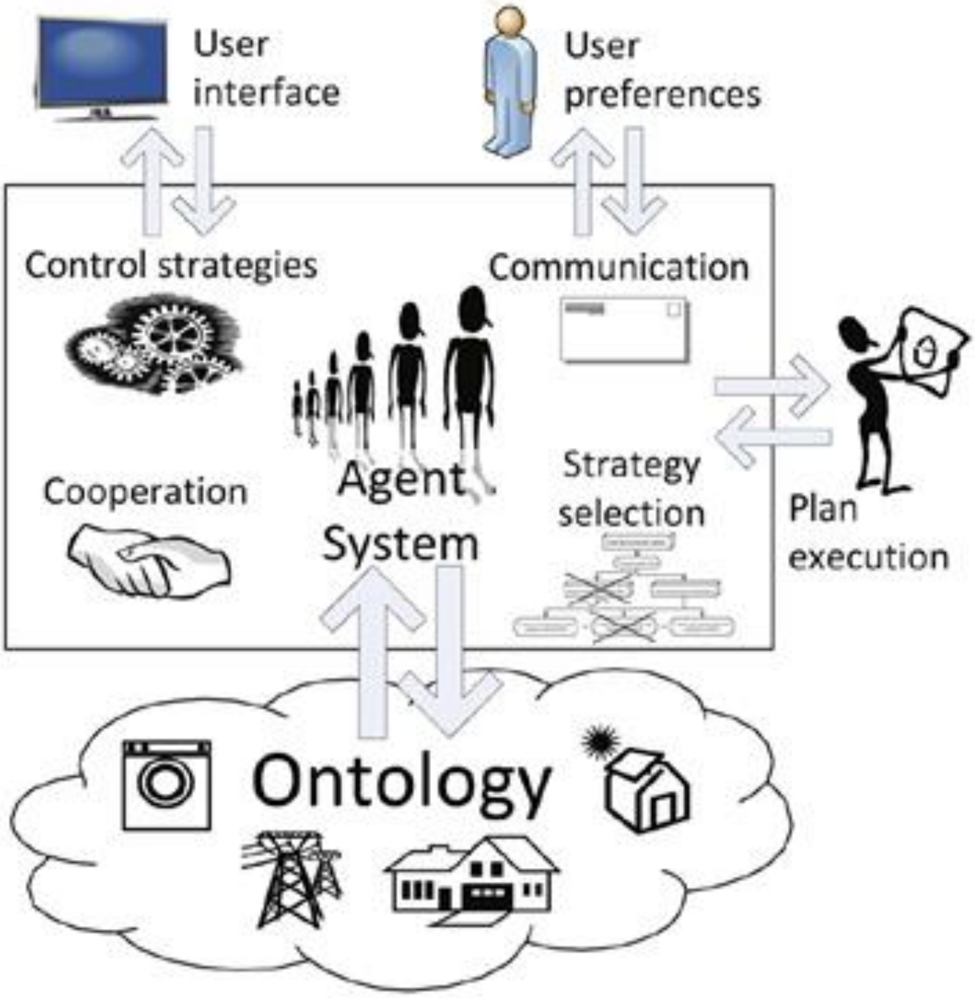

Figure 2.16 Schematic representation of data flow between a muliti agent sytsem and the associated external factors (Kofler *et al.*, 2012).

Each agent of the multi agent system described in Figure 2.16 inputs and outputs to and from the knowledgebase, passing information such as user preferences and execution plans which allow for user interaction and imposing user requirements on the control system. The system feeds back to the user through the same multi agent system and in turn controls the domestic energy systems according to the user defined inputs. This method of control allows the multi agent systems cooperation and strategy elements to work together taking into account user inputs to provide the optimal solution, satisfying the requirements of each individual agent and to not just act in isolation to maintain their own goals.

Central to the multi agent system is the knowledgebase which contains all the data the multi agent system requires to make intelligent decisions in building control on behalf of the user. A proposed knowledgebase is outlined in Figure 2.17 where each area of knowledge is segregated into its own ontology and each intelligent agent is free to interrogate whichever is relevant to its operation. The output from the system which is used to plan the execution will be controlled by the multi agent system and not by any one individual intelligent agent in order to not make any output detrimental to the overall goal of the system, which is to reduce the energy consumption whilst maintain user defined comfort parameters.

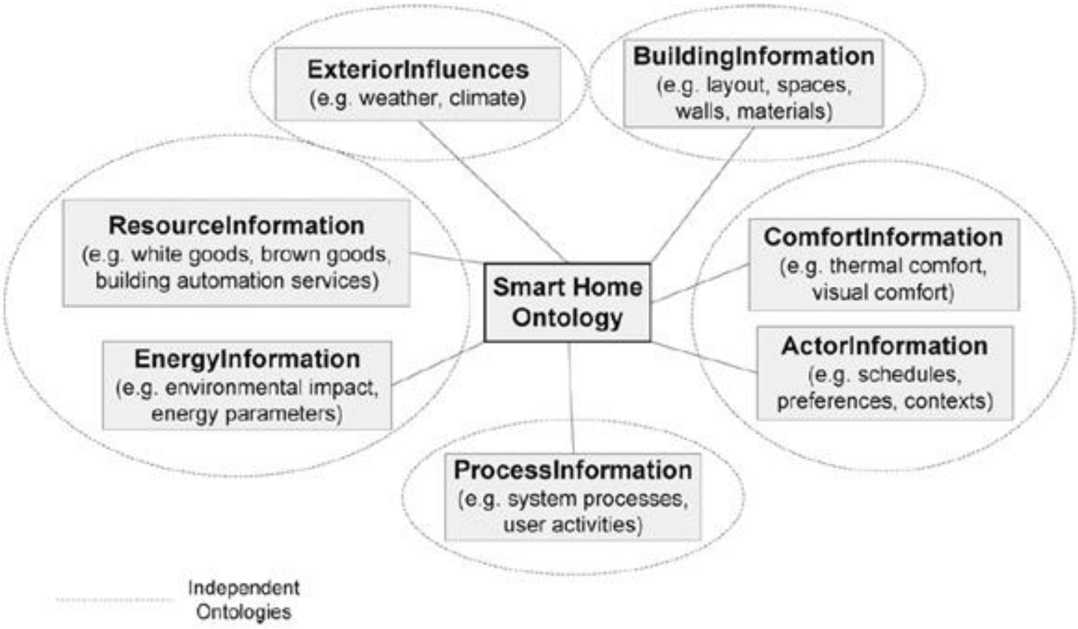

Figure 2.17. Schematic representation of a smart home ontology (knowledgebase) showing proposed groupings for similar knowledge banks (Kofler *et al.*, 2012)

Kofler *et al.* (2012) investigated the application of artificial intelligence to smart homes with a view to minimising energy demand whilst maintaining user comfort. The research used an agent based system populated by a society of autonomous agents that implements artificial intelligence techniques to achieve the control, similar to those depicted in Figure 2.16 and Figure 2.17. The structure that is proposed makes all knowledge easily available to the smart home system supports control processes with its logical construction.

2.4.3 Model Predictive Control

Model Predictive Control (MPC) systems use a dynamic thermal model of the building that is being controlled to provide more accurate prediction of future states and the real time control required to achieve it. This differs to the agent based system discussed in the previous section as there was no model of the building required in that case but agent based control systems an still yield energy savings.

Široký *et al.* (2011) describe an MPC system control method which uses a model of the system and attempts to minimise an objective function, in this case it is the energy usage. Figure 2.18 visually depicts a typical MPC system and how it could be used in a building control scenario.

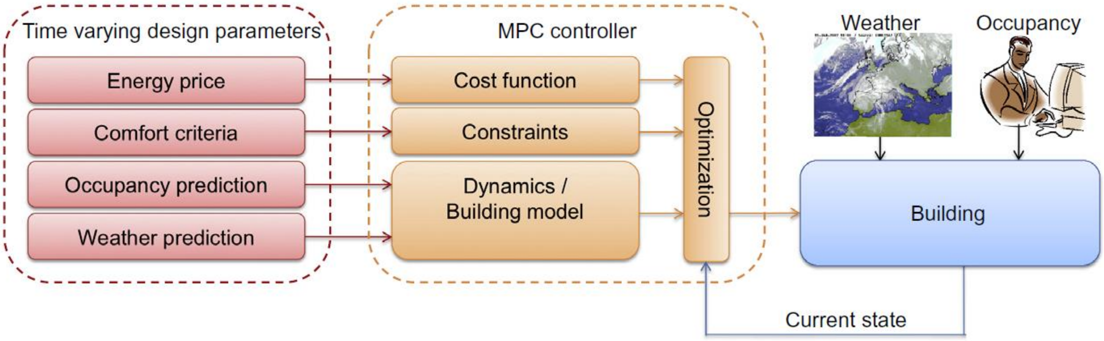

Figure 2.18 Schematic representation of a typical Model Predictive Control system showing external time varying factors, controller considerations and dynamic external factors (Široký *et al.*, 2011).

The system works by using predictive data for the variables, such as weather, cost of energy, internal gains and formulating a control strategy which the MPC controller implements for the coming hours to satisfy the users requirements and minimise the objective function (energy). When this control strategy is then implemented, the system then moves one time step forwards and repeats the process, where the results of the previous step act as feedback into the system as a further variable in the control calculations.

Oldewurtel *et al.* (2012) investigated the application of MPC and weather conditions to provide Integrated Room Automation (IRA) controlling HVAC, electrical lighting and blind position. Large scale factorial simulations, based on a range of weather conditions were undertaken and they demonstrated a stochastic model predictive control system that outperforms the current control practices within the realm of domestic energy management systems.

Ma *et al.* (2012) also investigated a model predictive control system based on a cost driven model predictive control technique which aims to reduce energy and demand costs for HVAC systems. The results obtained were compared to a control base case to determine the cost and energy savings and they demonstrated that, when combined with Time of Use (ToU) pricing, the MPC yields cost savings by shifting energy demand away from the peak hours.

2.5 Operation Techniques

Operational techniques are the ways in which control systems can be applied to the domestic home heating system. These are broken down into single zone control and multi-zone control. The section starts with discussing single zone control and how this can work to minimise energy consumption.

2.5.1 Single Zone

Single zone control is a typical control strategy involving one controlling thermostat for an entire heating system. The section begins with looking at existing heating control practices.

Liao *et al.* (2005) studied existing heating control practices in the UK for commercial buildings using occupant surveys, computer simulations and experimental studies. The survey of 35 buildings highlighted that boiler and emitter controls are poor. Computer simulations highlighted that the use of TRVs with limited flow control results in occupied rooms not maintaining their desired temperature. The study proposes a new boiler control algorithm which reduces the effect of poor TRV use. The survey discovered during walkthroughs that 35% of TRVs were left on the MAX setting, while 65% were set higher than required for optimal thermal comfort.

For single zone control, Peeters *et al.* (2008) identifies three main methods of heating control which are a central thermostat, a central thermostat with TRVs and TRVs on all radiators but no thermostat (boiler timeclock control).

Xu *et al.* (2011) undertook a study investigating the effectiveness of TRVs at reducing overheating in hydraulic heating systems for district heating serving apart block in China. Three cases were identified which were uneven distribution flow rate, excessive radiator area and excessive supply water temperature. The study found TRVs reduce overheating by up to 60% and up to 80% in the case of excessive water temperature. This has applications to the system outlined by Peeters *et al.* (2008) for heating systems that only have boiler and timeclock control. Mallaband *et al.* (2015) noted 17% of the homes surveyed had this type of system.

Monetti *et al.* (2015) undertook a study on an Italian house to investigate the impact that retrofitting thermostatic radiator valves (TRVs) has on the heating performance of a timeclock based district heating system. Figure 2.19 shows the heating system as installed in the apartment complex with the TRV installation to improve individual apartment thermal performance.

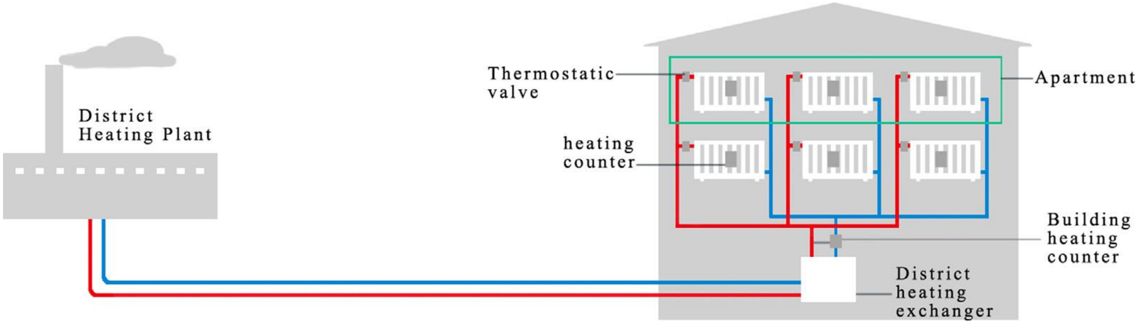

Figure 2.19 Schematic representation of the district heating system and TRV installation allowing individual radiator control in the building (Monetti *et al.*, 2015).

In Figure 2.19 the building heating counter in the basement keeps track of the overall building heat usage whilst the heating counter on each radiator monitors the individual heat output of the radiators. A TRV is installed on each radiator to regulate the water flow and thus the heat output of the radiator. The study took the form of a dynamic thermal model computer simulation of the case study building, modelling the building as is and then a range of different TRV scenarios. The study concluded that with the application of TRVs, energy savings of between 2% and 10% could be experienced, depending on the setpoints used for each thermal zone.

Mallaband *et al.* (2015) undertook a study of 12 homes in the UK, replacing existing controls with programmable digital controls in order to observe the impact this had on energy consumption and user influence on their heating system. The study noted a similar range of controls during the first stage of in home trials in the Digital Energy Feedback And Control Technology Optimisation (DEFACTO) project. It was observed that when users were presented with digital thermostatic controls, they opted not to use it and operated the heating system manually. During the study a failure rate of 8 out of the 12 houses of at least 1 sensor was seen due to the wireless communication and human interaction with the setup.

2.5.2 Multi Zone

Multi Zone Control or decentralised control consists of the occupied building being broken down into heating zones, each with their own control unlike the single zone system which is run from one thermostat. For example splitting a domestic home into an upstairs zone and a downstairs zone. The section begins with the energy wasted from incorrect thermostat settings and the temperature difference between upstairs and downstairs using only one thermostat.

The study conducted by Meyers *et al.* (2010) uses data from the residential energy consumption survey (RECS) in the US from 2005 to construct a framework to estimate energy wastage in different energy services including heating control, in home energy displays and appliance choice. The study finds that potential energy wastage from incorrect thermostat settings could be in the range of 2.5% - 8% of total energy used. These incorrect settings also include wastage due to lack of temperature control in areas far from the thermostat. A typical difference of about 4°C could be expected between upstairs and downstairs in single thermostat settings in the US. A multi – zone approach is proposed as a way to reduce domestic energy wastage.

Honeywell (2014) has on the market a decentralised heating system offered to home owners with suitable existing central heating systems. This consists of a number of Wi-Fi enabled thermostats which can be deployed in each zone along with Wi-Fi controllable thermostatic radiator valves (TRVs) to throttle the heating in each room to control the temperature. Whilst these systems have the potential to save energy and increase occupant comfort and control, there is little research published into the effect on the energy consumption of a heating system when installed.

Adolph *et al.* (2014) conducted a study to develop an algorithm to establish individual user profiles on each occupied room in a computer simulated building. The algorithm took user feedback on thermal comfort via a push button system to construct the profile. Figure 2.20 shows the role of user feedback in optimising the heating setpoint in a domestic heating system to help limit overheating.

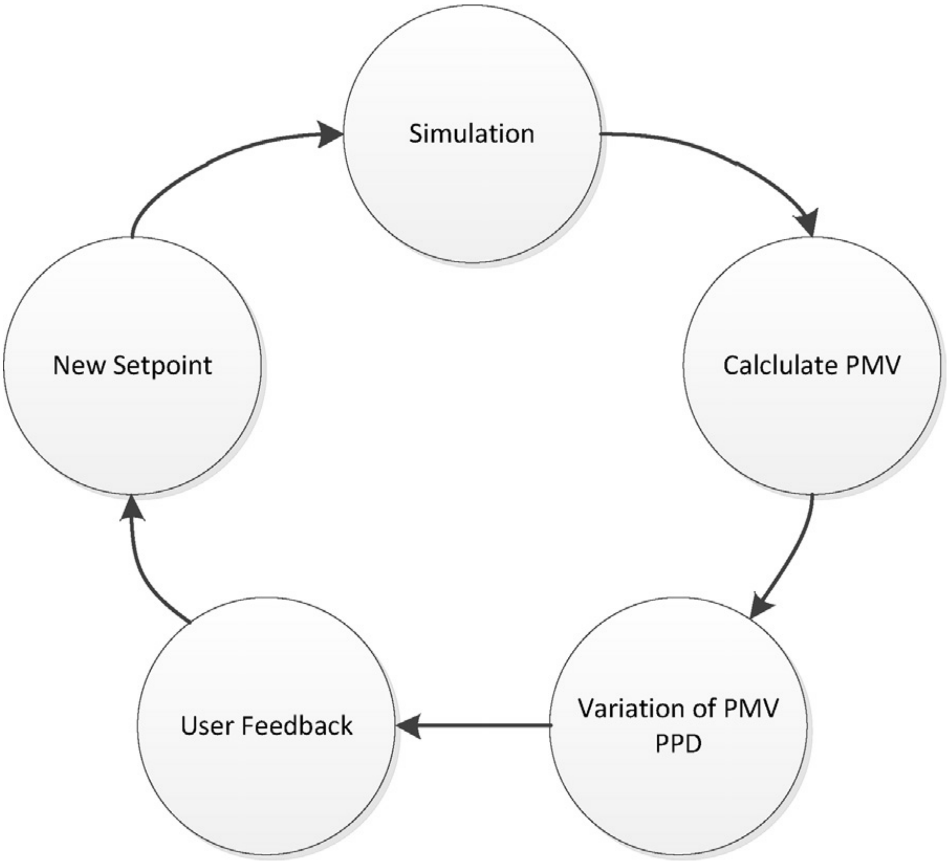

Figure 2.20 User feedback control loop used to optimise heating setpoint for each user in a simulated building (Adolph *et al.*, 2014).

In Figure 2.20 the user feedback informs the new setpoint which is then simulated to calculate the new Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) and attempted to maintain a high degree of user comfort. The study noted that often the advanced control techniques used in buildings provide higher temperatures than required and thus provided lower potential energy savings. Energy savings of 11% were provided with no impact on user thermal comfort.

Beizaee *et al.* (2015) used field measurement and experimentation on two identical houses in the UK to investigate the potential of zone space heating controls to reduce energy use in typical UK homes. This was done by having a standard programmable thermostat in one home, and with a zone control heating system in the second home. Identical synthetic occupancy was used in both homes in order to establish the effect on energy consumption the systems had without human influences. The study contained 8 weeks of useful data from between 16 February until 21 April 2014. A heating degree day method calculation was used to extrapolate gas consumption data to establish yearly expected savings. The study found that zone control had the potential to reduce gas consumption for space heating by 12%

2.6 Software

Dynamic thermal modelling software is used extensively in research into building energy consumption, summarised here are relevant recent studies using such software.

Dounis and Caraiscos (2009) explored state of the art control systems and with a focus on multi agent systems in the domain of smart homes. They constructed and ran a dynamic thermal and energy model in Transys and MATLAB. The study found that the system successfully managed user preferences for the luminance and comfort conditions along with energy conservation.

Al-ajmi and Hanby (2008) undertook a parametric study into optimal building façade, cooling systems and ventilation in Kuwait homes in order to propose improvements to the current energy conservation code. This was done using TRNSYS proprietary thermal simulation software. The study concluded that addressing a buildings air tightness and maintaining a low glazing ratio (and north – south glazing aspects) has a larger effect on the energy performance than the U-value of external walls.

Ampatzi and Knight (2012) studied domestic energy demand on active domestic solar systems. This was conducted as a computer simulation in TRNSYS modelling of 12 Welsh homes over the period of a year. The study finds that dynamic simulation tools, such as TRNSYS, can handle the complexity of elaborate building models.

Attia *et al.* (2012) conducted a study to establish building energy data sets and benchmark models for the residential energy sector. Using a field study of approximately 500 apartments in the three largest cities in Egypt, dynamic thermal models were produced in EnergyPlus which reflected the results of the field study. From these simulations it was concluded that the surveyed buildings had a very poor thermal performance which led to a high electricity usage during summer for air conditioning.

Mateus *et al.* (2014) detailed the validation of a naturally ventilated double skin façade in dynamic thermal modelling software. A test cell was manufactured and situated in Lisbon which provided temperature and air flow data for a 1 month period for use in the validation. A replica of this was constructed in EnergyPlus and run for the same period of time. The study reported average error rates for air and radiant temperature of 1.4°C and an average daily maximum error of 2.5°C.

Buratti *et al.* (2013) conducted a study to evaluate the thermal comfort and thermal performance of a lecture room in unsteady-state conditions. Field measurements of indoor and outdoor temperatures, solar radiation and internal surface temperatures were taken of a case study lecture theatre and used to validate simulations conducted in both Trnsys and EnergyPlus. After the validation parametric runs were conducted to investigate the effect of different room orientation and glazing had on the thermal performance. The study concluded that east facing glazing has the highest thermal comfort rating (12-15% PPD) and having glazing with sunlight control provides the best comfort conditions whilst maintaining good natural light inside.

Jokisalo *et al.* (2009) investigated the relationship between airtightness of a building envelope, infiltration and energy use in a typical modern Finnish detached house. Field measurements of the airtightness of 170 homes in Finland was conducted using a standardised fan pressurisation method at 50Pa. A typical timber house was then constructed in Indoor Climate and Energy (IDA-ICE) and the energy use simulated with these infiltration rates. The study concluded that infiltration is responsible for 15%-30% of the heating demands in Finnish buildings and this infiltration rate is increases linearly with the building leakage.

Motuziene and Vilutiene (2013) conducted a study into the effect occupancy profiles have on the energy performance of an energy efficient house in Lithuania. The study was conducted in EnergyPlus with a simulation period of 1 year using hourly timesteps. Four occupancy profiles were implemented with four heating strategies resulting in 16 total simulation scenarios. The study reported that age, behaviour and number of occupants have a large effect on the energy performance of the building and using a setback temperature during unoccupied hours could yield energy savings of 13-31%.

Ma *et al.* (2012) investigated a model predictive control system constructed in EnergyPlus which contains a fully constructed model of the building which simulates the building physics and the load requirements. This is connected to MATLAB via a middleware program (Building Controls Virtual Test Bed). MATLAB generates temperature and power consumption profiles and the MPC algorithms using the MATLAB system identification toolbox. These MPC controllers are then run in the original EnergyPlus model and with the actual zone temperatures, power and demand profiles are generated. The study indicated significant cost savings can be made by triggering pre cooling and shifting the peak load away from peak hours.

2.7 Validation methodologies

Validation of experimental and computational results is an essential step in producing results which are suitable to draw conclusions from. Different validation methodologies are available to establish the robustness of dynamic thermal models.

Validation between dynamic thermal models and statistical data has been used by Attia *et al.* (2012). The study developed benchmark models to investigate average energy consumption in Egyptian domestic residences. This was validated against public statistics and comparisons to utility bills obtained in public surveys. No criteria for validation was contained within this study and it is considered to be a less robust methodology. This is due to the dynamic thermal models representing typical buildings compared to typical energy consumptions rather than direct comparison between identical experimental observations and computational modelling.

Comparisons can be made between two different dynamic thermal models which was conducted by De Rosa *et al* (2014). To validate the new methodology the study proposed, the heating and cooling requirements were modelling using the new methodology for a number of case studies. These were compared directly to the same case studies modelled in leading dynamic thermal modelling software. These direct comparisons consisted of reporting the heating and cooling demand for the case studies over the period of one day.

Silva and Ghisi (2014) used uncertainty analysis to establish the robustness of dynamic thermal models. One set of results were the case study building and a further 15 produced which reflected the case study building but with slightly differing parameters such as occupancy patterns, thermal properties and heating system performance. Each were run over the same period and the results compared to the case study using a deterministic analysis, parameter variation analysis and uncertainty analysis with the conclusions being the percentage error between the case study figures and particular models. This methodology reported high uncertainties between the case study and dynamic thermal models and so does not present a good validation methodology.

Comparisons can be made between simulated and experimental results to establish the robustness of the dynamic thermal models, allowing conclusions to be drawn. Laouidi and Atif (1999) conducted a comparison study between simulation and field measurements of the internal thermal temperatures in a building atrium. The validationconsisted of comparison plots between measured and simulated temperatures for the same period with the difference in temperatures reported. This is illustrated in Figure 2.21.

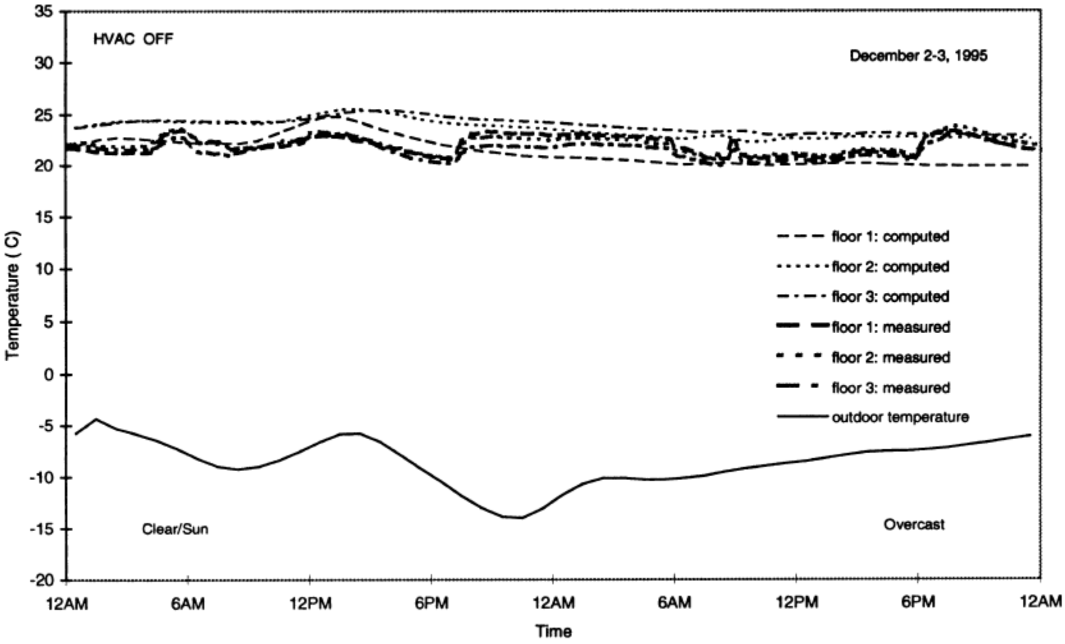

Figure 2.21 Temperature comparison between simulated and experimental temperature readings (Lauidi and Atif 1999).

The study found the models correlated with a maximum error rate of ±3ºC which was considered sufficient for the dynamic thermal modelling.

The study by Mateus *et al.* (2014) was validated using coupled measurements of average internal temperature and incident solar radiation for an experimental test rig and dynamic thermal modelling software. The difference between average internal temperatures were compared to establish the robustness of the dynamic thermal modelling with values between 0.6ºC and 1.8ºC being reported.

The study Buratti *et al.* (2013) conducted followed a similar validation methodology to the methodology of Mateus *et al.* (2014) where internal temperatures were compared between experimental and computational models. The comparison of a 2 day plot is shown in Figure 2.22.

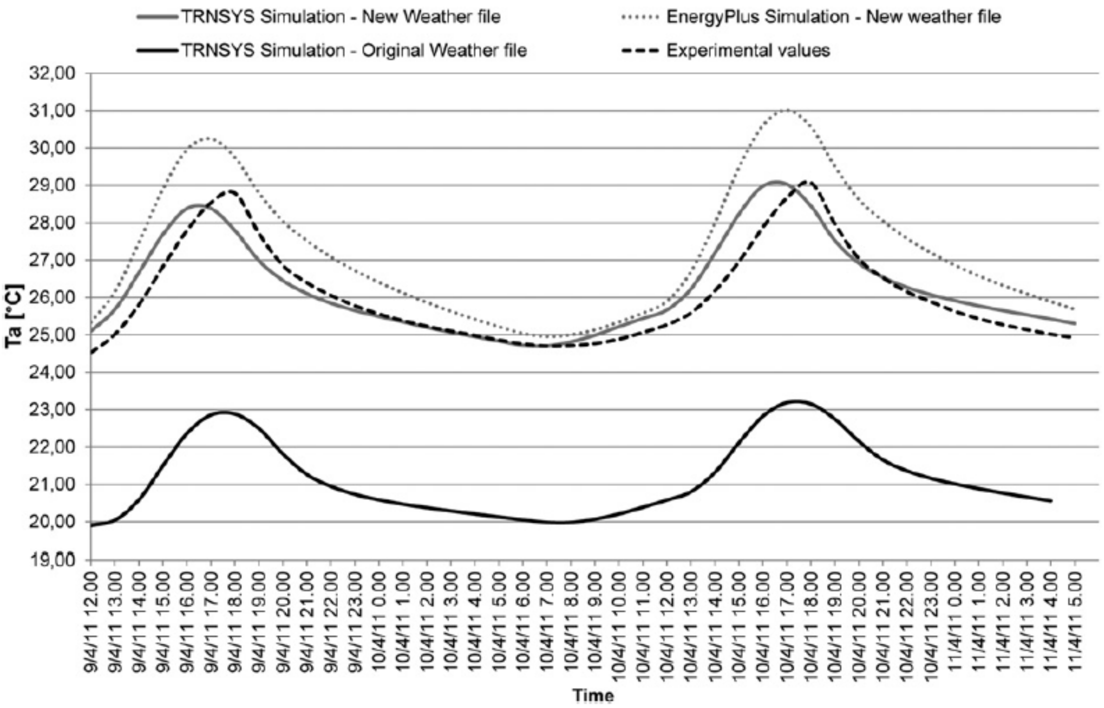

Figure 2.22 Comparison of internal temperatures between experimental and simulated results (Buratti et al. 2013)

The report details a maximum temperature difference of 2ºC between the experimental values and experimental values. With a validation based on temperature the study went on to draw conclusions on energy performance and occupant comfort. Buratti noted that a source of error for these comparisons could be due to the experimental facility reporting a spot value of temperature whereas the dynamic thermal models report a volume averaged value. The use of an average temperature in validation reduces the likelihood of these high spot values creating anomalies within the results.

The comparison between experimental and simulated results is considered to be the most robust validation methodology as it reflects the most realistic modelling for that study.

2.8 Research Gaps

The literature review presents a thorough analysis of current methods of energy reduction in homes through the use of building control systems. The review covers human behaviour, current technologies and their limitations, current research streams, research methods and tools used within this domain and validation methods.

However, the following gaps in the current literature are highlighted

- No data on the effect of retrofitting control systems to existing domestic building stock
- No data on applying a zonal heating control strategy on a UK domestic home

The present study seeks to explore the effect on retrofitting control systems to domestic building stock. A building control system will be designed and implemented within computer simulations to model the control of a domestic home, providing a reduction in energy use throughout the year. The computer model will be validated using field data gathered from existing domestic homes.

To achieve this, the following major research needs to be performed:

- Produce a full thermal model to act as the basis for simulations (Ma *et al.* (2012), Dounis and Caraiscos (2009)).
- Perform a full range of simulations to demonstrate a reduction in energy consumption in the computer simulations (Ma *et al.* (2012), Dounis and Caraiscos (2009)).
- Establish experimental buildings with different control systems, manual control, timed control and temperature control. (Beizaee *et al.* (2015), Mallaband *et al.* (2015)).
- Data acquisition from 3 case studies (Lomas and Kane (2013), Beizaee *et al.* (2015), Kane *et al.* (2015), Mallaband *et al.* (2015)).
- Implement control strategy on a case study building (Beizaee *et al.* (2015), Mallaband *et al.* (2015)).

2.9 Summary

This review indicates the methods in which domestic energy consumption can be controlled in order to achieve a possible reduction in the consumption of energy since this is becoming increasingly more important with rising fuel poverty in the UK, along with the increasing consumption due to the ever increasing numbers of electrical appliances that we commonly use in a domestic setting.

The ICT systems are an important backbone for any integrated automatic control system and provides a platform for ambient intelligent multi agent systems to operate and this will provide the largest reduction in energy consumption by removing the daily human interaction element which can increase energy consumption by up to 300%.

Whilst these systems provide the theoretical largest potential savings, there is very little research which investigates the implementation of these systems into existing domestic homes in a retrofit capacity. Since existing homes are the ones which potentially waste the most energy, as they are not built to the current stricter building standards with often old and outdated control systems within them.

Due to the nature of these older dwellings being bespoke and with undocumented changes, a system, which requires a computer energy model to function, such as an MPC system, would most likely not be suitable due to having to develop individual models for each house to ensure complete accuracy. The existing infrastructure does not exist within older dwellings to facilitate any demand side management, and this would require integration with systems outside the dwelling which requires the energy supplier to facilitate this. As such, an enhancement of the current domestic heating system with a zonal control approach which uses the existing building infrastructure to achieve a higher degree of control and subsequently achieve energy savings.

Chapter 3 Experimental Building Benchmarks

3.1 Introduction

Developing building benchmarks is an important part of this study to quantify any improvements in energy performance that result from the work. Post occupancy evaluation (POE) is used to develop experimental building benchmarks for validation of the dynamic thermal models and for quantification of any improvements. Over a three month period, three case study buildings with different heating control systems, manual control, time control and temperature control had their internal temperatures monitored and recorded at five minute intervals along with one external temperature measurement at the same intervals.

The chapter begins with defining post occupancy evaluation, its role within domestic energy consumption studies and where this has been recently utilised. Each of the three case study buildings will then be discussed in turn, first detailing the selection criteria and reason for selection. Each case study will then be discussed in detail covering the building geometry, construction and thermal performance, internal gains with schedules and finally the heating system with associated controls. The chapter finishes with a summary section outlining the key differences between each case study building.

3.2 Post-Occupancy Evaluation

POE is the process of obtaining feedback on a buildings performance in use. The value of POE is being increasingly recognised and is becoming mandatory on many projects. One facet of POE is POE – Environmental Monitoring. POE through environmental monitoring provides definitive physical measurement data on a buildings performance in use. This allows comparisons of its actual performance to be made with both the original design and environmental standards (BRE, 2015).

Three important outputs from POE – Environmental Monitoring relevant to this study are as follows:

i. Highlight problems with the building operation that can be addressed and solved.

ii. Provide knowledge and examples that can be used to improve future design.

iii. Act as a benchmarking aid to compare.

    a. Building performance between different systems.

    b. Building performance over time.

POE's have been used extensively in building energy consumption studies as highlighted by the following recent studies.

Lomas and Kane (2013) conducted a longitudinal survey into 268 homes in Leicester where the occupants were interviewed and internal temperatures taken to establish summertime operating temperatures. Vadodaria *et al.* (2014) monitored 20 homes for living room and bedroom temperature in the UK to compare these measurement with historical records, thus establishing any trend in increasing temperatures.

Mallaband *et al.* (2015) undertook a study whereby 20 homes were selected and temperature sensors were installed to monitor internal temperatures. Gas, electricity and temperature readings were taken over a two week settling period before an updated control system was installed. Comparisons were then made between energy use and internal temperature between the two control systems. Beizaee *et al.* (2015) used two case study houses to investigate the effect on domestic energy consumption and occupant comfort the installation of a multi – zone heating system had compared to a traditional heating system.

This study will use POE in order to obtain accurate temperature data for three case study buildings. The data will be used to provide validation for dynamic thermal models and identify the buildings thermal response to each control strategy. The following section will discuss how the case study buildings were selected for this study including the criteria for selection and a brief outline of the important differences between each building.

The following section will discuss a brief survey and questionnaire with the occupants, followed by the criteria for selection of the case study buildings. A detailed overview of each building including building geometry, construction, internal gains and occupancy schedules will then be discussed.

3.3 Case study occupant Survey

Qualitative surveys and interviews were conducted with the occupants of each case study home in order to establish the occupants thermal comfort and satisfaction with the performance of the heating system in their home. The surveys were either conducted in person or on the telephone, depending on the occupants availability with the interviewer noting down the responses. The survey questions were based on the surveys carried out by Andersen *et al.* (2009) and included the following topics:

- Building construction including insulation and double glazing
- Heating system and associated controls
- Thermal comfort during heated periods

The full surveys are contained in Appendix A

In addition to the occupant interviews and surveys, full inspections of each home were carried out in the study to gather first hand data on the buildings construction, heating system and heating controls. The questions on building construction are primarily there to assess the occupants understanding and knowledge of their own home and thus the priority they place on the energy performance of their heating system.

3.3.1 Manually controlled building survey results

The occupants of the manually controlled building were aware of the construction of their home but as the home is rented, they are not free to have insulation installed. The knowledge of the heating control system was reported as adequate, however the occupants have not changed the settings on the storage heaters under instruction from the landlord. It was noted the controls are very basic during the inspection with no programmable features.

Overall the occupants felt cool in the living room and kitchen. This is mainly due to only having a heater in the kitchen and varied working hours having a shift work pattern meant the heating was not always on when the occupants were in the room. The living room had a coal fire which they lit if they were spending time in the living room. The bedroom was comfortable and had an ancillary electric heater if the occupants did feel cool at certain times.

3.3.2 Timed controlled building survey results

The occupants of the timed controlled building were not aware of the state of the insulation in their home, which indicates they do not regard energy efficiency as a particular priority. Their knowledge of the heating system operation was good, however in the inspection it was noted that the time based control was not used to its fullest as the heating was generally left on throughout the day and night as there was a young child.

The living room and bedroom were comfortable with the kitchen being slightly cool. The occupants reported feeling drafts in the kitchen which was the source of their discomfort but after cooking for a while they did not notice any more.

3.3.3 Temperature controlled building survey results

The occupant of the temperature controlled building reported having the greatest knowledge of their control system, using the programmable thermostat to set a heating schedule matching their working hours. It was noted that the occupant did not differentiate between weekend and weekday heating schedules.

The occupant reported they were comfortable at all times in their home except at times late at night when it dropped significantly colder than the day. When this occurred the occupant used the heating boost for an hour at a time to raise the temperature of the home to achieve thermal comfort.

Overall the results of the occupant comfort surveys showed the find their homes thermally comfortable, sometimes a little cool which was counteracted by a mix of boosting heating, additional heat sources or using extra blankets and layers to warm.

3.4 Case Study Building Selection

Mallaband *et al.* (2015) identified the requirement to draw participants from a range of different circumstances in order to encapsulate a broad cross section of people covering as many different variables in building occupancy and type as possible.

The case study buildings were selected with a number of criteria in order to provide a diverse set of observation results. The criteria for selection are as follows:

i. Building heating control strategy

Three distinct heating control strategies are covered with the three case study buildings:

a. A manual control strategy where the building has individual storage heaters in each room.

b. A control strategy was timed central heating control.

c. A system with temperature controlled central heating which is the most up to modern control system.

ii. Building geometry and construction

Two homes were terrace houses and the other being a semi-detached home. These housing types represent 60% of UK building housing stock and are the two most common property types so will provide results relevant to the majority of UK homes (Palmer and Cooper, 2014).

iii. Occupancy patterns

There are three different occupancy typologies.

a. A single male in his 50s in full time employment.

b. A young couple who both work regular hours.

c. A young couple who both work on a variable shift pattern.

iv. Climatic location

The UK is divided into a number of regions relating to the average heating degree days in. The location of the case study buildings fall within region 11 (East Pennines) which is shown in Figure 3.1..

Figure 3.1 Map of degree day zoning for the UK (CIBSE,2006)

Mean annual heating degree days for each region are published in CIBSE guide A (CIBSE, 2009) with a historical average from 1976 – 1995 being used to calculate the average degree days for design. Figure 3.1 shows the distribution of degree days compared for the UK average case against the location of the case study buildings over a period of one year.

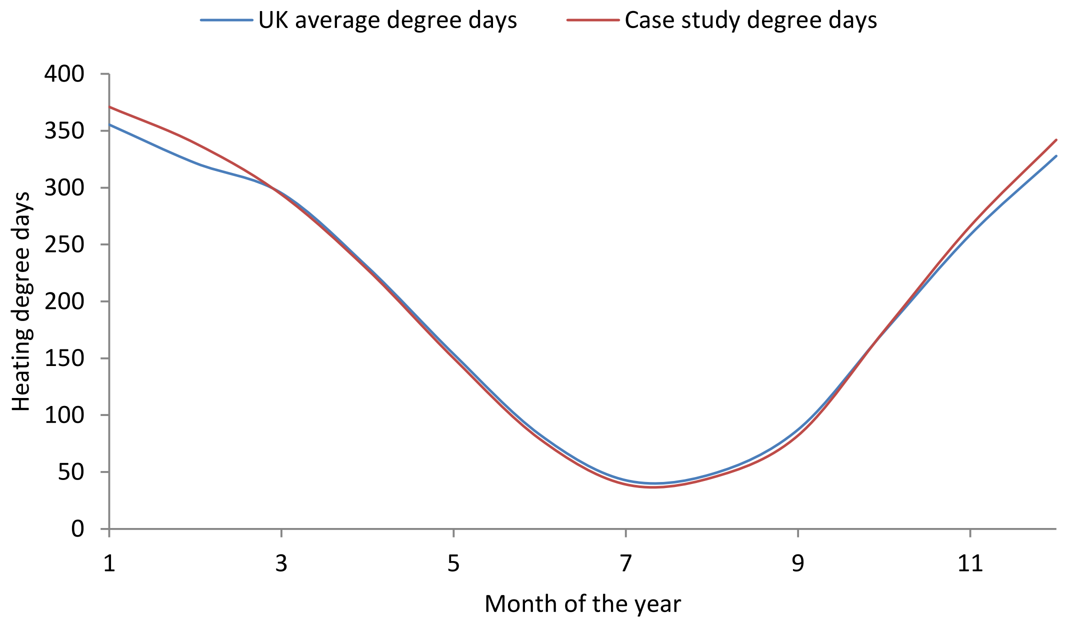

Figure 3.2 Comparison of degree day distribution between the UK average and the case study location (data from CIBSE, 2006)

During the spring and autumn months the UK average degree days and case study degree days match perfectly. During the summer the case study experiences less degree days than the UK average however in the winter, when the impact of heating is more pronounced the case study location experiences an increase in degree days compared to the UK average. This means the location is generally cooler than the UK average but the magnitude is small with a maximum difference of 17 degree days.

For the yearly average for region 11 there are 2307 annual heating degree days reported. The mean number of heating degree days country wide is listed as 2310 which results in a difference between the regional and country average of less than 1%.

This indicates that the location selected for the case study buildings is representative of average climatic conditions within the UK and as such, conclusions can be drawn based on the experimental and computer simulation in this region for the country as a whole.

The criteria for selection of the case study buildings has been established in Section 3.4. Sections 3.5, 3.6 and 3.7 will now detail each case study in turn, highlighting the variables which contribute to each of the selection criteria.

3.4.1 Determination of building thermal properties

In order to construct accurate dynamic thermal models, the building thermal properties must be defined to match the thermal properties of the building. In no cases were invasive techniques available to determine the construction of the building walls and so a mixture of inspection, discussion with the occupants and evidence from any past building work was used to determine the constructions which could not be readily got from data sources.

In all cases the thermal properties are defined in the dynamic thermal modelling software with the opaque building parts defined in an elemental layer configuration. The thickness and thermal properties for each material in a construction buildup are defined, and the overall elemental thermal properties calculated from this. The sources for the thermal properties detailed in this section as are follows:

- Double glazing was present in all the case study buildings. The thermal properties for this were selected from the software standard for double glazing obtained from Pilkington glass manufacturers.
- The ground floor slabs were assumed to be an uninsulated connection as is common for buildings of this age.
- The internal floors were assumed wooden joists with wooden floorboards covering, with insulation installed in the case of the ceiling, this was obtained during building inspections.
- The construction of the walls was determined by a mixture of investigation and consultation with the building occupants and landlords.
    - In the manual controlled building by a measurement of the depth of the wall and using the stone construction materials in the dynamic thermal modelling program to calculate the walls thermal properties.
    - Past building work photographs were used to determine the wall construction of the timed controlled building with the wall thermal properties calculated in the same way as the manually controlled building.

  - The modern insulated wall of the temperature controlled building was established through observation when the glazing was replaced shortly before the experimental monitoring occurred.

These building thermal properties will be validated using a comparison in building thermal performance between the experimental case studies and the dynamic thermal models.

3.5 Manual Control

The manually controlled building is an end of terrace home with a manually controlled decentralised electric storage heating system. This section will cover the reasons for selecting this building for the study followed by defining the building geometry and construction. The heating system of the building will then be discussed followed by a description of the internal gains.

Figure 3.3 shows an aerial view of the manually controlled building with the surroundings for site context.

Figure 3.3 Site of building for the manually controlled building (Google, 2015).

Figure 3.3 shows that the rear of the building faces west and the lounge windows facing east. The Northern exposure is a solid wall with the southern exposure having a party wall with the adjoining property. There are very few obstructions around the building with an open beer garden to the north, open road to the east and a garden to the west with trees at the end, but these do not overshadow the home.

The outside of the manually controlled building is shown in Figure 3.4.

Figure 3.4 External elevation of the manually controlled building (Google, 2015).

Figure 3.4 shows the building setting with the eastern side of the building including the living room and bedroom 1 windows. Demarcation lines are provided to show to indicate the boundary between the manually controlled building and the adjacent property.

The building has a solid wall construction with double glazed windows. The heating system differs from the other two case study buildings and so makes this building an appropriate choice for a case study.

The internal layout consists of two bedrooms (one unused), one bathroom, one kitchen and one living room. The building has decentralised electric storage heaters in each room except the living room which has a coal fireplace and no heater. The occupants both work variable shift patterns which are reflected in the schedules.

The building layout and geometry will be discussed in Section 3.5.1.

3.5.1 Building Geometry

The home is split over two floors with the living room and kitchen on the ground floor, bathroom and bedrooms on the first floor. Figure 3.5 shows the ground floor and first floor plans of the building.

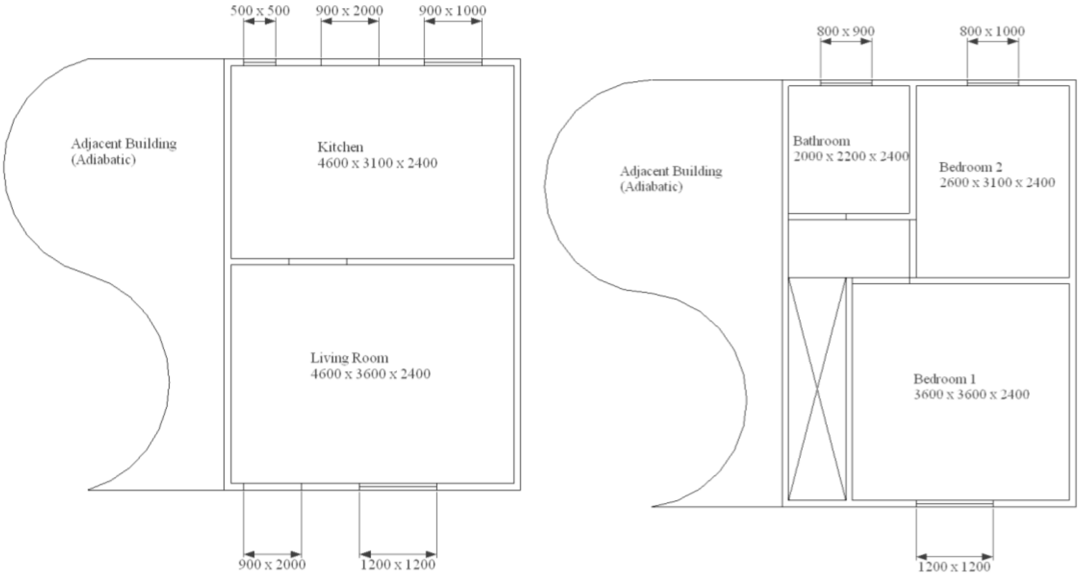

Figure 3.5 Ground floor and first floor plans for the manual control building respectively.

Figure 3.5 shows the adjacent building sharing a party wall with the kitchen and living room which is held adiabatically within the dynamic thermal simulation. The staircase to the first floor is in the living room with a fireplace on the right hand wall that is lit during winter to provide heat to the living room. Bedroom 2 is primarily used for storage with bedroom 1 being occupied. Again the adjacent building is shown with the adiabatic party wall.

This building geometry is generated with the dynamic thermal modelling program and pictorially shown in Figure 3.6.

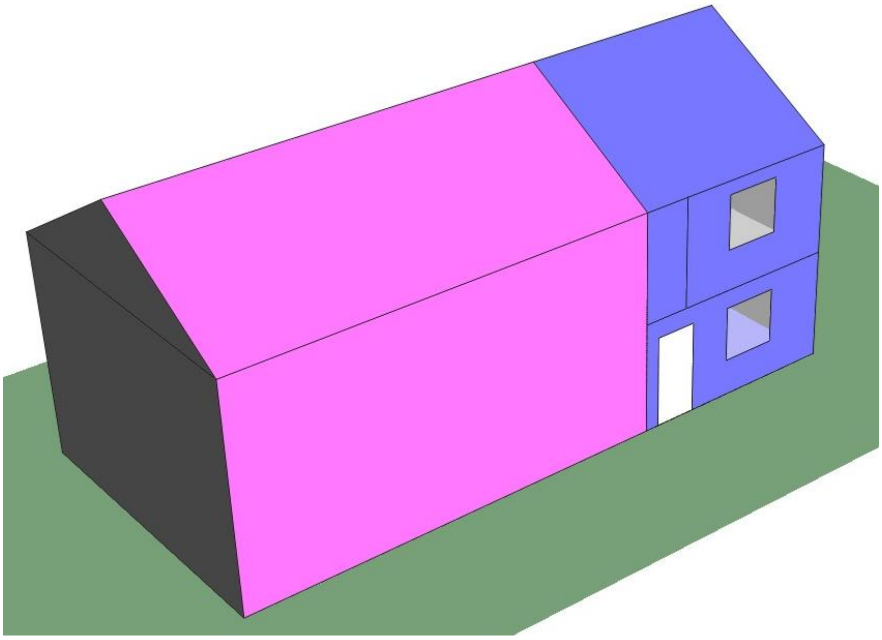

Figure 3.6 Geometrical representation in dynamic thermal modelling software of the manual control building.

Figure 3.6 shows the manually controlled building in purple indicating the thermal zones which will be simulated. The adjacent building is indicated in pink in the image which corresponds to the adiabatic state it is held so no heat transfer occurs through the party wall, it provides shading to the manual control building however.

The building construction and thermal properties will now be discussed in Section 3.5.2.

3.5.2 Building Construction and Thermal Properties

The thermal properties of the opaque and glazed building elements for the manually controlled building are detailed in Table 3.1. Table 3.1 provides the thermal transmittance (U-Value) of each opaque building element.

Table 3.1 Construction U-Values of the building elements for the manual control building.

Construction Element	U-Value (W/m^{2}K)	G-Value	Visible light Transmittance
Roof	0.34	-	-
Wall	1.52	-	-
Door	2.19	-	-
1st Floor	1.55	-	-
Ground Floor	0.25	-	-
Glazing	1.98	0.64	0.76

Table 3.1 shows the external wall to have a particularly poor U-Value due to the construction being of solid stone with no insulation. The wall is very heavyweight with high thermal mass which would help provide cool conditions in the summer but be susceptible to poor heat retention in the winter. The glazing to have a good thermal transmittance value but a high G-Value which indicates low solar performance.

The manually controlled building is expected to have a poor thermal performance as the walls are of a solid wall construction with no insulation, although the windows are double glazed. The building is expected to have one of the worst thermal performances within this case study group.

The heating system description for the manual control building will now be discussed in Section 3.5.3.

3.5.3 Heating System Description

Electric storage heaters use offpeak electricity to provide a heat charge to the indoor unit during offpeak times. This heat is stored in the room unit and released gradually during the day. This offpeak charging of the room unit allows a lower price tariff to be used for the electricity for heating which lowers the occupants heating cost. Homes with this type of heating system use an electricity tariff called Economy 7 where the home has two tariffs.

Figure 3.7 shows a schematic of the electrical supply for electric storage heaters.

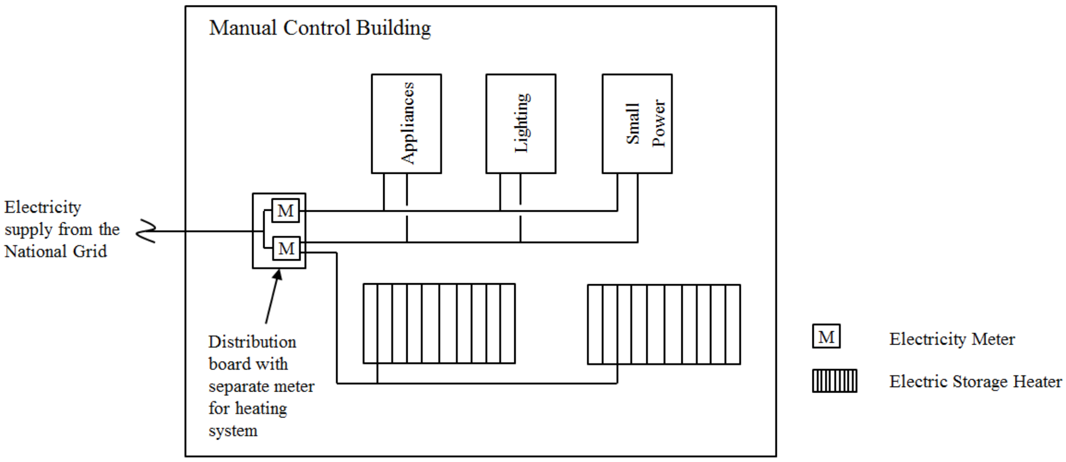

Figure 3.7 Schematic representation of off-peak electricity supply for electrical storage heaters.

Figure 3.7 shows the mains electricity supply going to two separate meters, one peak meter and one off peak meter. The entire home is connected to the offpeak meter and so during these hours everything has a lower tariff and the appliances, lighting and small power can run during peak hours whereas the domestic heating system cannot.

The electric storage heater has two dials, an output and input dial. The output dial controls the amount of heat available to the room which should be adjusted to provide instant occupant comfort. A low setting should be used to release small amounts of heat over a long period of time with a high setting providing a boost of heat but will deplete the stored heat in the room unit faster. The heat output is controlled by means of a damper which regulates the rate of heat loss from the unit.

The input dial controls the amount of electricity the heater will consume overnight and thus the amount of heat available for the following day. The outer case of the storage heater is heavily insulated and heat is stored within bricks which the heating elements run through.

Figure 3.8 details the component parts of a typical electric storage heater.

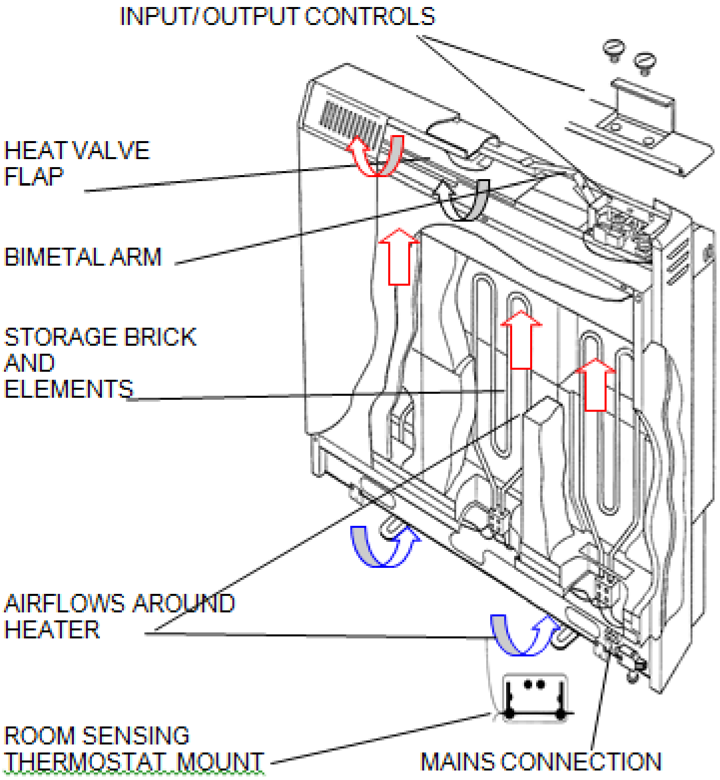

Figure 3.8 Schematic of storage heater with in-built automatic heat damper (StorageHeaters, 2015).

Figure 3.8 indicates the cool air entering the bottom of the heater and passing through the bricks with warm air passing out of the top, heating the room by convection.

Modern storage heaters can be thermostatically controlled by the use of a bi-metallic arm to control the storage heater output during the day, as the room cools the arm will contract releasing more heat to maintain a constant room temperature as well as being fan assisted. In this study however the heaters were basic and contained only manual input and output settings.

A schematic representation of the heating system installed in the manual control building is shown in Figure 3.9.

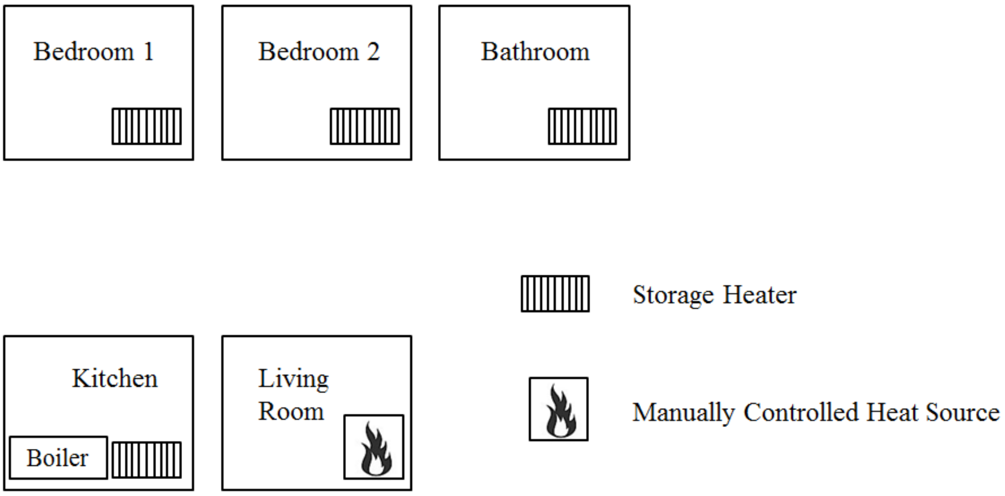

Figure 3.9 Schematic representation the manual heating system in the case study building.

Figure 3.9 shows each room having its own electric storage heater, except the living room which has a coal fire.

This method of heating is labour intensive as it requires each room to be manually controlled, turning the output of the heater down overnight and during unoccupied periods and then back up during occupied periods and high when a boost is required.

The internal gains for the manual control building will now be discussed in Section 3.5.4.

3.5.4 Internal Gains

The internal gains are split into lighting, small power, occupant and miscellaneous gains. Each are tabulated in turn with the schedule in which they are applied to the dynamic thermal model. The first gain considered in Table 3.2 are the lighting gains.

Table 3.2 Room Lighting Gains

Room	Value (W)	Daily Schedule
Living Room	50	18:00 – 22:00
Kitchen	50	07:00 – 08:00, 18:00 – 19:00
Master Bedroom	50	07:00 – 08:00, 23:00 – 23:30
Bedroom 2	50	20:00 – 22:00
Bathroom	30	07:00 – 08:00
Landing	-	-

Table 3.7 show a lighting gain attributed to bedroom 2 despite it not being occupied. This was to account for the occupants infrequently using the room but at times perhaps for extended periods of time. Lighting was only considered in the bathroom during the morning as that is when morning ablutions took place so the lights were on for a significant length of time.

The next internal gain considered is the small power see Table 3.3.

Table 3.3 Room Small Power Gain

Room	Value (W)	Daily Schedule
Living Room	100	18:00 – 22:00
Kitchen	-	-
Master Bedroom	-	-
Bedroom 2	-	-
Bathroom	-	-
Landing	-	-

Small power in the domestic scenario is electrical appliances such as computers and televisions which emit only sensible heat. The bathrooms and transient spaces have no small power considered for heat gains (items such as vacuum cleaners, electric shavers) as their heat gain is unpredictable and small compared to other sources of heat.

Table 3.4 details the occupancy considerations for the building.

Table 3.4 Room Occupancy Gain

Room	**Sensible (W)**	**Latent (W)**	**Daily Schedule**
Living Room	70	45	18:00 – 22:00
Kitchen	70	45	07:00 – 08:00, 18:00 – 19:00
Master Bedroom	35	22.5	23:00 – 08:00
Bedroom 2	-		20:00 – 22:00
Bathroom	70	45	07:00 – 08:00
Landing	-	-	-

The occupants of this building are a young couple who work in a varying shift pattern. Occupancy was allocated to both bedroom 1 and the living room during the evening as with the varying shift patterns, sometimes including unexpected night shifts, both rooms could potentially be occupied during those times.

The final gains covered in the study are the kitchen and miscellaneous gains from equipment, cooking and the living room fire in Table 3.5.

Table 3.5 Miscellaneous Gains

Gain	**Sensible (W)**	**Latent (W)**	**Schedule**
Fridge / Freezer	156 / 64	-	Continuous
Burners (4)	-	1930	18:00 – 19:00
Oven	100	-	18:00 – 19:00
Toaster / Kettle	1310 / 440	1160 / 230	07:00 – 07:03
Living Room Fire	-	-	-

A continuous background gain is allocated for the fridge / freezer within the kitchen with the other cooking gains only included when food preparation would be completed. Even though the occupants worked variable shifts, the cooking was allocated at more traditional times so the gains were always included, however the cooking could potentially be at different times depending on the shift. The living room is heated by a coal fire which was sometimes lit if the occupants were at home during the same time on an evening. The exact times of this however could not be determined and so this coal fire was emitted from the dynamic thermal simulation.

3.6 Timed Control

The second case study is of a single zone central heating system building with boiler mounted timeclock control. This section will cover the reasons for selecting this building for the study followed by defining the building geometry and construction. The heating system of the building will then be discussed followed by a description of the internal gains.

The timed control building is located within a village in West Yorkshire. Figure 3.10 shows an aerial view of the timed control building with the surrounding site for context.

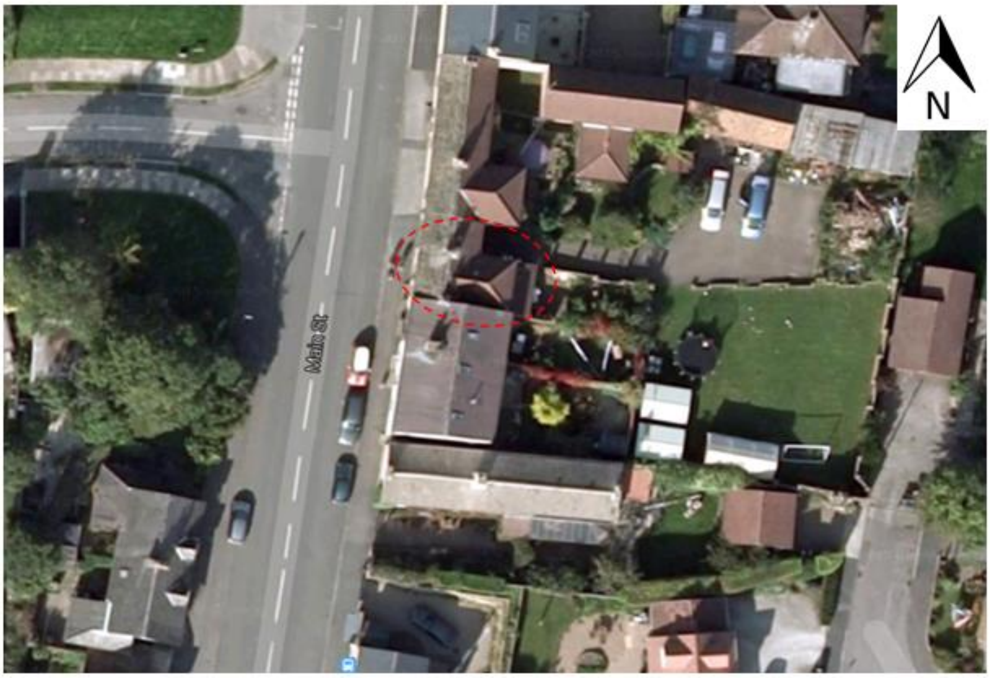

Figure 3.10 Site of the building for the timed controlled building (Google, 2015).

Figure 3.10 shows the rear of the building with the kitchen facing east and the lounge windows facing west. The northern and southern exposures are party walls with adjoining property. There are very few obstructions around the building with an open a small garden to the east with short trees which do not provide any overshadowing to the building façade.

The outside of the timed controlled building is shown in Figure 3.11.

Figure 3.11 External elevation of the timed controlled building (Google, 2015).

As can be seen in Figure 3.11, the building is a small stone terraced cottage. It has a traditional solid wall construction with a modern extension at the rear. The cottage consists of two bedrooms, bathroom, living room, kitchen and cellar. The building has a gas fired central heating system with thermostatic radiator valves in each room. There is no thermostatic control, the heating control is from the boiler with fine tuning using the TRVs in each room. One occupant works Monday to Friday five days a week while the second works a shift pattern.

The building layout and geometry will now be discussed in Section 3.6.1.

3.6.1 Building Geometry

The building is split over three floors. The basement is used only for storage and not suitable for habitation. The ground floor has the kitchen and living room with two bedrooms and a bathroom on the second floor. Figure 3.12 indicates the basement and ground floor dimensions.

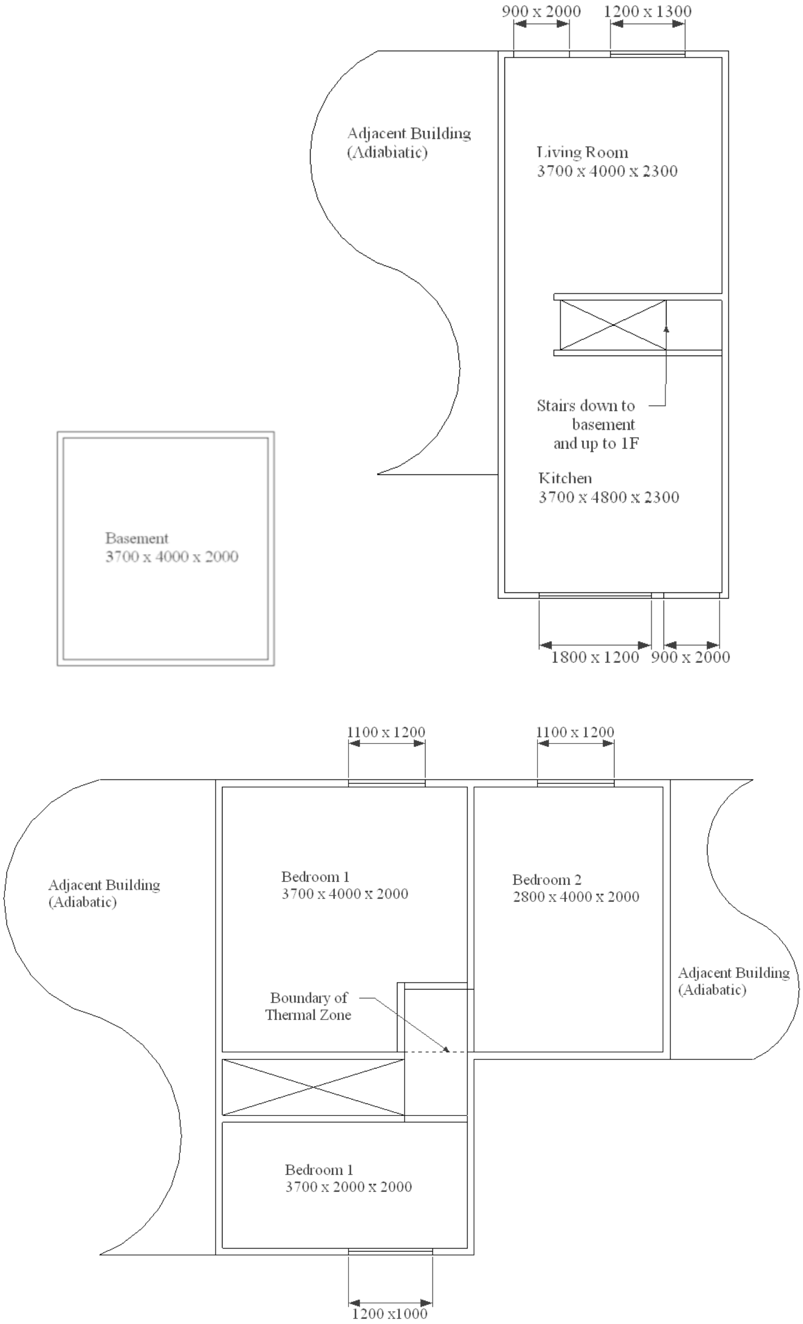

Figure 3.12 Basement and ground floor plan for the timed control building respectively.

The basement has a solid stone wall construction and is uninhabited, within this building it is solely used for storage. The ground floor plan shows the adjacent building connected to the ground covering the living room and kitchen which is held adiabatically in the simulation. The staircase in the centre of the floorplan goes down the basement as well as up to the first floor.

There are adjacent buildings to either side of the first floor plan in this terrace arrangement. The floor below bedroom 2 is external with significant heat transfer through it.

Figure 3.13 is the geometric representation of the timed control building in dynamic thermal modelling software.

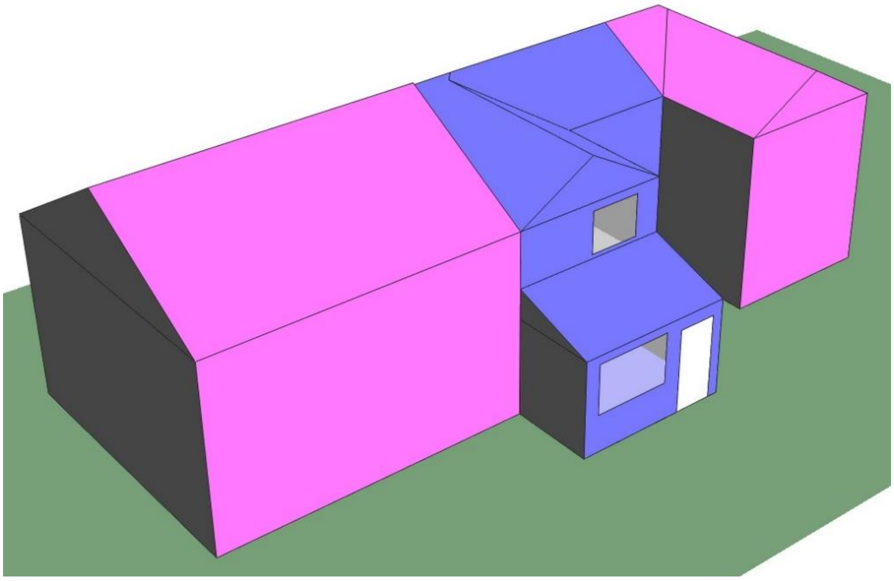

Figure 3.13 Geometrical representation in dynamic thermal modelling software of the timed controlled building.

Figure 3.13 shows the timed controlled building with adjacent buildings on both sides and bedroom 2 above an entrance archway adjacent to the right hand side building.

The timed controlled building construction and thermal properties will now be discussed in Section 3.6.2.

3.6.2 Building Construction and Thermal Properties

The thermal properties of the opaque and glazed building elements for the timed control building are detailed in Table 3.6. Table 3.6 provides the thermal transmittance (U-Value) of each opaque building element.

Table 3.6 Construction U-Values of the building elements for the timed controlled building

Construction Element	**U-Value (W/m^{2}K)**	**G-Value**	**Visible light Transmittance**
Roof	0.58	-	-
Wall 1	1.92	-	-
Wall 2	0.35	-	-
Window	1.98	-	-
Door	2.19	-	-
1st Floor	2.28	-	-
Ground Floor	0.25	-	-
Glazing	1.98	0.64	0.76

Table 3.6 shows the two external wall construction U-values. The first value is for the majority of the cottage with the second higher U-Value used for the small kitchen extension seen on the rear of the house. The glazing has a good thermal transmittance value but a high G-Value which indicates low solar performance in line with most domestic double glazing installed in the UK.

It can be seen that the thermal performance of this building in terms of U – Value is similar to the manually controlled building with solid wall construction, limited loft insulation and double glazing throughout. However there is much more glazing area and with the extra external walls formed by the cellar and raised bedroom above the archway, it provides a lot more area for heat loss. There is a small extension of modern construction on the kitchen but this forms a relatively small are of the home.

The heating control system for the timed controlled building will now be presented in Section 3.6.3.

3.6.3 Heating System Description

The heating system in the timeclock controlled building is a gas fired central heating system controlled by a timeclock on the boiler unit. A schematic of the timeclock central heating system is presented in Figure 3.14.

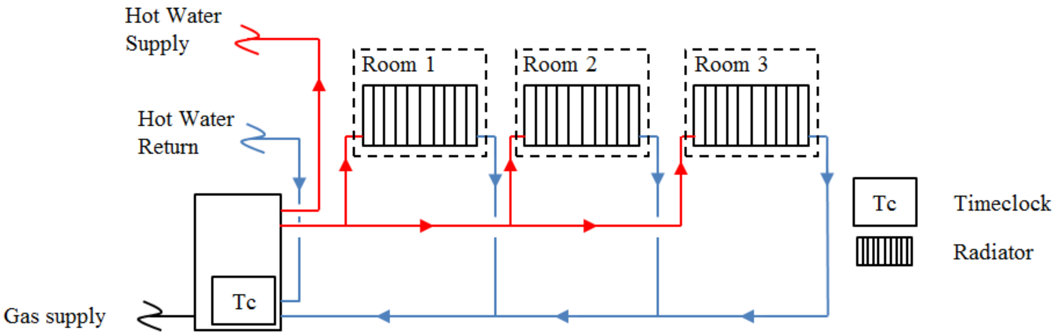

Figure 3.14 Schematic representation of the gas fired central heating system.

Figure 3.14 shows the gas fired boiler with integral pump feeding hot water to the central heating system. The boiler heats up the water contained within the closed loop heating system and circulates via a circulating pump. This passes through the radiators in each room which emit heat by convection to provide thermal comfort to the occupants.

This is controlled by the timeclock on the boiler which determines when the boiler fires and the circulating pump is switched on. This is set by using a series of pins around the outside which are pushed in next to the times which one requires heating on and pushed out at the times when one does not require heating. The heating is then set to automatic to follow this program or can be overridden on or off depending on the user requirements. Each radiator is fitted with a thermostatic radiator valve (TRV) to regulate the hot water flow reate through the radiator to provide local control to the heat output of each radiator. Figure 3.15 shows a typical boiler timeclock TRV.

Figure 3.15 Mechanical boiler timer showing the control face (Which, 2015) and TRV showing the room temperature setting scale (Danfoss, 2015).

Figure 3.15 shows the control pins pushed in all the way around which corresponds in this case with heating on constantly. The small switch at the bottom corresponds to the boiler following the timeclock if it is at the left, off if it is in the centre and on all the time if it is on the right. The clock face in the centre of the boiler dial is set to match the current time, this must be adjusted manually to account for daylight savings as appropriate.

Figure 3.15 shows the TRV which was installed directly onto the radiator in each room. This is manually set to a degree of heating (1-5) to control the amount of heat given out in that room by controlling the water flow to those radiators using a gas or wax plug. This plug senses the room temperature and expands to reduce the water flow to the radiator and limit the heat the radiator gives out as the room heats up. This allows some degree of heat regulation to each room however it is manual and heat can only be provided to that room whilst the whole heating system is running. A schematic representation of the heating system installed in the timed controlled building is shown in Table 3.11.

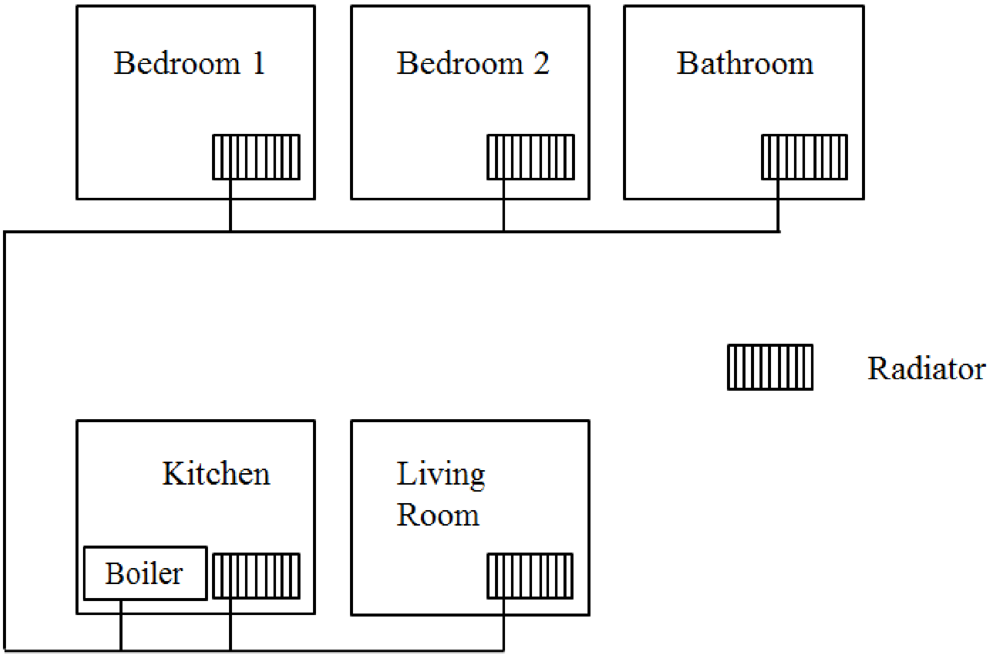

Figure 3.16 Schematic representation of the central heating system with a boiler based control.

Table 3.11 shows no thermostatic control within the heating system. The heating power is on a scale from 1-6 set using a dial on the boiler, with 1 being minimum heat and 6 being maximum heat. Within this case study the heating was either on or off with no time based schedule applied due to the occupants lack of knowledge on how to use a timeclock.

The internal gains for the timed controlled building will now be discussed in Section 3.6.4.

3.6.4 Internal Gains

The internal gains are split down into lighting, small power, occupant and miscellaneous gains. Each are tabulated in turn with the schedule in which they are applied to the dynamic thermal model. The first gains considered in Table 3.7 are the lighting gains.

Table 3.7 Room Lighting Gains

Room	Value (W)	Daily Schedule
Basement	-	-
Living Room	50	08:30 – 09:00, 18:00 – 22:00
Kitchen	50	08:00 – 09:00, 18:00 – 19:00
Bathroom	30	08:00 – 09:00, 18:00 – 18:30
Master Bedroom	50	08:00 – 09:00, 22:00 – 23:30
Bedroom 2	50	21:00 – 22:00
Landing	-	-

Table 3.7 shows no lighting gain to the basement. This is because it is used for storage and rarely visited so was not allocated any gains. Transitional spaces were not given lighting gains as these transient spaces are only lit whilst the occupants move through them and so their significance in the simulation is small compared to the other gains. Lighting was only considered in the bathroom during the morning and evening as one of the occupants worked in a physical job and so ablutions took place in the morning and evening.

The next internal gain considered is small power in Table 3.8.

Table 3.8 Room Small Power Gain

Room	Value (W)	Daily Schedule
Basement	-	-
Living Room	100	08:30 – 09:00, 18:00 – 22:00
Kitchen	-	-
Bathroom	-	-
Master Bedroom	100	22:00 – 23:30
Bedroom 2	-	-
Landing	-	-

Table 3.8 shows the bathrooms and transient spaces have no small power considered for heat gains (items such as vacuum cleaners, electric shavers, etc.) as their heat gain is unpredictable, short duration and small compared to other sources of heat. Small power

in domestic scenarios are electrical appliances such as computers and televisions which emit only sensible heat.

Table 3.9 details the occupancy consideration for the building.

Table 3.9 Room Occupancy Gain

Room	Sensible (W)	Latent (W)	Schedule
Basement	-	-	-
Living Room	70	45	08:30 – 09:00, 18:00 – 22:00
Kitchen	70	45	08:00 – 09:00, 18:00 – 19:00
Bathroom	70	45	08:00 – 09:00, 18:00 – 18:30
Master Bedroom	35	22.5	22:00 – 08:00
Bedroom 2	-	-	-
Landing	-	-	-

Table 3.9 shows no occupancy allocated to bedroom 2 as this is a spare bedroom and rarely used. Occupancy is allocated all day to the living room and kitchen twice per week as one of the occupants works shifts and has two days off per week.

The final gains covered in the study are the kitchen miscellaneous gains from equipment and cooking detailed in Table 3.10.

Table 3.10 Kitchen Miscellaneous Gains

Gain	Sensible (W)	Latent (W)	Schedule
Fridge / Freezer	156 / 64	-	Continuous
Burners (4)	-	1930	18:00 – 19:00
Oven	100	-	18:00 – 19:00
Toaster / Kettle	1310 / 440	1160 / 230	08:30 – 08:33

Table 3.10 shows a continuous background gain allocated for the fridge / freezer within the kitchen with other cooking gains only included when food preparation would be completed. The equipment heat gain values are taken from CIBSE Guide A – Environmental Design (CIBSE, 2009).

3.7 Temperature Control

The temperature controlled building is a semi-detached home with a heating system controlled by a programmable thermostat. This section will cover the reasons for selecting this building for the study followed by defining the building geometry and construction. heating system of the building will then be defined followed by a description of the internal gains and miscellaneous variables which contribute to modelling uncertainty.

Figure 3.17 shows an aerial view of the temperature control building with the surroundings for site context.

Figure 3.17 Site of building for the temperature controlled building (Google, 2015).

Figure 3.17 shows that the rear of the building faces north and the kitchen windows faces south. The east façade has the living room windows and patio doors with the garage covering the west. There are very few obstructions surrounding the building, a public house carpark to the rear with a low wall and short trees to the east in the garden.

The outside of the STCB is shown in Figure 3.18.

Figure 3.18 External elevation of the temperature controlled building with demarcation line for adjacent building (Google, 2015).

Figure 3.18 shows the building setting with the kitchen and bedroom 1 and bedroom 2 windows. Demarcation lines are provided to indicate the boundary between the temperature control building and the adjacent property.

The building has an insulated cavity wall with double glazed windows. The wall construction differs from the other two case study buildings and so makes this building an appropriate choice for a case study.

The internal layout consists of three bedrooms (one used as a study), two bathrooms, living room, kitchen and garage. The building has a gas fired central heating system with thermostatic radiator valves in each room and thermostatic control from the living room. The occupant works 9-5 Monday to Friday which is reflected in the heating schedule.

The building layout and geometry will now be discussed in Section 3.7.1.

3.7.1 Building Geometry

The home is split over two floors with the living room and kitchen on the ground floor, bathrooms and bedroom on the first floor.

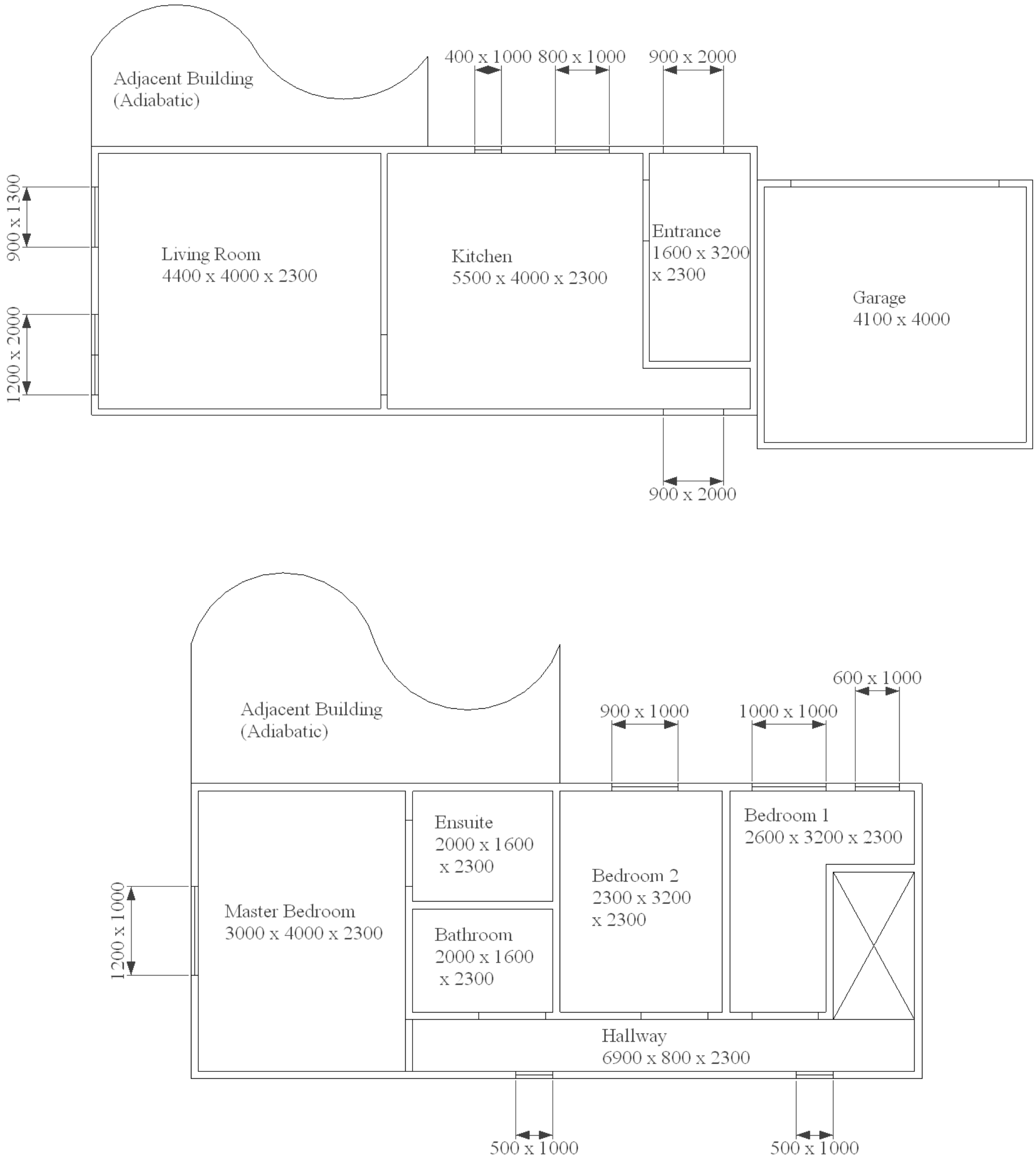

Figure 3.19 Ground floor and first floor plan for the temperature control building respectively.

Figure 3.19 shows the adjacent building is shown adjoining the living room. Within the dynamic thermal model this party wall is held adiabatically with respect to the case study building so no heat transfer occurs between the buildings. The garage is an untreated space but is included as it provides shading from solar gains which would fall on the western wall. Bedroom 2 is primarily used as a home office for the occupant with intermittent use. The adjacent building is shown on the first floor as it connects to the case study building all the way to the roof, thus providing an adiabatic party wall and blocking solar gains.

This building geometry is generated with the dynamic thermal modelling program and pictorially shown in Figure 3.20.

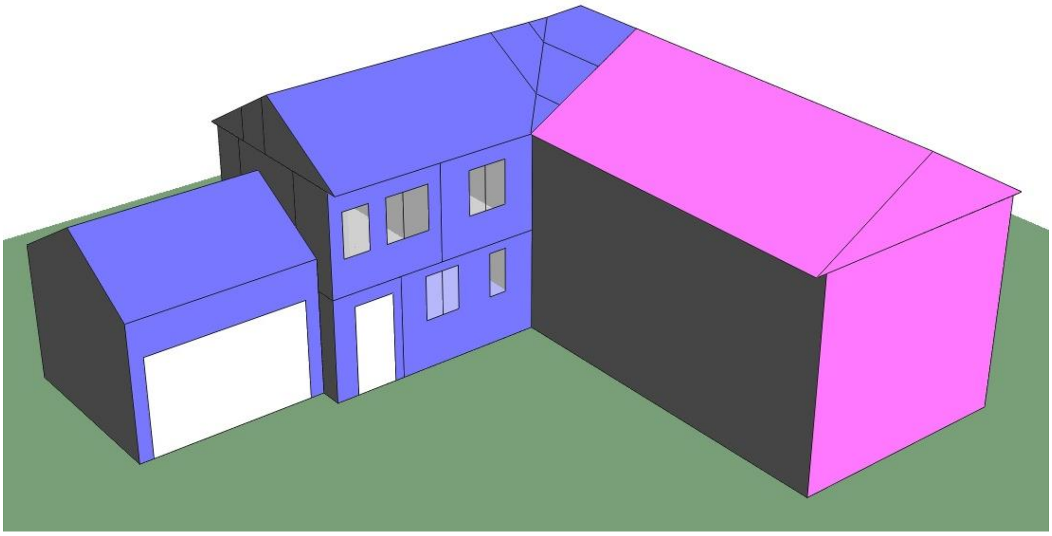

Figure 3.20 Geometrical representation in dynamic thermal modelling software of the temperature controlled building.

Figure 3.20 shows the temperature controlled building in purple indicating the thermal zones which will be simulated. The garage is included in this but is untreated and so is a free running space connected to the building, thus preventing any solar effect on the western wall. The adjacent building is indicated in pink in the image corresponding to the adiabatic state so no heat transfer occurs through the party wall, however it provides shading to the temperature controlled building.

The time controlled building construction and thermal properties will now be discussed in Section 3.7.2.

3.7.2 Building Construction and Thermal Properties

The thermal properties of the opaque and glazed building elements for the temperature controlled building are detailed in Table 3.11 which provides the thermal transmittance (U-Value) of each opaque building element.

Table 3.11 Construction U-Values of the opaque elements for the temperature controlled building.

Construction Element	U-Value (W/m^{2}K)	G-Value	Visible light Transmittance
Roof	0.18	-	-
Wall	0.35	-	-
Window	1.98	-	-
House Door	2.19	-	-
Garage Door	5.88	-	-
1st Floor	1.55	-	-
Ground Floor	0.25	-	-
Glazing	1.98	0.64	0.76

Table 3.11 shows the garage door having a very high thermal transmittance. This however connects to an unconditioned space and so has very little impact on the results. The glazing has a good thermal transmittance value but a high G-Value which indicates low solar performance.

The temperature controlled building has a much higher thermal performance than the previous two buildings, being of modern construction with cavity wall insulation and double glazing throughout the whole building. This building is expected to have the best thermal performance of the case study group.

The heating system for the temperature controlled building will now be presented in Section 3.7.3.

3.7.3 Heating System Description

The temperature controlled case study uses a digital programmable thermostat to control the occupants heating system. The heating system is a gas fired central heating system with the same components as the time controlled heating system in Section 3.6 with the addition of a thermostat rather than boiler mounted timeclock controls. The remote thermostat is shown in Figure 3.21.

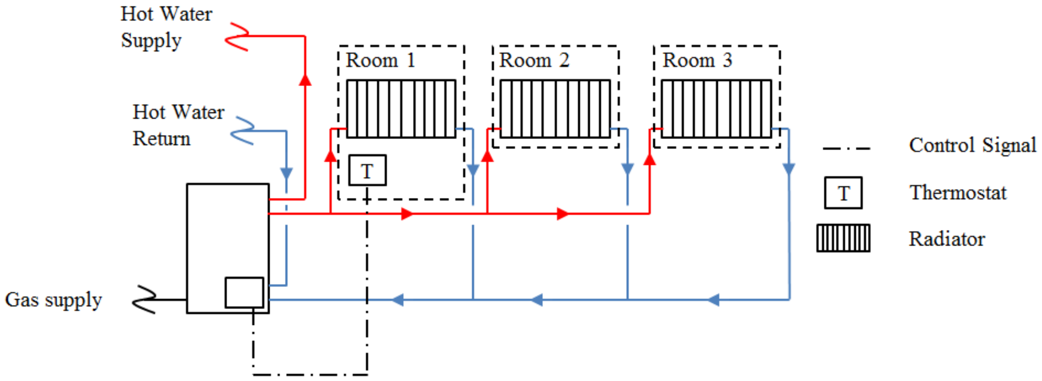

Figure 3.21 Schematic representation of thermostatically controlled domestic heating system.

Figure 3.21 shows the room thermostat connected to the boiler with a control signal indicating if the boiler should fire. In this study the room thermostat is in the living room and signals for heat when the ambient room temperature falls below a pre-set threshold.

A digital thermostat uses a thermistor to measure the room temperature which works by its electrical resistance changing with temperature. The microcontroller within the digital thermostat can then convert this resistance into a temperature value which in the domestic case is the ambient room temperature. This value is used to determine if the heating should be switched on or off.

A digital thermostat can have a different schedule for each day of the week along with other overriding settings such as heating boost, holiday setback, etc. In this study the occupant made basic use of the program features, setting one schedule which was used on every day of the week but using the boost function when the occupant felt cold. A schematic representation of the heating system installed in the temperature controlled building is shown in Figure 3.22.

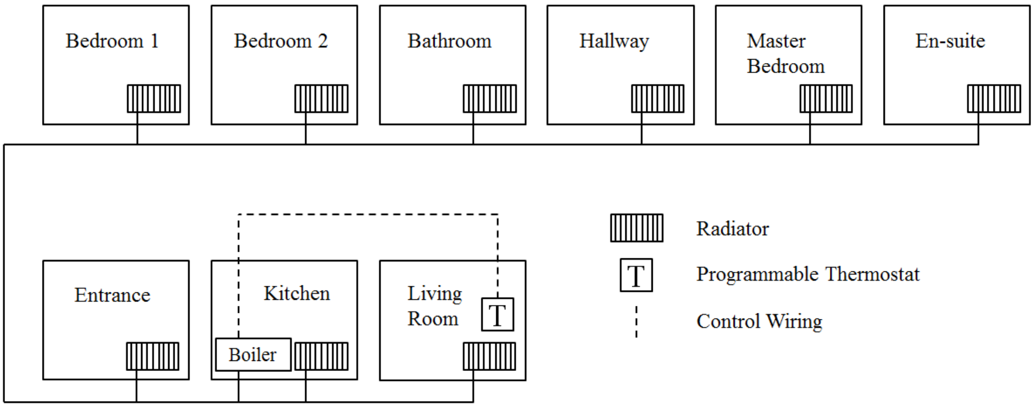

Figure 3.22 Simplified schematic representation of the single zone thermostatically controlled heating system.

Figure 3.22 shows the controlling programmable thermostat located in the living room. This provides the control signal to the boiler located in the kitchen controlling when the heating system is on or off. Every other room is a slave to the controller in the living room and only receives heat when the living room requires it. With the programmable thermostat, both the temperature and time can be set to control the heating system. In this case the heating setpoint was 18°C and the timing of the heating was from 07:00 – 08:30 and 17:00 – 23:00 7 days per week.

The internal gains for the temperature controlled building will now be discussed in Section 3.7.4.

3.7.4 Internal Gains

The internal gains are split into lighting, small power, occupant and miscellaneous gains. Each are tabulated in turn with the schedule in which they are applied to the dynamic thermal model. The first gains considered in Table 3.12 are the lighting gains.

Table 3.12 Room Lighting Gains

Room	Value (W)	Daily Schedule
Entrance Hall	-	-
Kitchen	50	06:30 – 08:00, 18:00 – 20:00
Living Room	50	18:00 – 22:30
Bedroom 1	50	06:30 – 07:30, 22:30 – 23:30
Bedroom 2	50	06:30 – 07:30, 18:00 – 23:30
Master Bedroom	50	06:30 – 07:30, 22:30 – 23:30
En-suite	30	07:00 – 08:00
Bathroom	30	07:00 – 08:00
Hallway	-	-

Table 3.12 shows no lighting gain for a number of transient spaces. This is because transient spaces only have their lighting turned on whilst occupants move through them which is only for a considerably short space of time and so was deemed as insignificant compared to the other gains within the home. Lighting was only considered in the bathrooms during the morning as that is when morning ablutions took place so the lights were on for a significant length of time.

The next internal gain considered is small power in Table 3.13.

Table 3.13 Room Small Power Gain

Room	Value (W)	Daily Schedule
Entrance Hall	-	-
Kitchen	-	-
Living Room	100	18:00 – 22:30
Bedroom 1	-	-
Bedroom 2	100	18:00 – 23:30
Master Bedroom	100	22:30 – 23:30
En-suite	-	-
Bathroom	-	-
Hallway	-	-

Small power in the domestic scenario is electrical appliances such as computers and televisions which emit only sensible heat. The bathrooms and transient spaces have no small power considered for heat gains (items such as vacuum cleaners, electric shavers) as their heat gain is unpredictable, short duration and small compared to other sources of heat.

Table 3.14 details the occupancy considerations for the building.

Table 3.14 Room Occupancy Gain

Room	Sensible (W)	Latent (W)	Schedule
Entrance Hall	-		-
Kitchen	70	45	06:30 – 08:00, 18:00 – 20:00
Living Room	70	45	18:00 – 22:30
Bedroom 1	-	-	-
Bedroom 2	70	45	18:00 – 22:30
Master Bedroom	35	22.5	22:30 – 07:30
En-suite	70	45	07:00 – 08:00
Bathroom	70	45	07:00 – 08:00
Hallway	-	-	-

The occupant of this building is a single male working full time. Occupancy was allocated to both Bedroom 2 and the Living Room during the evening as the occupant would regularly work in that bedroom during those hours. Without the schedule of this out of hours work being fixed a gain in both rooms was included in the study.

The final gains covered in the study are the kitchen miscellaneous gains from equipment and cooking detailed in Table 3.15.

Table 3.15 Kitchen Miscellaneous Gains

Gain	Sensible (W)	Latent (W)	Schedule
Fridge / Freezer	156 / 64	-	Continuous
Burners (4)	-	1930	18:00 – 19:00
Oven	100	-	18:00 – 19:00
Toaster / Kettle	1310 / 440	1160 / 230	07:00 – 07:03

A continuous background gain is allocated for the fridge / freezer within the kitchen with the other cooking gains only included when food preparation would be completed. The equipment heat gain values are taken from CIBSE Guide A – Environmental Design (CIBSE, 2009).

The miscellaneous variables which affect the accuracy of the case study buildings outlined in Sections 3.5,3.6 and 3.7 will now be discussed in Section 3.8.

3.8 Miscellaneous Variables

Within all the case studies, the dynamic thermal models have fixed schedules and the inputs are pre defined for each case study and so behave in a predictable way. The scenarios that they are simulating however have changing inputs which cannot be fully incorporated within the dynamic thermal model and this leads to uncertainties in the results.

For example the heating system has the ability to be boosted manually for one hour to 21°C. This can be done intermittently and unpredictably. In addition to this the heating and some internal gains can be removed if the house is unattended for an extended period of time.

Occupancy is defined within the dynamic thermal models in fixed schedules where as occupancy can vary on any given day due to changes within the occupants work schedules or non-regular activities such as cleaning or working from home.

A comparison of the case study buildings discussed in Sections 3.5,3.6 and 3.7 will now be presented in Section 3.9.

3.9 Comparison of the Simulation Variables

The main simulation variables which have the largest impact on the thermal performance of the case study buildings are compared in Table 3.16 to highlight the differences between each case study building.

Table 3.16 Comparison of the physical properties and inputs of the three case study houses.

	Building Element	Manual Control	Timed Control	Temperature Control
U-Value (W/m^{2}K)	Roof	0.34	0.58	0.18
	Wall	1.52	1.92 / 0.35	0.35
	Window	1.98	1.98	1.98
Area (m^2)	Internal Floor	61.6	68.9	76.8
	External Wall	76.3	49 / 15.5	92.1
	External Window	5.6	6.4	9.5
	Roof	35.6	49.8	50.81
Internal Gains (W/m^2)	Lighting	4.1	3.7	4.7
	Small Power	6	13.5	8.5
Occupancy (Number)	-	2	2	1

Table 3.16 shows a comparable roof U-Value for each building as they had retrofitted loft insulation in each case although with varying degrees of thermal resistance and thickness. The largest difference is within the wall constructions where the temperature controlled building has considerably better thermal performance than the timed controlled building and the manually controlled building due to construction techniques. All houses had retrofitted double glazing which is reflected in the same U-Value for each.

The building types have progressively larger internal floor areas, however the external wall areas do not follow this pattern due to the building setting. The manually controlled building is an end terrace with large exposed wall areas whereas the timed control building is a mid terrace with adiabatic connections at two sides of the building, the temperature controlled building is a semi-detached home similar to the manually controlled building. The manually controlled building and the time controlled building have similar external window areas where as the temperature controlled building has over 50% more glazing than the other two properties, being of modern construction. In this case the external patio doors of the temperature controlled building were included in the window area as they are of the same construction and fully glazed.

When comparing the internal gains of the three homes, the lighting doesn't vary a large amount but slight differences are driven by variations in floor area which have the same light source (i.e. one 50W bulb). The small power however varies considerably and does not correlate with the number of occupants. This is due to the number of electronic appliances in each home which is driven by occupant preference rather than the building type or size.

A comparison of the simulations has been established with the difference between each case study building highlighted. A comparison between each control strategy will now be presented, highlighting how each strategy differs.

3.10 Comparison of Control Strategies

Each case study building has a different control strategy as identified in Sections 3.5, 3.6 and 3.7 and are compared beside each other in Figure 3.23.

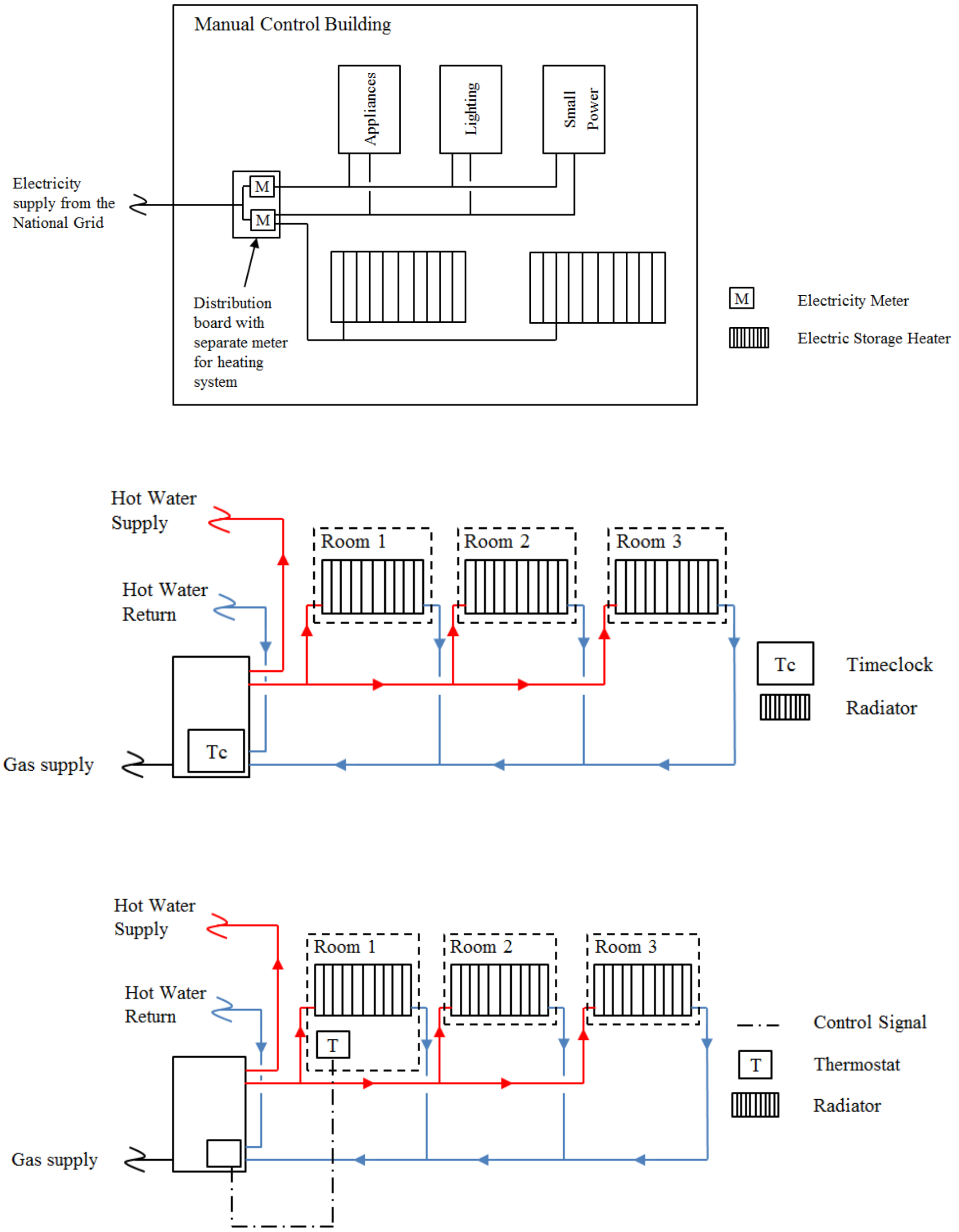

Figure 3.23 Comparison of the manual controlled, timed controlled and temperature controlled heating systems respectively.

The manually controlled heating system consists of a decentralised manually controlled heating system. There is no central control as there is with the timed and temperature controlled systems. Each heater is controlled locally with an electrical input and heat output setting. There is no thermostatic or time based control so the heater is always on and if the occupants leave and want to reduce the heating or turn it off, this has to be done manually on each heater. No pre-heating can be set during cold periods and the heaters must be manually turned up when the occupants arrive.

The timed controlled heating system is centrally controlled by a timeclock on the boiler with heat output selection. This control operates on a single zone with the whole system being on or off depending on the timeclock heating schedule. There is no thermostatic control in this system and therefore manual control is used to either turn down the heat output on the boiler or manually control the TRV's in each room. The TRVs provide the same level of control in each room as the manual control heating system provides but with the addition of central control to automatically turn the system on or off depending on the boiler schedule, thus providing energy saving during unoccupied periods and pre-heating during cold periods.

The temperature controlled building consists of a single zone central heating system controlled by a programmable thermostat in the living room. This has a time based control similar to the timed control system but with the addition of temperature control with the sensor located in the thermostat in the living room. This system will turn on and off depending on the time schedule and operate at a room temperature setpoint to conserve energy and increase thermal comfort by turning off when the thermostat reaches the desired temperature. Similar to the timed controlled system, the whole system is controlled from this central point with individual room control provided by manually operated TRVs.

A comparison between each heating system has been presented with similarities and differences established. A summary of Chapter 3 will now be given in Section 3.11.

3.11 Summary

Chapter 3 established the benchmark case study buildings with one manually controlled building, one timed controlled building and one temperature controlled building. A comparison of the physical parameters of the building construction and internal gains, as well as the heating systems, were defined in Sections 3.5, 3.6 and 3.7 and then subsequently compared in Sections 3.9 and 3.10. These case study buildings will be used to provide a benchmark for this study in order to evaluate modifications to be made to the heating systems.

The study will now go on to discuss and define the computational research methodology used for the study which is applied to each of the case study buildings.

Chapter 4 Computational Research Methodology

4.1 Introduction

Computational investigations of building energy consumption takes the form of dynamic thermal models which use numerically based energy balance calculations in discrete time steps to solve the model over a defined time period.

Computer simulations have advantages over traditional numerical methods in that more complex calculations can be undertaken with higher accuracy and greater speed than non-computer based simulations. This provides the most cost effective solution to studying building energy consumption.

The basic steps for the production and solving of a dynamic thermal modelling are as follows :

i. Computational Domain – Generation of the geometrical building model including all the different building elements.

ii. Boundary Conditions – Definition of the boundary and external conditions such as external weather, building fabric thermal properties and internal gains and schedules.

iii. Processing – Selection of the numerical methods to be used within the simulation depending on the type of the simulation and required outputs.

iv. Post – Processing and Data Analysis – Outputs from the dynamic thermal model.

This chapter provides an overview of the underlying equations, namely the degree day methodology for predicting building energy consumption followed by the formal definition of the numerical methods, energy balance and discretisation used in dynamic thermal modelling. The chapter will then outline the outputs and post processing for the simulation solutions and quantify uncertainties.

4.1.1 Energy Consumption in Buildings

Energy consumption in buildings can be estimated in two distinct ways. The first is by means of simplified calculation methods such as the degree day method. This method provides an overview and estimate of building energy performance based on heat transfer through the building fabric, solar gains and air infiltration gains. This is usually limited to whole building energy consumption. Such calculations are useful for early stage concept design to establish performance benchmarks for design guidance and building performance which can be compared against at later stages of design.

The second approach to building energy modelling is numerical based simulation with dynamic thermal models. These provide more detailed outputs from building simulation including not only energy but occupant comfort, accurate zone temperatures and modelling of complex control systems. Whilst numerical methods give these extra results without the use of computing the calculations which would be prohibitively time consuming.

There are a number of assumptions within the calculations, such as fixed occupancy patterns and homogeneity in construction element thermal properties, and whilst these assumptions and simplifications are required in order to solve the calculations they are sources of uncertainty.

Maintaining or improving the thermal comfort of the building occupants is a significant driver for heating homes in the UK. The following section details how thermal comfort is defined and the calculations governing thermal comfort indices.

4.2 Thermal Comfort

The body attempts to regulate its core body temperature to be 37°C. The body thermos-regulatory system can respond to overheating (sweating, increase blood flow to extremities) and underheating (decrease blood flow to extremities, hairs standing up) in order to maintain this temperature.

CIBSE (2009) defines the heat balance of the human body to be governed by the following equation:

$$\phi_m - \phi_w = \phi_{rc} + \phi_{re} + \phi_k + \phi_r + \phi_c + \phi_e + \phi_s \qquad \text{Equation 4.1}$$

Where,

Φ_m	Metabolic rate(W)
Φ_w	Rate of performance of external work (W)
Φ_{rc}	Convection in respiratory tract (W)
Φ_{re}	Evaporation in respiratory tract (W)
Φ_k	Conduction from surface of a clothed body (W)
Φ_r	Radiation from surface of a clothed body (W)
Φ_c	Convection from surface of a clothed body (W)
Φ_e	Evaporation from the skin (W)
Φ_s	Body heat storage (W)

In order to maintain this heat balance so occupants feel comfort rather than overheating or underheating, our homes are heated and cooled to maintain comfortable conditions. Thermal comfort is not only governed by internal room temperatures but consists of a number of factors. Environmental factors which contribute to thermal comfort are as follows:

i. Air Temperature

ii. Mean Radiant Temperature

iii. Relative Air Speed

iv. Humidity

Along with these environmental factors there are also personal factors which affect thermal comfort which are as follows:

i. Metabolic Heat Production

ii. Clothing

There are two extensively used ways to numerically determine thermal comfort which are Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD).

PMV combines these environmental and personal factors into one value and rank occupant thermal satisfaction a thermal sensation scale.

Fanger and Christensen (1986) conducted an empirical study of 100 participants. Each was dressed to obtain a neutral thermal sensation and then exposed to a range of air velocities and temperatures in order to rank their thermal sensation on a thermal sensation scale. This was then extended by Fanger *et al.* (1988) in a similar empirical study into the effect of air turbulence on thermal sensation where 50 participants were subjected to varying air velocities and asked to report how they felt. From these studies the current equation governing PMV was derived and is as follows :

$$\begin{aligned} PMV = (0.303e^{0.036M} + 0.028)\{(M - W) \\ - 0.00305[5733 - 6.99(M - W) - p_s] \\ - 0.42[M - W - 58.15] - (1.7x10^{-5})M(5867 - p_s) \\ - 0.0014M(34 - \theta_{ai}) \\ - (3.96x10^{-8})f_{cl}[(\theta_{cl} + 273)^4 - (\theta_c + 273)^4] \\ - [f_{cl}h_c(\theta_{cl} - \theta_{ai})]\} \end{aligned} \qquad \text{Equation 4.2}$$

where,

M	Metabolic rate of body surface (Wm^{-2})
W	External work of body surface (Wm^{-2})
f_{cl}	Ratio of clothed to unclothed area of human body
θ_{ai}	Average air temperature surrounding the body (°C)
θ_c	Operative temperature (°C)
p_s	Partial water vapour pressure in the air surrounding the body (Pa)
h_c	Convective heat transfer coefficient at the body surface (Wm^{-2}K^{-1})
θ_{cl}	Surface temperature of clothing (°C)

The scale of thermal sensation used in the studies by Fanger and Christensen (1986) and Fanger *et al.* (1988) is given in Table 4.1.

Table 4.1 Scale of Thermal Sensation

Thermal Sensation	Index Value
Hot	3
Warm	2
Slightly Warm	1
Neutral	0
Slightly Cool	-1
Cool	-2
Cold	-3

Table 4.1 allows occupants to express their thermal sensation based on the current conditions in the room to establish their level of thermal comfort.

The second measure of thermal comfort, PPD, illustrates how many people are dissatisfied by the current thermal conditions (dissatisfied corresponds to a PMV > 1 or < -1) based on the results on the PMV results.

To calculate the PPD the following equation is used:

$$PPD = 100 - 95e^{[-(0.03353\ x\ PMV^4 + 0.2179\ x\ PMV^2)]} \qquad \text{Equation 4.3}$$

The relationship between PMV and PPD is illustrated graphically in Figure 4.1.

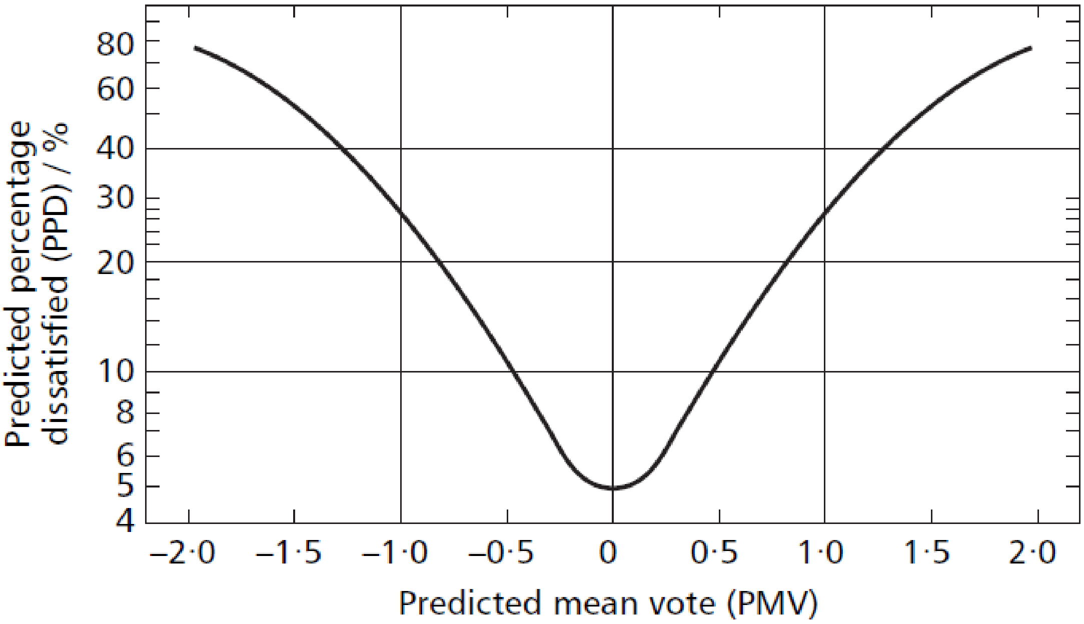

Figure 4.1 Relationship between PMV and PPD (CIBSE, 2009).

It can be seen in Figure 4.1 that even with a PMV of 0, there is still a PPD value of 5% (5% of the population are unsatisfied by the thermal conditions). This is because individual thermal sensation varies and the votes of actual people will be scattered around the calculated PMV for the room. Since the calculations involve identical clothing and activity where as in reality people are free to choose their own clothing level and activity level varies, the actual PPD would normally be lower than the calculated PPD.

In order to maintain these comfort conditions, the temperature within a building must be controlled and in the UK the majority of buildings are heated to achieve this. The following section will discuss the estimation of a buildings heating requirement through the use of the degree day method.

4.3 Degree Day Method

There are a number of simplified calculation methods, such as the CIBSE Degree Day Method or BS EN ISO 13790:2006 Energy performance of buildings – Calculation of energy use for space heating and cooling. BS EN ISO 13790:2006 uses monthly mean external air temperature whereas the degree day method uses 24 hour average temperature which accounts for short term fluctuations in external temperature to capture periods where no heating is required and extremes of temperature that BS EN ISO 13790:2006 cannot. This makes the degree day method more reliable at predicting accurate building energy consumption during milder months along with extreme cold events.

Degree days were originally established to identify the length of the crop growing seasons. The method was developed by Lt-Gen Sir Richard Strachey, a member of the member of the Meteorological Council to the Royal Society in 1878. Further work was then conducted by Hitchin and Hyde (1979) to estimate the heating energy use in buildings using degree days. Hitchin (1981) went on to analyse temperature records and compare them to estimates made with various published procedures with year to year variations examined. The study proposed a new procedure for altering base temperature using mean annual degree day totals. followed by modifications in the base temperatures for heating calculations.

Day and Karayiannis (1999) investigated different interpretations of the base temperature as a means of describing building energy balance, concluding that using mean internal temperature is more reliable than the application of correction factors previously used. Day and Karayiannis (1999a) conducted further studies into the degree day method by investigating two different approaches for establishing energy use, the admittance method and the derived model. The study concluded that the derived model was more suited to lightweight and medium weight buildings with the admittance method appearing better for heavyweight buildings, however suffering from sensitivity due to inputs. The current methodology is published and maintained by CIBSE in TM41

– Degree-days: theory and application (CIBSE, 2006). Degree days are the summation of the temperature differences between the buildings base temperature (free running temperature) and the external temperature over a defined period. If the external temperature is lower than the building base temperature, heating is required to maintain comfort conditions. Since heat loss from a building is proportional to the internal to external temperature difference (Equation 4.5), the energy consumption of the building heating system is related to the sum of these temperature differences or rate of heat addition to maintain the required indoor temperature. This concept is illustrated pictorially in Figure 4.2.

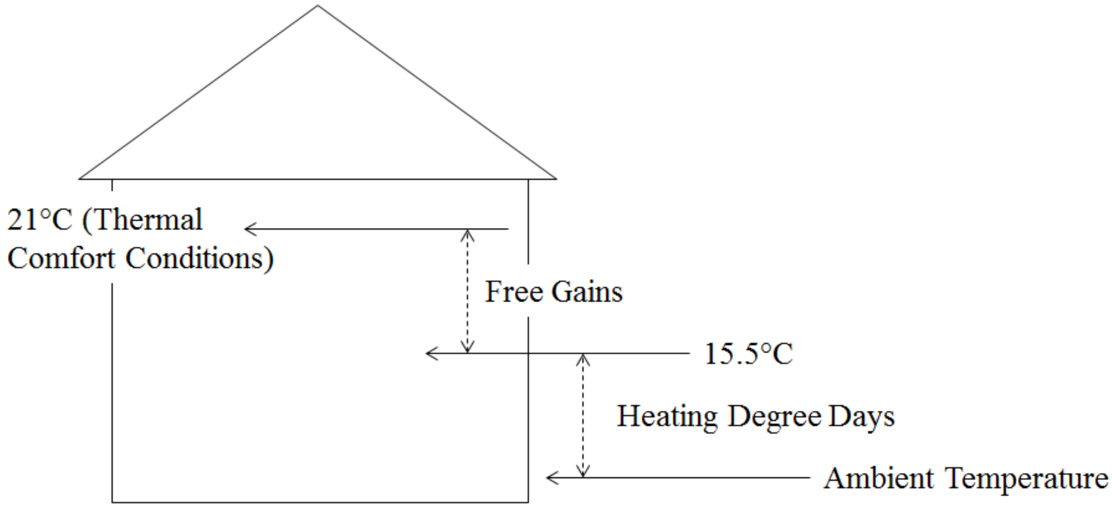

Figure 4.2 Illustration showing the application of heating degree days in estimating building heating requirement.

Figure 4.2 illustrates the Heating Degree Days being used to calculate the heating requirement to raise the ambient temperature up to the free running base temperature of 15.5°C which is traditionally used for the United Kingdom (CIBSE, 2006). Free gains consisting of internal gains from equipment, people, lighting and solar gains then raise the building temperature from the base temperature (free running temperature) up to the thermal comfort conditions.

Being a simplified paper based method to estimate the complex behaviour of a building, any derived answer is an approximation due to a number of underlying assumptions that are made. The main assumption is that of average conditions (temperatures, internal gains and infiltration rates). The degree day method has been used in a number of recent studies including Beizaee *et al.* (2015), Verbai *et al.* (2014), De Rosa *et al.* (2014), De Rosa *et al.* (2015) and Al-Hadhrami (2013). This study is only concerned with heating degree days and not cooling degree days as it is not common practice to install mechanical cooling in domestic homes in the UK.

CIBSE (2006) sets out a paper based calculation for building energy consumption using the Degree Day Method. The following section describes the first step in using the degree day method which is to establish the base temperature for the building.

4.3.1 Base Temperature Calculation

The building base temperature is the free running temperature where the internal gains and solar gains are strong enough to maintain comfort conditions within the dwelling. The energy balance for this calculation is shown in Figure 4.3.

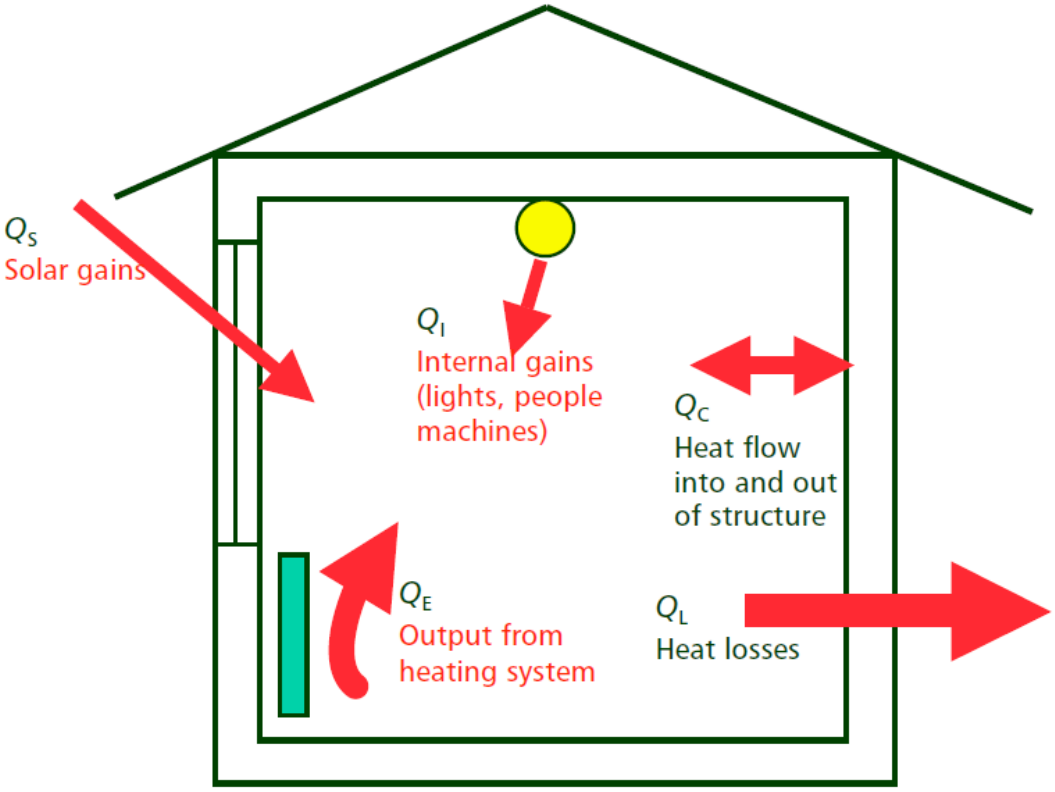

Figure 4.3 Pictorial representation of domestic building energy balance used within the degree day method calculation (IES, 2015).

The standard base temperature for domestic buildings in the UK is 15.5°C as published by the Carbon Trust (CarbonTrust, 2007), however for more accurate estimations adjusted base temperatures can be used and calculated as follows :

$$T_{base} = T_{24} - \left(\frac{Q_I + Q_S + Q_C}{(\sum UA + \ 0.33nV)}\right) \qquad \text{Equation 4.4}$$

where,

T_{basee}	Building base temperature (°C)
T_{24}	24 Hour average internal temperature (°C)

In continuous heating scenarios, the Q_c term is ignored as it has little effect on the energy performance of the building. However this study is concerned with intermittent heating and as such the thermal storage of the building becomes more important. To account for this, an adjustment in base temperature is made. The mean internal temperature is taken for an intermittently heated building in the calculation rather than the heating setpoint temperature as is the case for a continuously heated building (Day and Karayiannis, 1999).

Once the base temperature for the building is established, the next step is to use this in the calculation of the heating degree days. The following section will discuss this along with using the degree days to estimate the building heating requirement.

4.3.2 Degree Day Calculation

This base temperature is used to calculate the degree days for a building given the external temperature. Figure 4.4 gives an example for the external temperature variation for each day with the mean daily temperature shown.

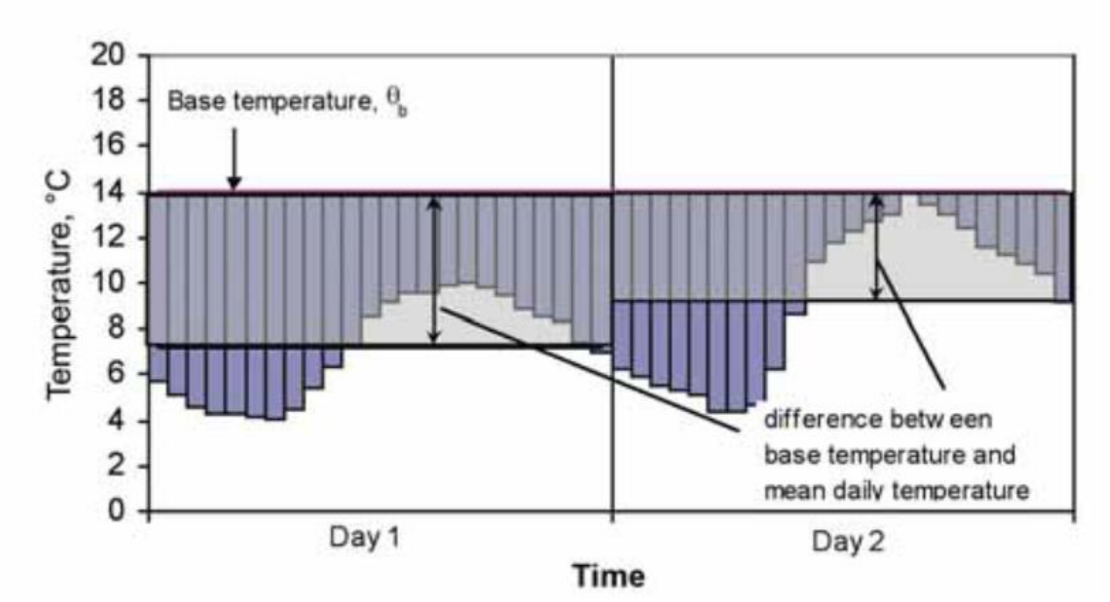

Figure 4.4 The external temperature variation over a two day period with the daily internal mean temperature indicated (CIBSE, 2006).

In the example shown in Figure 4.4, the mean daily temperatures are 7.3°C on day 1 and 9.4°C on day 2. With a base temperature of 14°C the degree days for day 1 is 6.7 °C day and 4.6 °C day for day 2 giving a total of 11.3 K day for the 2 day period. This can be converted into a more useful heating energy demand using the following equation:

$$Q_E = \left(\sum UA + \ 0.33nV\right) \Delta T \ x \ Degree \ Days \ x \ 24 \qquad \text{Equation 4.5}$$

Here the total heat loss coefficient is multiplied by the heating degree days and by 24 to convert from days to hours. This can be performed for the duration of the heating period to estimate the heating requirement for the building.

When more details in the calculations are required to deliver the improved accuracy and resolution of results, numerical methods can be used to calculate the energy consumption in a home along with other values, such as occupant thermal comfort and energy use unrelated to heating. The following section discusses this numerical methodology starting with the equations which underpin the calculations followed by their application in dynamic thermal modelling.

4.4 Numerical Method

The second approach is using a numerical method to estimate the energy consumption. This has benefits over a simplified method, such as increased accuracy and provision of a wider range of results including occupant comfort and building thermal response. These numerical calculations take into account the building response to external weather and temperature but also internal factors such as occupancy related gains and an occupants interaction with the building.

This section details the underlying equations used within the numerical analysis and provides context as to where the equations apply on a building. The equations and modelling procedures are obtained from the IES VE simulation software literature.

The numerical calculations can be broken down into seven distinct parts which are as follows:

i. Conductive heat transfer and storage

ii. Convective heat transfer

iii. Heat transfer by air movement

iv. Long-wave radiation heat transfer

v. Solar radiation

vi. Casual gains

vii. Heating control

Each of the calculation types will be covered in turn in the next sections.

4.4.1.1 Conductive Heat Transfer and Storage

Conduction is the transfer of heat through materials without net mass motion of the material (Myers, 1971). The fundamentals of heat conduction and heat storage within a numerical thermal model are governed by the following two of equations:

$$\underline{W} = -\lambda \nabla T$$ Equation 4.6

$$\nabla.\underline{W} = -\rho c \frac{\partial T}{\partial t}$$ Equation 4.7

Where,

$T_{(x,y,z,t)}$	Temperature in the solid at position (x,y,z) at time t (°C)
$\underline{W}_{(x,y,z,t)}$	Heat flux vector at position (x,y,z) at time t (W/m^2)
ρ	Density (kg/m^3)
c	Specific heat capacity (J/kgK)

Equation 4.6 describes the partial differential equation which controls the heat conduction within each layer of a building element and Equation 4.7 governs the heat storage within each building element.

Combining these equations leads to the heat diffusion equation where ρ,λ and c can all vary with the nodal position in the building element.

$$\nabla.(\lambda\nabla\mathrm{T}) = \rho\mathrm{c}\frac{\partial T}{\partial t}$$ Equation 4.8

Within the numerical calculations, it is common to make a number of assumptions to model the heat conduction and storage accurately.

i. Heat flow in each building element is assumed to be uni-dimensional.

ii. The thermo-physical properties within each building element layer are assumed to be homogeneous within that layer.

These two assumptions allow Equation 4.8 to be described as follows:

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho c}{\lambda}\frac{\partial T}{\partial t}$$ Equation 4.9

This equation now assumes a uni-directional building element along with uniform values of ρ,λ and c within the building element. The system of equations is closed by the application of appropriate boundary conditions and the stipulation that W is continuous at the layer boundaries.

Air gaps are considered in the heat conduction calculation and are modelled as pure resistances with the following equation:

$$\mathrm{W} = -\frac{(T_1 - T_2)}{R_{com}} \qquad \text{Equation 4.10}$$

Where,

W	Heat flow (W)
T_1	Temperature at surface 1
T_2	Temperature at surface 2
R_{com}	Combined radiative and convective resistance of the air gap (m^3K/W)

The boundary conditions for each conductive element are dictated by the conditions in the spaces adjacent to them which may be internal or external. Where an adjacent room is inactive, the conditions on the far side are assumed identical to those on the near side which is termed a reflexive boundary condition. In this case the thermal mass of the element is taken into account however the element performs adiabatically with respect to heat transfer, with the value tending to 0.

Heat storage in the rooms air mass is described by the following equation.

$$Q = c_p \rho_a V \frac{dT_a}{dt} \qquad \text{Equation 4.11}$$

Where,

Q	Energy (W)
c_p	Specific heat capacity of air at constant pressure (J/kgK)
ρ_a	Density of air (kg/m^3)
V	Volume (m^3)
T_a	Bulk Air Temperature (°C)

4.4.1.2 Convective Heat Transfer

Convection is heat transfer resulting from the flow of a fluid over a surface, in this case air over building elements. Convective air driven by external forces such as wind is referred to as forced convection. Natural convection describes convection arising from buoyancy.

It has been experimentally shown that convective heat transfer can be accurately described by the equation:

$$W = K(T_a - T_s)^N \qquad \text{Equation 4.12}$$

Where,

T_s	Mean surface temperature (°C)
K	Coefficient
N	Coefficient

For forced convection (convection due to the wind) at sufficiently high air velocities it is found that N=1 approximately and thus the process is linear.

For natural convection, although N is usually somewhat greater than 1, its value is often sufficiently close to 1 for the approximation:

$$W = h_c(T_a - T_s) \qquad \text{Equation 4.13}$$

Where,

h_c	Convective heat transfer coefficient

When there is a significant departure of N from unity, the McAdams' empirical approach for external convection can be used.

Exterior convection is predominately wind driven, with atmospheric wind data taken from the external weather file. External forced convection is modelled with a wind speed dependant convective heat transfer coefficient calculated from McAdams' empirical equations

$$h_c=5.6+4.0v \quad (v<4.88) \qquad \text{Equation 4.14}$$

$$h_c = 7.2v^{0.78} \quad (v \geq 4.88) \qquad \text{Equation 4.15}$$

Where,

v	Wind speed (m/s)

Within naturally ventilated numerical analysis in domestic homes, it is common for internal convection to be simulated using the CIBSE fixed convection coefficients due to the low air velocities.

4.4.1.3 Heat Transfer by Air Movement

Heat transfer by air movement is directly related to wind and buoyancy pressure on the building external openings. The equation governing wind pressure is as follows:

$$p_w = C_p \frac{1}{2} \rho v^2 \qquad \text{Equation 4.16}$$

Where,

p_w	Wind pressure (Pa)
C_p	Wind pressure coefficient
ρ	Density of air (kg/m^3)
v	Reference wind speed (m/s)

In order to calculate the wind pressure, coefficients must be applied governed by the surrounding terrain. Wind pressure coefficients are obtained by a variety of means such as CFD simulation, wind tunnel testing or in situ measurements:

$$v = uKh^a \qquad \text{Equation 4.17}$$

Where,

u	Metrological wind speed at 10m in open country (m/s)
h	Height (m)
a	Coefficient relating to terrain type
K	Coefficient relating to terrain type

Buoyancy pressure varies with height due to the changing density of air. Within `domestic homes this is a much smaller part of air movement due to the short height of the buildings. The equation governing buoyancy pressure is as follows:-

$$p_n(h) = p_n(0) - h\rho_n g \qquad \text{Equation 4.18}$$

Where,

$p_n(h)$	Pressure in room n at height h
ρ_n	Density of air in room n (kg/m^3)
g	Acceleration due to gravity (9.81m/s^2)

For external air infiltration, both wind pressure and buoyancy must be included and are governed by the following equation:

$$p_{0,i}(h) = p_{w,i}(0) - h\rho_0 g$$

Equation 4.19

Where,

$p_{0,i}(h)$	External pressure (Pa)experienced by opening i
$p_{w.i}$	Wind pressure (Pa) experienced by opening i
ρ_0	Outside air density (kg/m^3)

Air infiltration through windows is primarily through the cracks between the window frame and the glass. For a crack, the dependence of flow on pressure difference is governed by the following equation:

$$q = CL\left({}^{\rho_{ref}}/_{\rho}\right)^{0.5} \Delta p^{0.6}$$

Equation 4.20

Where,

q	Air flow through crack (l/s)
C	Crack flow coefficient (ls^{-1}m^{-1}Pa$^{-0.6}$)
L	Length of crack (m)
ρ	Density of air entering the crack kg/m^3
ρ_{ref}	Reference air density (1.21kg/m^3)
Δp	Pressure difference across the crack (Pa)

Where flow is not through a crack but through a larger opening such as an open window, the flow characteristics are defined by:-

$$p = 0.62A_{op}\left({}^{2}/_{\rho}\right)^{0.5} \Delta p^{0.5}$$

Equation 4.21

Where,

0.62	Air flow through crack (l/s)
A_{op}	Crack flow coefficient (ls^{-1}m^{-1}Pa$^{-0.6}$)

For window opening which varies in time with an opening schedule, the opening area is governed by the following equation:

$$A_{op} = spfA \qquad \text{Equation 4.22}$$

Where,

A	Area of opening as geometrically modelled (m^2)
f	Equivalent area fraction
p	Degree of opening (fraction of opening)
s	Control signal for window opening

4.4.1.4 Long-Wave Radiation Heat Transfer

All building surfaces emit thermal radiation due to their absolute temperature. This heat transfer is governed by the following equation:.

$$dW = \frac{1}{\pi}\varepsilon A\sigma\Theta^4 \cos\theta\, d\omega dA \qquad \text{Equation 4.23}$$

Where,

ε	Surface emissivity (W/m^2)
σ	Stefan-Boltzmann constant (W/m^{2}K^4)
Θ	Absolute temperature of the surface (K)
$d\omega$	Element of solid angle
θ	Direction angle measured from the surface normal
dW	Radiation flux (W/m^2)
dA	Element of surface area (m^2)

This equation describes a small surface area (dA) of a Lambertian emitter, the radiation flux emitted into a small solid angle (dω) lying in a direction making an angle θ to the surface normal.

On integrating over the solid angle, the total radiation emitted by a plane surface over area A may be expressed as :

$$W = \varepsilon A\sigma\Theta^4 \qquad \text{Equation 4.24}$$

Where,

ε	Fraction of incident radiation absorbed known as surface emissivity

This is an approximation of the physics of radiation emission as the equation does not go into the details of the wavelength dependence of emission and instead assume Lambertian angular characteristics.

Within numerical methods of building energy calculations, it is common to model interior long wave radiation is as mean radiant temperature. The CIBSE mean radiant temperature model which is governed by the following equation :

$$W = h_r(T_s - T_{mrt}) \qquad \text{Equation 4.25}$$

Where,

W	Net radiative loss from the surface (W)
T_{mrt}	Mean radiant temperature of the enclosure (°C)
h_r	Surface heat transfer coefficient for exchange with the MRT node.

The presence of air inside a room has a large effect on the long wave radiation exchange within the space. The emissivity of the air is mainly due to the water vapour present. For water vapour in air for a typical room the emissivity can be approximated empirically by the following curve :

$$L(\varepsilon_{air}) = -0.619 - (2.958 - 0.2184 Ln(p_w\, L_e))^2 \qquad \text{Equation 4.26}$$

The emissivity calculated from Equation 4.26 is used to modify the calculation for the internal long wave radiation.

In this model the net longwave radiation gain for an external surface of inclination β is given by:

$$L^*(\beta) = \varepsilon_e\left[L_{sky}(\beta) + L_g(\beta) - \sigma\Theta^4{}_e\right] \qquad \text{Equation 4.27}$$

Where,

$L^*(\beta)$	Net long wave radiation gain (W/m^2)
ε_e	Emissivity of the external surface
$L_{sky}(\beta)$	Long wave radiation received directly from the sky (W/m^2)
$L_g(\beta)$	Long wave radiation received from the ground (W/m^2)
Θ_e	Absolute temperature of the external surface (K)
β	Inclination (°)

This can be further expressed in terms of the horizontal and inclined surfaces with radiation from the sky or ground.

For a horizontal surface, long wave radiation from the sky is estimated from the temperature and water vapour content of the air with a modification for cloud cover as follows:

$$L_{sky}(0) = \sigma\Theta^4{}_e \left\{0.904 - \left(0.304 - 0.061p_w^{\frac{1}{2}}\right)(1 - c_{cloud}) - 0.005p_w^{1/2}\right\}$$

Equation 4.28

Where

Θ_a	External absolute air temperature (K)
p_w	External air water vapour pressure (hP)
c_{cloud}	Cloud cover

For an inclined surface, the long-wave radiation received directly from the sky is obtained using Cole’s correlation:

$$L_{sky}(\beta) = L_{sky}(0)F_{sky} + 0.09k_3(\beta)\{1 - c_{cloud}[0.7067 + 0.00822T_e]\}\sigma\Theta_a^4$$

Equation 4.29

Where,

T_e	External air temperature

and the shape factor from the surface to the sky is given by :

$$F_{sky} = \cos^2\left({}^{\beta}/{}_{2}\right)$$

Equation 4.30

and

$$k_3(\beta) = 0.7629(.01\beta')^4 - 2.2215(.01\beta')^3 + 1.7483(.01\beta')^2 + 0.054(.01\beta') \qquad \text{Equation 4.31}$$

Where,

$$\beta' = \beta \qquad (\beta \leq 90)$$
$$\beta' = 180 - \beta \qquad (\beta > 90)$$

The reason for this deviation from the CIBSE method and substitution for β' is to avoid unphysical behaviour for slopes greater than 90°

Long wave radiation received from the ground is modelled as follows:

$$L_g(\beta) = \sigma\{0.980\Theta_a + 0.037(1-\rho_g)I_{glob}\}^4 F_{gnd} \qquad \text{Equation 4.32}$$

Where,

ρ_g	Short wave ground reflectance (albedo)
I_{glob}	Total solar flux on the horizontal plane (W/m^2)
F_{gnd}	$1-F_{sky} = Sin^2(\beta/2)$ Shape factor from surface to ground

Finally where there is external shading, the numerical analysis must be modified to take into account view factors to the sky and ground using a diffuse sky shading factor as follows:

$$F_{sky} = f_{shd} \cos^2 \left({}^{\beta}/_{2} \right) \qquad \text{Equation 4.33}$$

Where,

f_{shd}	Diffuse sky shading factor for the surface

Once the long wave radiation is simulated in the dynamic thermal model, the solar radiation must be considered.

4.4.1.5 Solar Radiation

The top of the earth's atmosphere experiences approximately 1353 W/m^2 of energy from the sun which is then reduced as it moves through the gasses in the atmosphere. Not only do the gasses affect the value experienced on the surface, but the angle of the sun relative to the surface also has a large impact.

There are three major components of solar radiation which are incident on the surface of a building :

i. Direct (beam) from the sun's disc in the sky

ii. Diffuse from the entire sky vault

iii. Radiation scattered by the ground

The culmination of the three above parts make up the total incident solar flux. This is governed by the following equations :

Direct solar flux

$$I_{dir} = I_{beam} \cos(\theta_i) \qquad \text{Equation 4.34}$$

Where,

I_{dir}	Direct solar flux incident on the surface (W/m2)
I_{beam}	Solar flux measured perpendicular to the beam (W/m^2)
θ_i	Angle of incidence

Diffuse solar flux

$$I_{sdiff} = I_{hdiff} \cos^2 \left({}^{\beta}\!/_{2} \right) \qquad \text{Equation 4.35}$$

$$I_{gdiff} = \rho_g I_{hglob} \sin^2 \left({}^{\beta}\!/_{2} \right) \qquad \text{Equation 4.36}$$

Where,

I_{hglob}	$I_{hdiff} + I_{beam} \sin \alpha$
I_{sdiff}	Diffuse sky solar flux incident on the surface (W/m^2)
I_{hdiff}	Diffuse sky solar flux on the horizontal plane (W/m^2)
β	Inclination of the surface
I_{gdiff}	Diffuse ground solar flux incident on the surface (W/m^2)
α	Solar altitude

For the purpose of numerical analysis, the sky diffuse radiation is generally assumed to be isotropic with a circumsolar disc representing the intensity around the sun. Values of β result from integrating the isotropic radiation over the solid angle.

4.4.1.6 Casual Gains

Casual gains into the space are internal comfort or occupant related gains internal to the home. These can be classified according to the gain type:

i. Fluorescent lighting
ii. Tungsten lighting
iii. Machinery
iv. Miscellaneous
v. Cooking
vi. Computers
vii. People

Each gain has a sensible and a latent component. Sensible gains add or remove heat from the room, with a portion being radiation dictated by the radiant fraction and the remainder being conductive to the air. The latent gains add water vapour to the room air.

4.5 Dynamic Thermal Modelling

The US Department of Energy maintains a Building Energy Software Tools Directory (BESTD) with an up to date list of software for evaluating energy efficacy, renewable energy and sustainability in buildings (DoE, 2015). At the time of writing there are 417 pieces of software listed covering all aspects of building analysis.

There is a large degree of commonality between the different software programs which perform similar functions. Both EnergyPlus and Integrated Environmental Solutions (IES) use first-principal mathematics along with energy balances to iteratively solve the problem. IES was selected for this study due to the program accuracy and modular expandability allowing for detailed analysis using different modules on the same base model. IES has been used in previous studies and provides good modelling of control systems as well as providing very reliable outputs (Day and Karayiannis, 1999). The software itself is widely used in industry and performed comparatively to other similar softwares in the ASHRAE standard 140-2007 tests, standard method of test for the evaluation of building energy analysis computer programs.

The first step in to conducting a dynamic thermal modelling study is to define the computational domain. The following section discusses the definition of the building geometry.

4.5.1 Computational Domain

There are a number of ways to generate the building geometry in IES. The geometry can be imported directly into the simulation software which results in the geometry being available straight away. However this requires the geometry to be generated in an external program (Sketchup, AutoCAD or similar) and be made available in the correct file format.

This method of importing geometry can streamline the modelling when the external files are provided by architects for simulations but in this case, where the geometry is not available and has to be generated from scratch, there are no benefits to using external programs to import and this extra step has the potential to introduce errors. The second method for generating the geometry is to use the inbuilt tool in ModelIT.

Here the geometry can be defined and the consistency of adjacencies within the model guaranteed by using the in-built grid and snap functions. Figure 4.5 shows the building geometry built within IES.

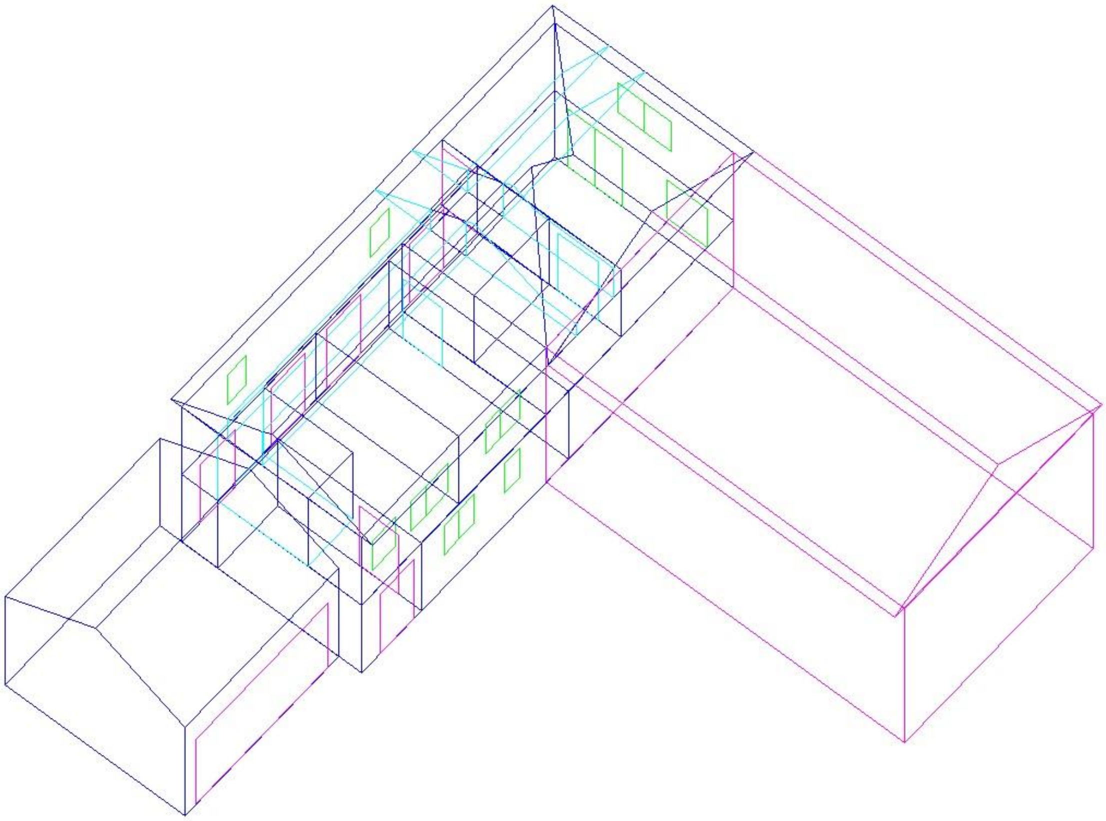

Figure 4.5 Pictorial representation of the building geometry generated in IES.

Each building element type in Figure 4.5 is a different colour to differentiate its role. Green elements are glazed sections with blue being the opaque building elements. Pink elements are adiabatic adjacent zones such as adjacent buildings. In each building case study the geometry was generated in this way and then constructions assigned to each element to provide a thermal representation of the case study building. In the following chapter we discuss the discretisation procedure undertaken by the dynamic thermal modelling software on the computational domain in order to perform the calculations outlined in Section 4.4.

4.5.2 Nodal Network (Discretisation)

The conduction calculation takes a finite-difference approach to the calculation of the conduction for the building elements. For this calculation methodology, each building element is split in to a number of discrete nodes as indicated in Figure 4.6

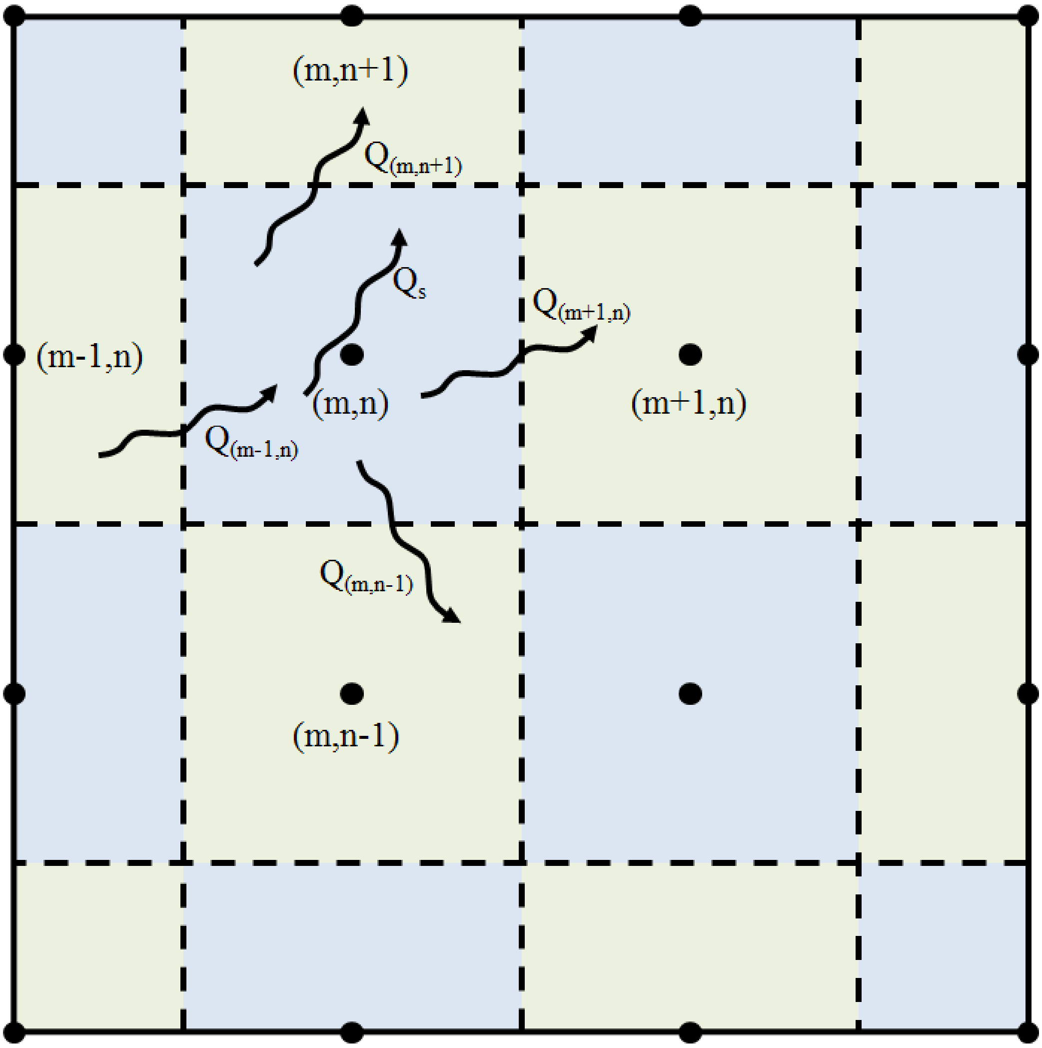

Figure 4.6 Pictorial representation of a building element broken down into a number of discrete nodes for simulation (illustration modified from Myers (1971)).

Forward-difference methods (explicit) such as the Euler Method can be used which use present and future values of the node temperature to express the time derivative at the current time. Whilst being accurate, these methods are prone to numerical oscillations which can become unstable if the time step used is too large. These oscillations are also present in the Crank-Nicolson implicit method however they do not become unstable, but can be large enough to make the solution inaccurate.

A second method is the backward-difference method (pure implicit) which does not suffer from these oscillations and will be more accurate than explicit methods if very large time steps are being used. In the backward difference method the computed time derivative is applied one step in the future. (Myers, 1971)

In order to provide an optimal mix of accuracy and stability, IES uses the hopscotch method where each node alternates between forward difference and backward difference methods (indicated on Figure 4.6 by the alternating colours). This provides a high level of accuracy with very efficient computation as longer time steps can be taken without numerical oscillations.

The heat diffusion equation which is solved by this finite-difference method and when spatially-discretised, Equation 4.8 takes the following form:

$$\frac{T_{n-1} - 2T_n + T_{n+1}}{{\delta_n}^2} = -\left(\frac{\rho c}{\lambda}\right)\frac{\partial T}{\partial t}$$ Equation 4.37

Where

T_n	Temperature at node n (°C)
δ_n	Local node spacing (m)

Distribution of the nodes within the layers are defined to maintain accurate modelling of the heat transfer and storage characteristics without using too many resources for the chosen time step The longer the time step, the more coarse the node resolution is. The node spacing is based on constraints imposed on the Fourier number as follows:-

$$\mathrm{F} = \frac{\left(\frac{\lambda}{\rho c}\right)\Delta}{{\delta_n}^2}$$ Equation 4.38

Where

Δ	Simulation time step (s)
F	Fourier Number

Rearranged for the spacing value, Equation 4.38 can be expressed as

$$\delta_n = \sqrt{\frac{\left(\frac{\lambda}{\rho c}\right)\Delta}{F}}$$ Equation 4.39

This equation demonstrates that the spacing on each element is dependent on the time step taken as well as the physical properties of the material that the element is made from. The nodal spacing cannot be controlled or altered within IES aside from selecting the simulation time step.

Once discretisation has occurred, the dynamic thermal model must set boundary conditions to establish the building inputs in order to perform the calculations for the correct conditions. Each boundary condition is discussed in turn in the following section.

4.5.3 Boundary Conditions

Boundary conditions are required in order to provide inputs for the numerical modelling along with a starting point. In the case of dynamic thermal simulation, the boundary conditions are the simulation and building inputs, including building geometry and fabric, external weather conditions, internal schedules and heating control systems. In the following sections the boundary conditions are defined in detail.

4.5.4 Coupled heat and mass transfer

The buoyancy driven infiltration detailed in 4.4.1.3 is calculated within the MacroFlo module in tandem with the energy balance calculations being completed within the ApacheSim module. Each calculation is interdependent to one another and solved using an iterative procedure at each simulation time step.

4.5.4.1 Mass transfer

For a given set of room thermal conditions (temperature and humidity provided by ApacheSim) the net air mass flow into and out of each zone is calculated. This is performed by first undertaking a linearisation exercise within MacroFlo as illustrated in Figure 4.7.

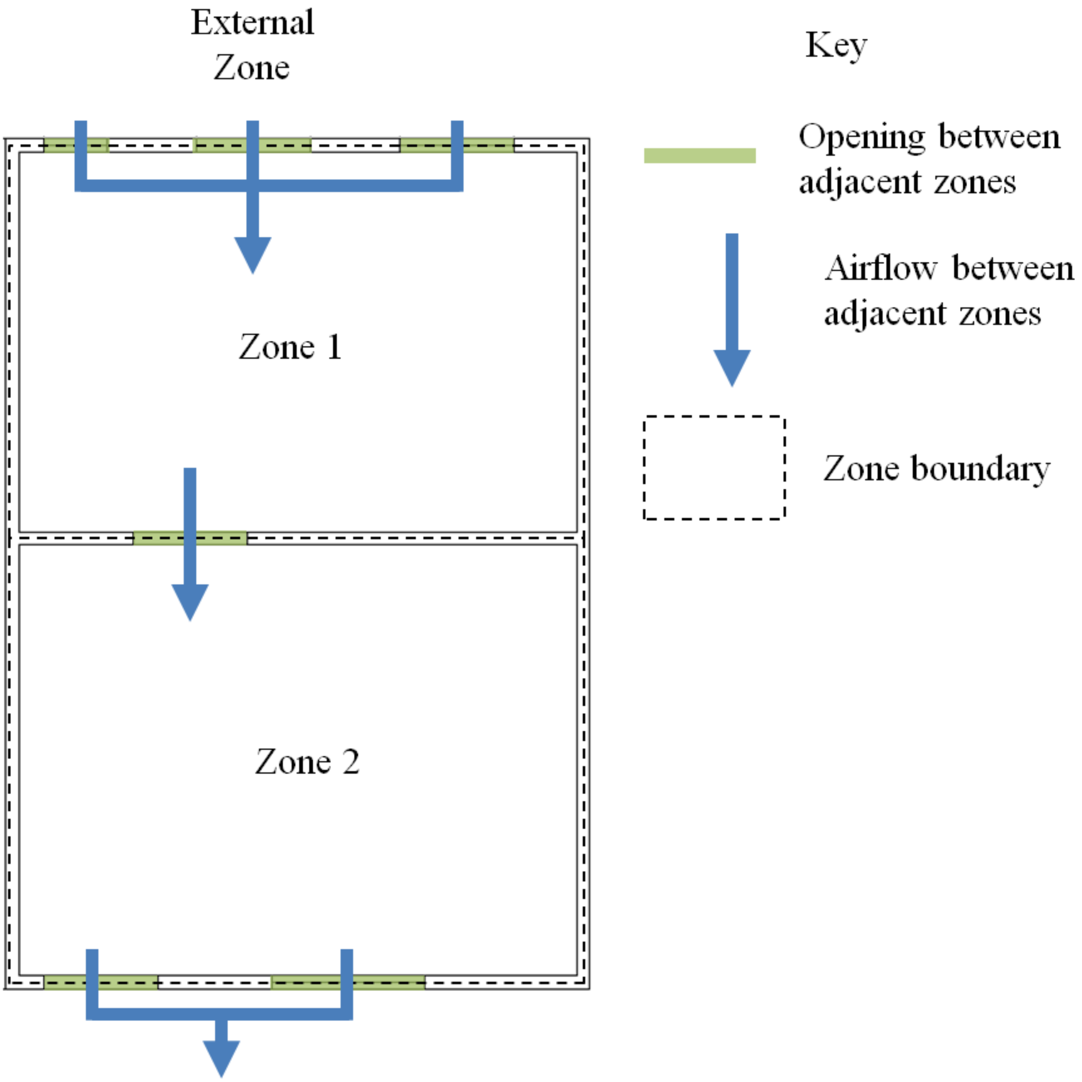

Figure 4.7 Linearisation of zone airflow within MacroFlo

The air flow for each opening is calculated individually by the MacroFlo module but then during the linearisation procedure these values are combined to form a net airflow from one zone to another. This airflow is passed back to the ApacheSim module.

4.5.4.2 Calculation iteration

MacroFlo exchanges the mass air flow and pressure with ApacheSim dynamically. This is to achieve the simultaneous solution of the inter-dependant thermal and air flow balances. Once ApacheSim has calculated the new room thermal conditions these values are passed back to MacroFlo to perform the next iteration.

A flow chart to graphically illustrate the coupled heat and mass transfer methodology is shown in Figure 4.8.

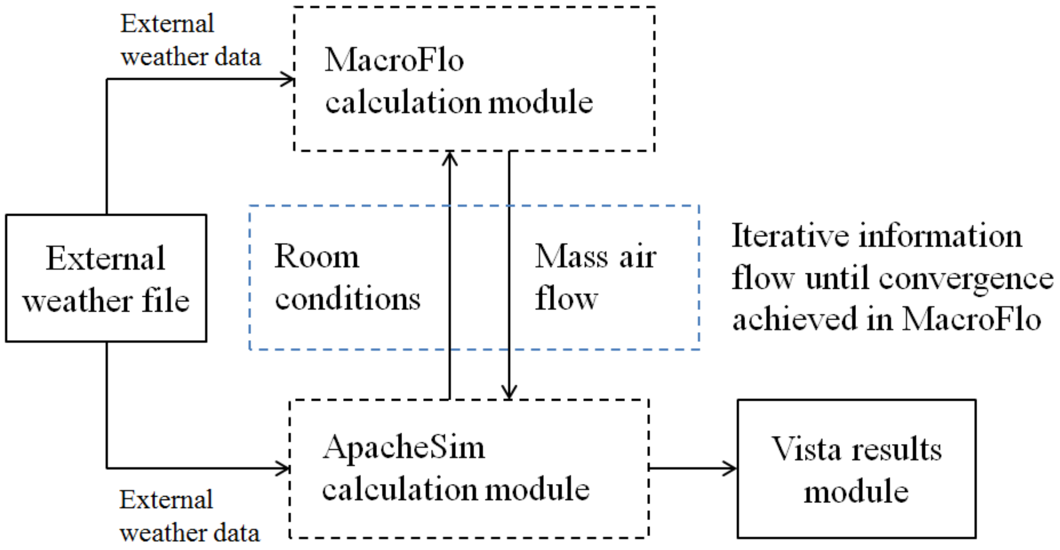

Figure 4.8 Coupled heat and mass transfer solver flowchart

Once the iterative calculation achieves a convergence of 0.0001kg/s, the final room condition for that time step is known and the calculation moves on to the next time step.

4.5.4.3 Weather Data

It is an important step to correctly define the location and orientation of the subject building in the software in order to use the correct external weather and solar conditions whilst performing the calculations. Also it is important to establish the difference between the design weather data and simulation weather data.

- Design weather data is concerned with extreme design scenarios which are typically what one would use when sizing a plant to service a building. This weather data does not need to be continuous and can just contain the maximum and minimum values for the solar and temperature values.

- Simulation weather data must be continuous to allow for a yearly simulation of building performance and more often will be yearly averaged values, excluding the extreme values which are not experienced very often and which would have a small effect on yearly performance, but a large effect on plant sizing.

There are a range of different weather file sources available for use in the simulations, the relevant ones are as follows:

i. TMY / 2 – The are Typical Meteorological Year weather files which consist of hourly solar radiation and meteorological elements for a 1 year period.

ii. CIBSE – Test reference years and design summer years for 14 locations in the UK are provided by the Chartered Institute of Building Services Engineers for use with building energy simulations.

iii. IWEC – Consists of typical weather files for use with building energy simulation programs for locations outside the USA and Canada.

The weather file used in this study is a TMY2 format, converted to EPW so the simulation program can read it. The data is for the closest weather station to the case study area which is Cawood (weather station 39950). This location is approximately 7 miles from the manually controlled building 1, 11 miles from the time controlled building and 14 miles from the temperature controlled building and so provides a very good representation to the weather which can be expected in the test locations.

Actual hourly external temperature readings taken at the location of the case study building was substituted into the simulation weather file to increase accuracy of the results during the observed period February – April 2014.

Linear interpolation can be used to compute wind speed values at each time step from the hourly data provided in the weather file to the time step used in detailed simulation.

Solar information is contained within the external weather file and read into the numerical simulation. There are three values contained within the weather file which are as follows:

i. Direct solar radiation measured perpendicular to the beam (W/m^2).

ii. Diffuse solar radiation measured on the horizontal plane (W/m^2).

iii. Solar altitude and azimuth (°).

The solar altitude and azimuth are calculated for the location of the weather station together with time zone and summertime clock adjustment information.

Shading and solar tracking are two important parameters to establish when dealing with direct beam radiation from the sun. To account for this, a shading file is generated for the 15th day of each simulation month and contains hourly shading factors for all external and internal building surfaces. These shading factors are used to modify the beam radiation and calculate which internal surfaces are irradiated, along with secondary irradiation through internal glazing or holes.

The diffuse component of the solar radiation incident on an external glazed element is partially transmitted and partially absorbed. The transmitted portion is distributed proportionally depending on the internal surface areas.

The next boundary conditions to establish are the thermal properties of the building fabric.

4.5.4.4 Building Fabric

The furniture thermal mass is not considered within the thermal models for this study. Due to the furniture low thermal mass compared to that of the heavyweight structure of the building it has a negligible effect on the temperature of the room which is the controlling mechanism for the heating system. Comfort conditions relating to the radiant properties of the materials are subject to frequent change in a home due to coverings such as throws or objects on surfaces and so it was felt prudent to remove this from the study to focus on the role of the heating system controls to improve thermal comfort.

Detailed construction information is used for each element of the building in order to calculate the associated U-Values which provides the thermal performance of the building.

Each element is built up in a number of layers, each containing the values for the following :

i. Thickness (mm)

ii. Conductivity (W/mK)

iii. Density (kg/m^3)

iv. Specific Heat Capacity (J/kg.K)

These values are used in the calculation of the elemental thermal transmittance (U-Value) as follows:

$$U = \frac{1}{\sum R_n + R_{int} + R_{ext}} \qquad \text{Equation 4.40}$$

and for each element

$$R_n = \frac{d}{\lambda} \qquad \text{Equation 4.41}$$

Where,

d	Thickness (mm)
R_{int}	Internal surface resistance (m^{2}K/W)
R_{ext}	External surface resistance (m^{2}K/W)
R_n	Thermal resistance of layer n (m^{2}K/W)
U	Thermal transmittance (W/m^{2}K)
d	Thickness (mm)
λ	Thermal Conductivity (W/mK)

This defines the rate of heat flow through each opaque building element by conduction at different temperatures.

For glazed elements there are the following additional physical parameters:

i. Transmittance

ii. Outside reflectance

iii. Inside reflectance

iv. Refractive index

These are used in the calculation of the transmitted solar gains to the rooms by radiation. This calculation is discussed in more detail in Section 4.4.

Thermal bridging within IES is taken care of by the use of a bridging coefficient applied to the element constructions.

Once the thermal properties of the building fabric are established, the schedules for the internal gains must be defined in order for the correct gains to be attributed to the calculations at the correct times.

4.5.4.5 Internal Schedules

Schedules are used to control the internal gains of the building which consist the following :

i. Heating system
ii. Occupancy
iii. Small power
iv. Lighting

Each of these heat gains is controlled by either absolute schedules or modulating schedules depending on their requirement.

Absolute schedules control the variable to an absolute value whilst modulating schedules control a variable as a fraction of its maximum capacity. Absolute schedules can be implemented to have different heating setpoints at different points throughout the day making use of setbacks during unoccupied hours.

The resolution of the schedules being controllable down to each minute and these daily schedules are used to build up complex weekly and yearly scenarios. The programmer has the ability to define a unique daily schedule for each internal gain for each day of the year down to a maximum resolution of 1 minute steps if required, although such detail is rarely required as building heating control tends to be on an hourly or half hourly basis and the results are reported at hourly intervals.

The control methodology for the building heating system is defined in order for the dynamic thermal model to simulate the performance of the heating system as if it were installed in a real home.

4.5.4.6 Heating Control

Heating system control within dynamic thermal models can be controlled on a number of different variables which include:

1. Temperature
2. Humidity
3. CO_2
4. Occupancy

For the purpose of this study, temperature was selected as the controlling input to mimic current design practice for heating control. The method in which the heating control is achieved is shown in Figure 4.9.

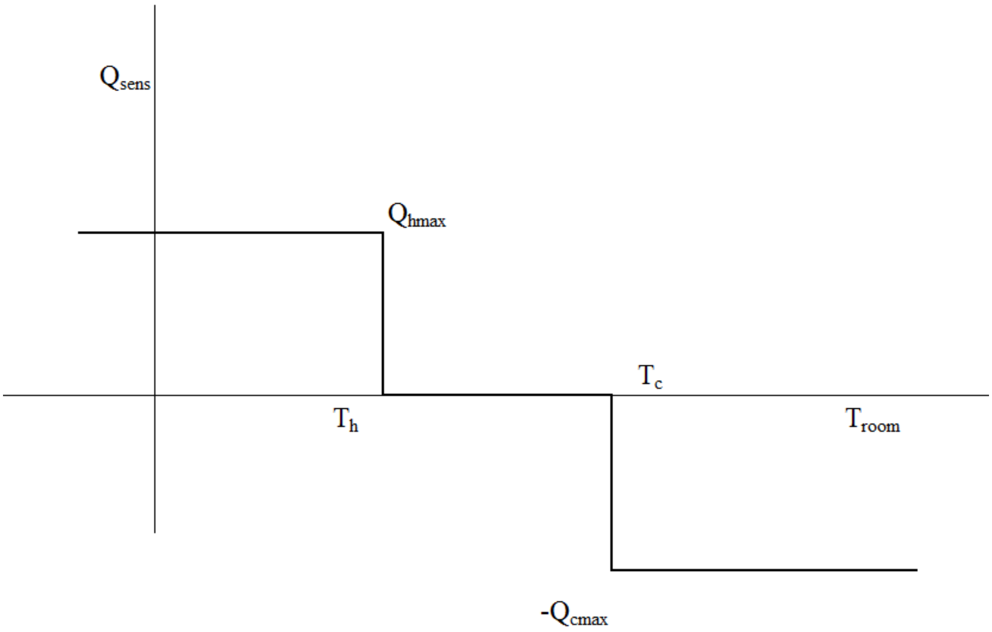

Figure 4.9 Illustration of the heating and cooling control within IES switching around the heating a cooling thermostat temperatures.

Here when the temperature in the room is below the heating setpoint (T_h), the heating system switches on and when the room temperature rises above the cooling setpoint (T_c) the cooling switches on. Between T_h and T_c neither heating nor cooling operate. Each setpoint is controlled by a deadband of 1°C to avoid continuous switching. Whilst the setpoints are static in this example, in the software these can be varied at different points in the day as discussed in Section 4.5.4.5 Internal Schedules.

Once the computational domain and boundary conditions have all been defined, the calculation can be performed by the dynamic thermal modelling software. The processing methodology options are described in the following section which are selected based on the applicability to the type of simulation carried out along with the type of results that are required in the study.

4.5.5 Processing

For the processing stage there are a number of underlying methodologies which can be controlled for the simulation which are as follows:

i. External convection model
ii. Internal convection model
iii. Longwave radiation model
iv. Air emissivity
v. Solar radiation

4.5.5.1 External Convection

The external convection model can be either the McAdams external convection model which is a wind speed driven model or a fixed value provided by the user. In this study the McAdams' model was used for maximum accuracy which are empirical formulas derived from CIBSE Guide A (CIBSE, 2009) and discussed in Section 4.4.1.2, Equation 4.14 and Equation 4.15.

4.5.5.2 Internal Convection

Internal convection can either be the CIBSE fixed value method, CIBSE variable method, BS EN, 15265 or the Alamdari and Hammond method. Internally in a domestic home in winter there is not a significant air movement as all external openings are normally closed. Because of this, the CIBSE fixed value method is suitable to use over the other more complex methods to give accurate results whilst maintaining a good simulation speed. At higher internal air velocities, where mechanical ventilation may be used, the other methods would become more applicable. The convection coefficient is set at 3.0 W/m^2K for all internal surfaces to simulate an average value.

4.5.5.3 Longwave Radiation

The sky and ground long wave radiation model can either be the CIBSE method or a black body at air temperature method. The CIBSE method was selected to provide a higher degree of accuracy for the simulations. The calculations are discussed in Section 4.4.1.4.

4.5.5.4 Air Emissivity

Internal air emissivity due to water vapour can be either on or off and for this study was included. Air emissivity has an effect on the radiant temperature of the surfaces and since occupant comfort was of interest within the study it was important to include this in the simulations. The calculation is discussed in Equation 4.26.

4.5.5.5 Solar Radiation

Solar radiation can either be anisotropic, isotropic or off. The anisotropic model was selected for this study which makes a portion of the diffuse radiation circumsolar, meaning it emanates from the suns position. This proportion varies with the intensity of the beam radiation and provides more accurate simulations of the solar gains to the building. The solar radiation calculations are discussed in Section 4.4.1.5.

Once the calculations are performed dynamic thermal simulation software provides the results. The type of results along with the way in which they are provided is discussed in the next section.

4.5.6 Post Processing and Data Analysis

Results from the dynamic thermal model are provided at each simulation time step. For long simulations this is hourly, reducing down to a time step of 6 minutes when a higher resolution was required for smaller time periods. This is to maintain a good balance between computational time and the required fidelity.

Building specific analyses and results are available from the dynamic thermal modelling software, including shadow and sunpath analysis as shown in Figure 4.10.

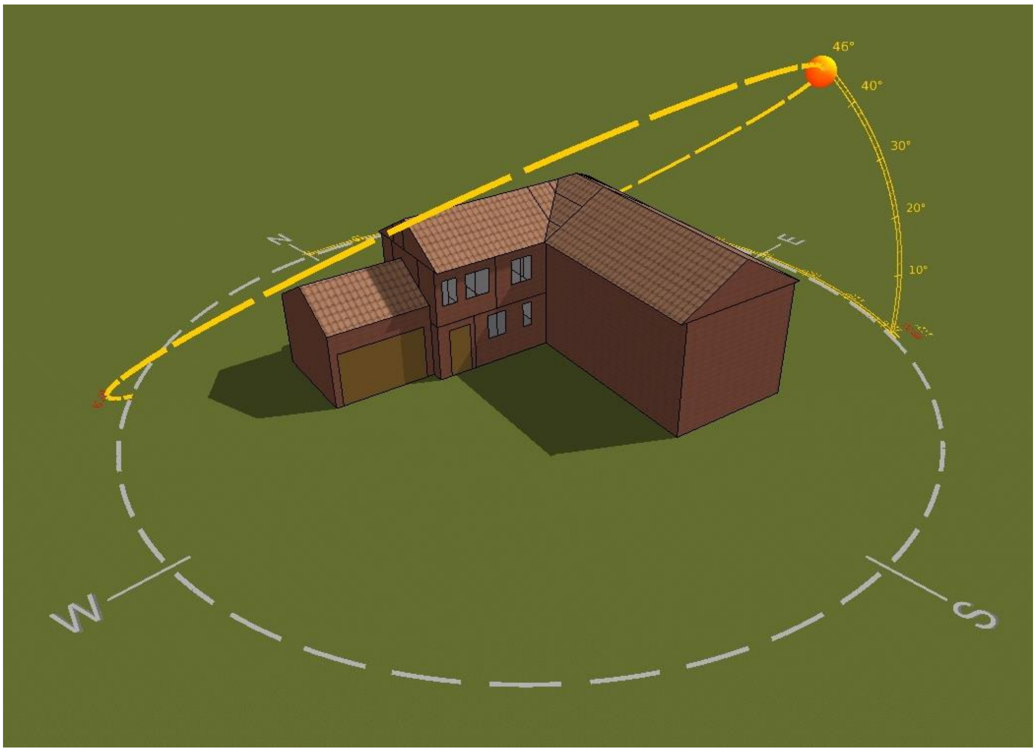

Figure 4.10 Sunpath and shadow analysis for 1st June at 9.30am.

Results are displayed in the software in a tabular form or graphically for all simulated variables and for each zone or element. In this study the results were primarily exported to a spreadsheet where the data could be handled and further calculations performed.

It is important to understand the limitations of the dynamic thermal modelling software as it has a number of assumptions which have been discussed in this chapter and a number of different calculation methodologies which can be used. The following section quantifies the uncertainties that are expected within a dynamic thermal modelling study.

4.6 Quantification of the Uncertainties

Errors and uncertainties are unavoidable during the simulations and these stem from approximations and assumptions contained with the simulations.

Buratti (2013) noted that the comparison of experimental point values of temperature measurement and the zonal average temperature reported in dynamic thermal modelling software would be a large contributor to uncertainty within the modelling validation.

ApacheSim version 2014, which was used in this study, has been tested and verified against ASHRAE Standard 140 – 2007, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. Analytical verification tests HE100 – HE170 and comparative tests HE210 – HE230 were conducted and all results were found to be satisfactory.

4.7 Summary

This chapter presented a background summary of the underlying methods of dynamic thermal modelling beginning with the background and description of the degree day method followed by the specific theory and methodology which was selected for this study.

The four main steps for conducting a dynamic thermal modelling study were defined as computational domain, boundary conditions, calculation methodology options and outputs and post – processing. The model definition outlined the building geometry with the boundary conditions implemented to allow the model to run. The calculation methodology was defined to describe the calculation to be used for this specific study with the outputs and post processing discussed for obtaining useful results.

Finally quantification of uncertainties were presented based on previous peer reviewed studies highlighted that error rates of between 10%-14% should be expected for domestic buildings temperature ranges.

Chapter 5 Experimental Research Methodology

5.1 Introduction

The measurement of internal temperatures and the data use in investigating domestic energy consumption has been a commonly used method with recent studies by Huebner *et al.* (2013a), Kane *et al.* (2015) and Lomas and Kane (2013). This methodology will be used for this study to gather real time temperature data over a three month period for the development of benchmark models and validation.

Three internal temperature sensors were deployed in each of the three case study houses to record the internal temperatures every 5 minutes over the course of a three month measuring period. One global external temperature sensor was used. Each building had a different heating system, building construction and occupancy pattern. This allows the validation to provide confidence that any results obtained correlate well with the majority of UK domestic households regardless of the building typology.

The chapter begins with identifying recent studies which have used temperature measurement and data logging as a method to gather data for use in dynamic thermal modelling. The chapter then moves onto the specific methodology used within this study to gather the data, ensure its continued accuracy and download the data for developing the benchmark models.

The field equipment is then discussed in detail outlining the physical parameters of all the temperature sensing, data logging and information gathering equipment used. These are compared to recent studies to ensure the resolution and accuracy of data being gathered in this study is sufficient to draw conclusions from.

The chapter then moves on to identify the location of each sensor in the case study buildings outlining the reasons for selecting that location along with identifying any elements of note such as unavoidable heat sources in proximity to the sensor. Finally the experimental error is established for the experimental methodology.

5.2 Data Acquisition

As discussed in Chapter 2, there have been recent studies conducted which use internal and external temperature measurements to investigate energy use within domestic buildings. There are three main recent studies which use this methodology, namely Living in Leicester (LiL), digital energy feedback and control technology optimisation study (DEFACTO) and the carbon reduction in buildings study (CaRB).

The living in Leicester survey took temperature measurements in July 2009 – February 2010. Kane *et al.* (2015) studied the heating patterns of 249 homes in Leicester. Heating data loggers which were placed in the living room and master bedroom of these houses and studied a period of three months from December 2009 to February 2010. The study found that although 90% of the homes were heated, the heating patterns and temperatures were hard to define, and frequently modified by user intervention. Lomas and Kane (2013) used the same data set to investigate internal temperatures for two months in summer 1st July 2009 – 31st August 2009. The study found that summertime temperatures varied greatly with 15% of bedrooms being over 26°C for 30% of the time and that modern homes with cavity wall insulation were generally warmer than older homes with a solid wall construction.

The DEFACTO project installed temperature measuring equipment in two identical homes with central heating systems. One home had a traditional TRV control system while the second had a zone control system for each room using programmable TRVs. The study was conducted over an 8 week period in winter. Beizaee *et al.* (2015) noted in the study that the zone control reduced heating gas consumption by 11.8%. Mallaband *et al.* (2015) monitored the temperature in 12 homes for a two week. All homes had gas central heating with a range of control systems. After two weeks. a new digital thermostat was installed in each home and the temperatures again monitored for 4 weeks. The measurements along with an occupant survey were used to draw conclusions on the occupant heating patterns.

The CaRB project investigated heating patterns in UK domestic homes and compared them to building energy modelling assumptions used to inform UK energy policy. Huebner *et al.* (2013a) conducted a study which focused on an observation period of November 2007 to January 2008 where internal temperatures were recorded at 45 minute intervals. Conclusions were drawn that an average temperature during the heating period was observed to be 19.5 °C which is lower than the normally assumed

21°C and the entire data set showed a large degree of variability in period and degree of heating. Huebner *et al.* (2013b) conducted a further study using the same data set investigating the variability in heating durations and concluded that current assumptions for heating demand and duration in modelling do not match those in UK homes.

In each case temperature data loggers were placed in domestic homes and used to monitor the internal room temperatures over a period of time. A comparison between the measurement variables in each study is presented in Table 5.1.

Table 5.1 Comparison of measurement variables used in internal building temperature studies.

Study	Data Logger	No.of rooms	Period (months)	Resolution	Accuracy (°C)
LiL	Hobo	2	3	1 hour	±0.4
DEFACTO	Hobo	2	1	1 min	±0.2
CaRB	Hobo	2	2	45 min	±0.47 (0.19)
This Study	Tinytag	3	3	5 min	±0.01

Table 5.1 has a comparison of the observation variables for each recent study comparing it to the study undertaken here. All studies use a spot measurement where the temperature is instantaneously recorded rather than a maximum temperature. Recording a maximum temperature could lead to misleading results if there are spikes in temperature then these would be recorded as the room temperature at that time. In this study the resolution is much higher than the other studies (5 minutes compared to 45 minutes / 1 hour). These 5 minute readings were then used to generate average hourly readings to ensure the most accurate temperature for hourly calculations was used compared to spot measurements. The accuracy reported for the Tinytag sensors used in this study is ±0.01 °C which is a greater accuracy than the Hobo sensors which report a minimum accuracy of 0.2°C. This studies observation period is in line with the LiL study being over a 3 month period, where-as the DEFACTO study drew conclusions over a much shorter period of 1 month per heating trial.

This provides confidence that the observation period and method of temperature recording in this experimental study are sufficient to provide accurate results for the rest of the study.

A review of recent experimental studies has been presented which demonstrates the period and methodology used within this experimental study are sufficient for the results to be used in the study and provide accurate conclusions. The field equipment used in this study will now be discussed.

5.3 Methodology

The methodology for the experimental portion of this study is in line with previous work in other studies as outlined in Section 5.2. Temperature sensors with integral data loggers were deployed in three rooms in three case study houses.

The main factors taken into consideration when deciding on the placement of the temperature sensors were :

i. Proximity to sources of heating / cooling

ii. Proximity to drafts

iii. Accessibility for maintenance and checking readings

iv. Obstructions from furniture

v. Agreement from the homeowner

Taking into account these factors, each room was individually considered for the placement of the sensor.

The study ran for a period of three months from February 1 2014 until 31 April 2014 with a two week preliminary observation period to ensure the data gathered was accurate and the location of the sensors posed no problems for the building occupants.

Periodic checks were made to ensure the data loggers were still running correctly. This was done by connecting them via a USB lead to a laptop with proprietary software which monitored the readings in real time and also provided an historical view of the data without disturbing current logging operations. The data was visually inspected for anomalous readings, obvious errors and current data being recorded correctly.

At the end of the observation period all the data was downloaded using this proprietary software into Microsoft excel for post processing. The data was downloaded in 5 minute timesteps which was converted to hourly figures for use in the external weather file and dynamic thermal modelling software. This was done over taking hourly spot readings to minimise the effect sudden spikes in temperature the sensor can detect and provide an accurate averaged hourly value for use in calculations.

5.3.1 Field Equipment

The temperature monitoring devices used in this study were Tinytag data loggers from Gemini. The data loggers have integral 10K NTC thermistor to measure the temperature. An image of the data logger is shown in Figure 5.1.

Figure 5.1 Tinytag internal temperature data logger.

The data logger has two lights on its front, the green light flashes every 4 seconds to indicate the unit is logging or every 8 seconds when the unit is waiting for a pre-determined time to start logging. The red light activates when an alarm condition is reached such as temperatures out of bounds or a user defined alarm.

A thermistor is an electrical resistors which are temperature sensitive. The temperature sensing elements made from semiconductor materials that display large changes in resistance in proportion to small changes in temperature. The value of resistance compared against the temperature are reproducible and so can be used to accurately determine ambient temperature.

An NTC thermistor is a negative temperature coefficient thermistor which are non linear and the resistance of the thermistor will decrease as temperature increases. The resistance is determined by passing a small direct current through the thermistor and measuring the voltage drop.

Figure 5.2 Image of a 10k NTC thermistor, the type used in the data logger (image from www.digchip.com).

Figure 5.2 shows a typical 10k NTC thermistor, the same type as used within the tiny tag data logger. This consists of a sintered ceramic head which performs the temperature measurement function and metallic arms used to attach the thermistor to the circuit.

At each time step, the data logger unit passes a current through the thermistor, recording the voltage drop and converting this to the temperature measurement of the ambient air around it. This value is then recorded in the data logger memory and stored for analysis in the study.

The performances for the internal and external data logger, respectively, are described in Table 5.2

Table 5.2 Temperature sensor performance

Sensor	**Temperature Range (°C)**	**Tolerance (°C)**	**Memory (readings)**	**Interval**	**Reading Type**
Tinytag Ultra 2 (IP54)	-40-85	±0.01	32,000	1s – 10 days	Actual / Min / Max
Tinytag Plus 2 (IP68)	-40-85	±0.01	32,000	1s – 10 days	Actual / Min / Max

Table 5.2 shows both data loggers suitable for operating within the range of temperatures experienced both internally and externally in UK domestic homes. As shown in Table 5.1, the tolerance, memory and interval used in this study are all equal or more accurate than previous studies. Table 5.2 shows the whole range in which the data loggers can operate and with a large degree of flexibility it allows the study to gather data in the most appropriate ways.

A laser measuring tool was used to accurately map the dimensions of the buildings and provide the geometry for the dynamic thermal models.

These laser measurement devices work by shining a laser at a surface and measuring the laser which is reflected back into the hand held unit. As the speed of the laser is know, the distance between the hand held unit and object reflecting the laser can be accurately calculated and dimensions of the building quickly established.

Table 5.3 details the performance characteristics of the measurement device.

Table 5.3 Measurement device performance

Measurement Device	**Range (m)**	**Tolerance (mm)**	**Interval (mm)**
Leica DISTO A6	0.05 – 200	±1.5	1

Table 5.3 shows the range and tolerance of the measurements to be sufficient for accurately measuring the case study buildings for the purpose of dynamic thermal models.

A review of all field equipment used within the case study has been presented with an overview of the equipment function, accuracy and tolerance. The deployment of the data loggers will now be discussed detailing the criteria for placement of the sensors, the location within each case study building room and the reasons for this location.

5.4 Sensor Deployment

A temperature sensor was deployed in the living room, kitchen and master bedroom of each building. The placement of these sensors is key in order for them to accurately reflect the internal temperature. As Kane *et al.* (2015) identified, in their study it is important to keep the sensors away from sources of heat (radiators, direct solar radiation, electrical appliances) whilst still leaving them uninsulated from temperature swings to accurately record internal temperature.

In the following images the colour key will be used to identify different internal zones and thermal elements :

i. Green is an adiabatic party wall

ii. Red being the master bedroom zone

iii. Purple being the living room zone

iv. Blue being the kitchen zone.

The ideal height for a temperature sensor is 1.5m from the floor as detailed in the carbon trust heating control guidance (CarbonTrustb, 2011). Wherever possible this was allowed for in order to best predict the temperature a thermostat would sense in each room.

5.4.1 External Sensor

One external temperature sensor was used as the case study buildings were less than 9km apart which would see no appreciative difference in weather as there are no significant water bodies or mountains between them. The modified weather file also uses the same solar radiation values for each site and so it was felt prudent to keep the same external factors to clearly demonstrate the effect the domestic heating systems have on thermal comfort rather than having an additional factor of different external weather conditions.

In this case the temperature sensor was shielded from direct solar radiation to accurately report the ambient temperature and was installed for the same period as the internal investigations were conducted.

5.4.2 Manually Controlled Building

The main factor for sensor deployment in the manually controlled building was the occupant desire to keep the sensors out of sight as far as practicable. The sensors were installed at a height of 1500mm where possible with adjustments made to accommodate the occupants wishes.

5.4.2.1 Sensor Locations

Sensors were installed on the ground floor and first floor of the manually controlled building as indicated in Figure 5.3 and Figure 5.4 respectively.

All dimensions shown in Figures 5.3 to 5.8 are in millimetres.

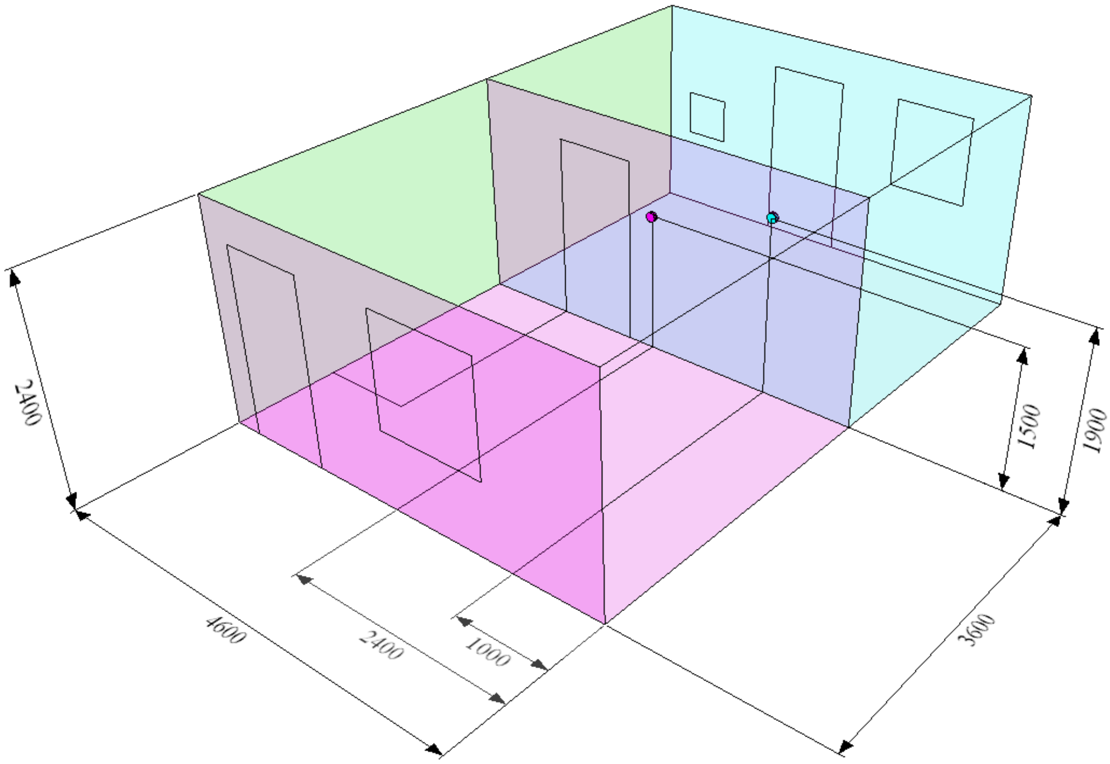

Figure 5.3 Ground floor temperature sensor locations in the manually controlled building.

The location of the kitchen temperature sensor for the kitchen is to the right of a refrigerator at a height of 2m. It is located away from the windows and not in line with the two doors to minimise drafts as well as being away from the storage heater and oven which are the two main heat sources in this room.

In the living room sensor of the manually controlled building is located away from the fireplace on the right hand wall, fixed on the wall at a height of 1.5m. The sensor is located out of line of the doorways and away from the external window to minimise drafts. The sensor in this room was at the nominal height of 1500mm. The left hand wall is a party wall which is assumed adiabatic in the dynamic thermal model.

A temperature sensor is also placed in the master bedroom as indicated in Figure 5.4.

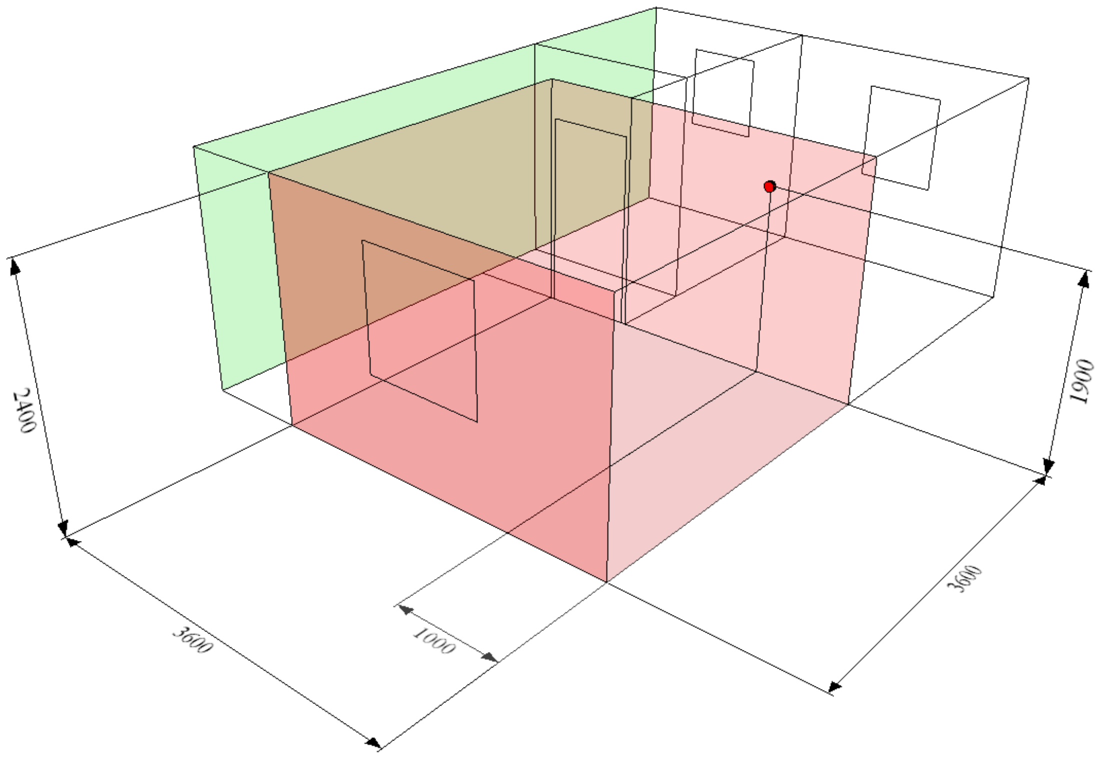

Figure 5.4 First floor temperature sensor locations in the manually controlled building.

In the master bedroom the sensor is located on top of a wardrobe on the back wall at a height of 1900mm. The sensor is located away from both the storage heater on the left hand wall and the window on the front wall. The left hand wall is a party wall which is assumed adiabatic in the dynamic thermal model.

5.4.3 Time Controlled Building

The main requirement in the time controlled building was the occupants request to try to keep wall fixings to a minimum as the building was newly renovated and the occupants wanted to minimise any damage to the building that would result from the fixing of the sensors. Taking this into consideration the sensors were hung or place on existing furniture as far as practicable whilst still maintaining a height of approximately 1500mm to ensure accurate occupied zone temperature readings.

5.4.3.1 Sensor Locations

The sensor locations for the ground floor and first floor are shown in Figure 5.5 and Figure 5.6.

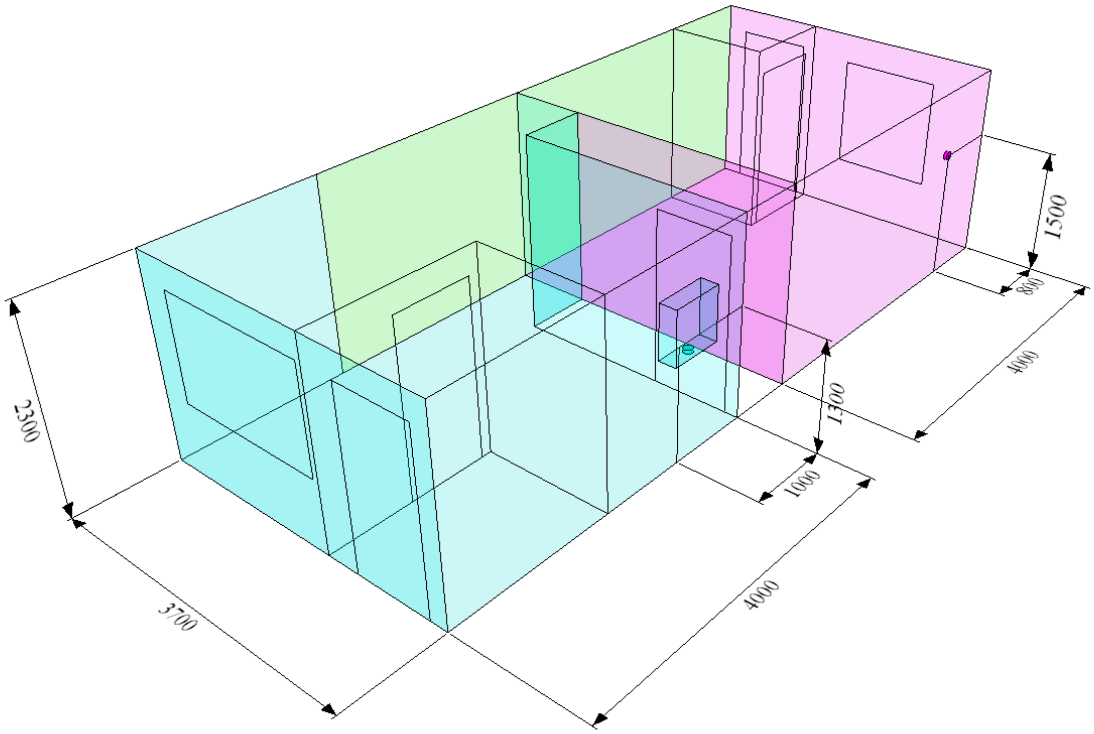

Figure 5.5 Ground floor temperature sensor locations in the timed control building.

The sensor in the kitchen is located in an alcove on the left hand wall at a height of 1300mm. The front and left wall are taken up by fitted kitchen cupboards with the back wall housing the radiator. Drafts from the door are minimised by the use of a porch and the sensor is kept away from the external window and sources of heat. The left hand wall is partially a party wall which is assumed adiabatic in the dynamic thermal model.

In the living room the sensor was hung on a recessed cupboard in the corner at a height of 1.5m. Space in this room is limited for fixing the sensor with a large portion of the room taken up by furniture which prevented fixing it on the wall. The sensor is kept away from the fireplace and radiator as far as practicable with a small television set below the sensor. The television is a modern set with a low energy consumption and thus very low heat output and should not have a significant effect on the room temperature reading. The left hand wall is a party wall which is assumed adiabatic in the dynamic thermal model.

The location of the master bedroom sensor for the time controlled building is shown in Figure 5.6.

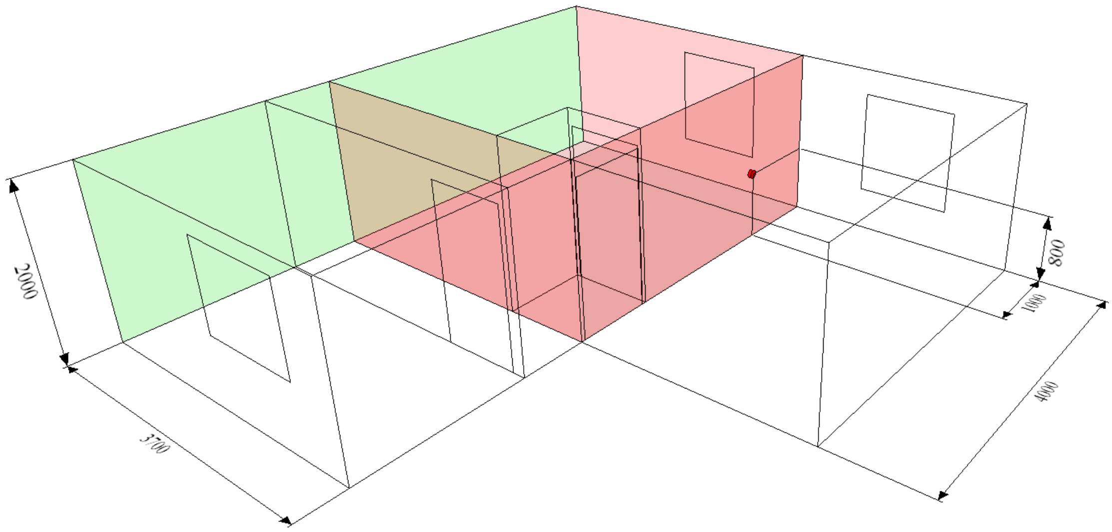

Figure 5.6 First floor temperature sensor locations in the timed control building.

The master bedroom sensor was placed on a small chest of drawers on the back wall at a height of 800mm. The sensor is kept away from the window and radiator to minimise their effects on the results. The bedroom door is kept closed and so drafts through here will be kept to a minimum. A more preferable location would have been on the left hand wall towards the corner opposite the door and away from the radiator and window, however the occupant was adamant to not have it fixed there due to the recent refurbishment. The left hand wall is a party wall which is assumed adiabatic in the dynamic thermal model.

5.4.4 Temperature Controlled Building

In the temperature controlled building the occupant allowed the sensors to be fixed anywhere in the chosen rooms, as such the height of 1500mm was used everywhere except in the kitchen where a convenient point in a cupboard allowed the sensor to be located at 1400mm. In each case the sensors were located away from sources of drafts, heat and cooling to give the most accurate representation of room temperature possible with one sensor.

5.4.4.1 Sensor Locations

The sensor locations for the ground floor and first floor are shown in Figure 5.7 and Figure 5.8.

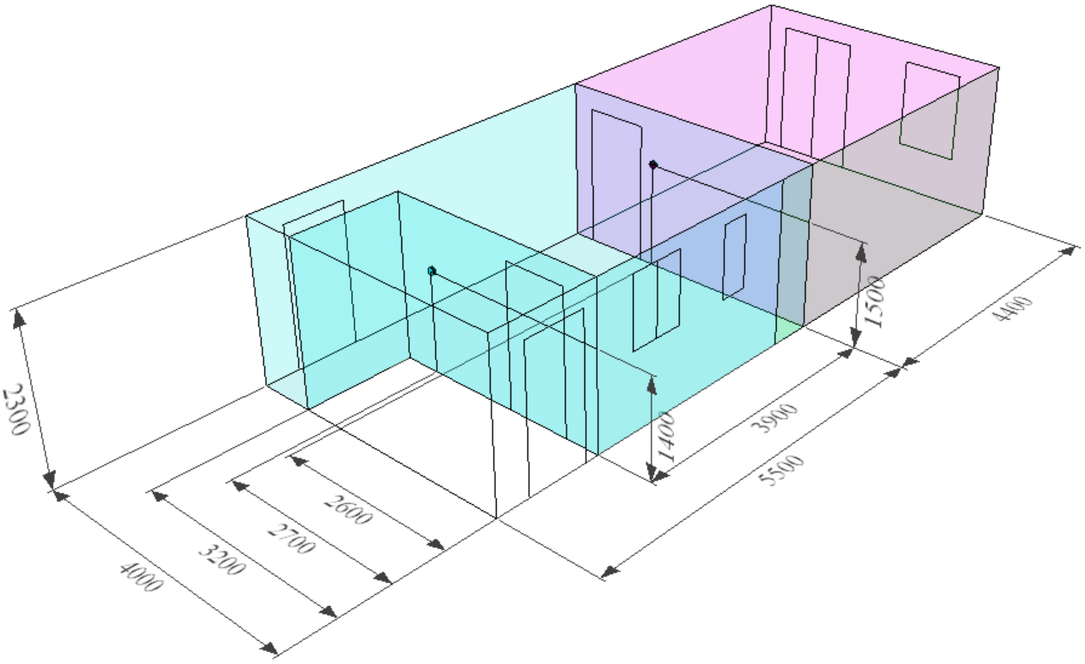

Figure 5.7 Ground floor temperature sensor locations in the temperature controlled building.

There are three major sources of heat in the kitchen, namely the radiator, refrigerator and the oven range. The sensor was placed as far away from these as possible, and away from the work surfaces with high level cupboards. The sensor location shown maximises the distance from these heat sources, and places it away from the work surfaces which could have intermittent sources of heat and presented problems with sensor fixing. The sensor was able to be placed 1.5m from the floor, thus allowing the best approximation of a thermostat location. A small portion of the right hand wall is a party wall which is assumed adiabatic in the dynamic thermal model.

The sensor in the living room is located at a height of 1.5m adjacent to the building thermostat to get the most accurate view of the temperature the building heating system is controlled by. This is away from all sources of heat and the external windows. The entire right hand wall is a party wall and so is assumed adiabatic in the dynamic thermal model.

The location of the master bedroom sensor for the temperature controlled building is shown in Figure 5.8.

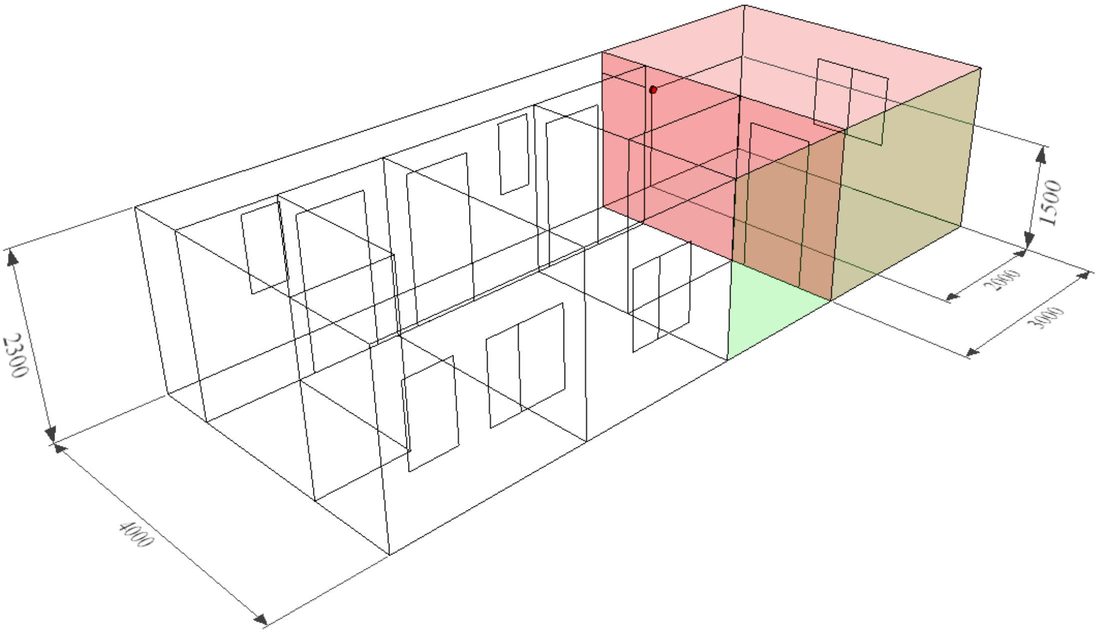

Figure 5.8 First floor temperature sensor locations in the temperature controlled building.

The sensor is located at a height of 1500mm above a small chest of draws in the master bedroom. This is located away from the radiator and windows to minimise any radiant heating or cooling effects on the sensor. The bedroom door is kept closed and so the effects of drafts are also kept to a minimum. The entire right hand wall is a party wall and so is assumed adiabatic in the dynamic thermal model.

5.5 Experimental Error

The sources for error in the experimental measurements are the error of the temperature data loggers and any error within the laser measuring device used for the geometric models.

Table 5.4 Equipment tolerances

Device	Tolerance
Temperature Data Logger	±0.01°C
Disto Laser Measurer	±1.5 mm

Table 5.4 shows low experimental error associated with the measurement devices in the range of 0.05% at 21°C and 0.15% over the length of 1m (typical window dimension). These tolerances are deemed to have no significant impact on the results.

5.6 Summary

Chapter 5 provides a summary of recent work which uses environmental temperature logging to investigate domestic energy consumption. A comparison was made between the data logging parameters used in these studies and the parameters proposed for this study and found that the error in measurements along with the frequency of measurements is more rigorous in this study.

The equipment used is described in Section 5.3.1 and outlining the tolerances which it operates at and the way in which each piece of equipment functions. The location and criteria for selection of each of the sensor locations is detailed in Section 5.4. The sensors are located away from sources of heat or cool, away from drafts and at a height of 1.5m where practical.

The experimental error for the measuring devices is discussed in Section 5.5, showing that the measurement tolerances are very stringent and so the data acquired is accurate.

The results of this study is now presented in Chapter 6 for each case study building for the three month observation period. Further work will then be conducted to investigate the effect the domestic control system has on the energy performance of the temperature controlled building.

Chapter 6 Results

6.1 Introduction

Chapter 4 and Chapter 5 laid out the methodologies for performing both the experimental and computational investigations within this study. The results of these investigations are detailed in this chapter.

The experimental investigation was conducted first into the internal room temperature of the living room, kitchen and bedroom of the three case study buildings. This was achieved by deploying data logging temperature sensors to the rooms for a period of three months from 1 February 2015 until 30th April 2015.

The thermal performance of these case study buildings was then compared against current design guidance (CIBSE) in order to establish how well the currently installed heating systems keeping the homes at these recommended internal temperatures.

Following this a computational investigation was conducted where a dynamic thermal model of each case study building was constructed and used to determine the thermal response of the case study buildings along with estimating the energy used to heat the building.

The computational models were validated against the experimental data to provide confidence that the thermal response of the models responded as expected and the results provided would be accurate to draw conclusions from.

Modifications were then made to the dynamic thermal models control systems in order to investigate the effect these had on the overall building energy performance and finally new control systems modelled to establish their effect on the building energy performance

From these results conclusions are drawn on the current energy performance of domestic heating control systems, the effect the heating schedules has on the energy performance and finally the effect of introducing zone control as a method of reducing energy consumption.

6.2 Experimental Results

Chapter 3 discussed the experimental building benchmarks with Chapter 5 discussing the experimental research methodology. The results for the experimental investigation are now detailed for each case study building in turn discussing the internal temperatures and points of interest for each.

Three internal temperature sensors were deployed in each of the three case study buildings, the manual control building, the time control building and the temperature control building. These sensors acquired data for a period of three months, recording the instantaneous temperature every five minutes. A two week calibration period for the sensors was used for each case study building. The 5 minute instantaneous temperature readings were subsequently converted to average hourly readings for each sensor and it was these values were used in the study.

6.2.1 Manually Controlled Building

As discussed in Section 3.5, the manual control building had individual electric storage heaters installed in each occupied room except the living room which had only a coal fire. These were manually controlled by the occupants as they worked rotating shift patterns and so did not maintain a regular occupancy patterns to set their heating to.

6.2.1.1 Master Bedroom

Figure 6.1 shows the temperature profile for the master bedroom of the manual control building. There are two points of interest highlighted which show distinct changes in temperature behaviour. The recommended internal room temperature for a bedroom as defined by CIBSE is 17°C -19 °C during occupied hours which is highlighted with the coloured band.

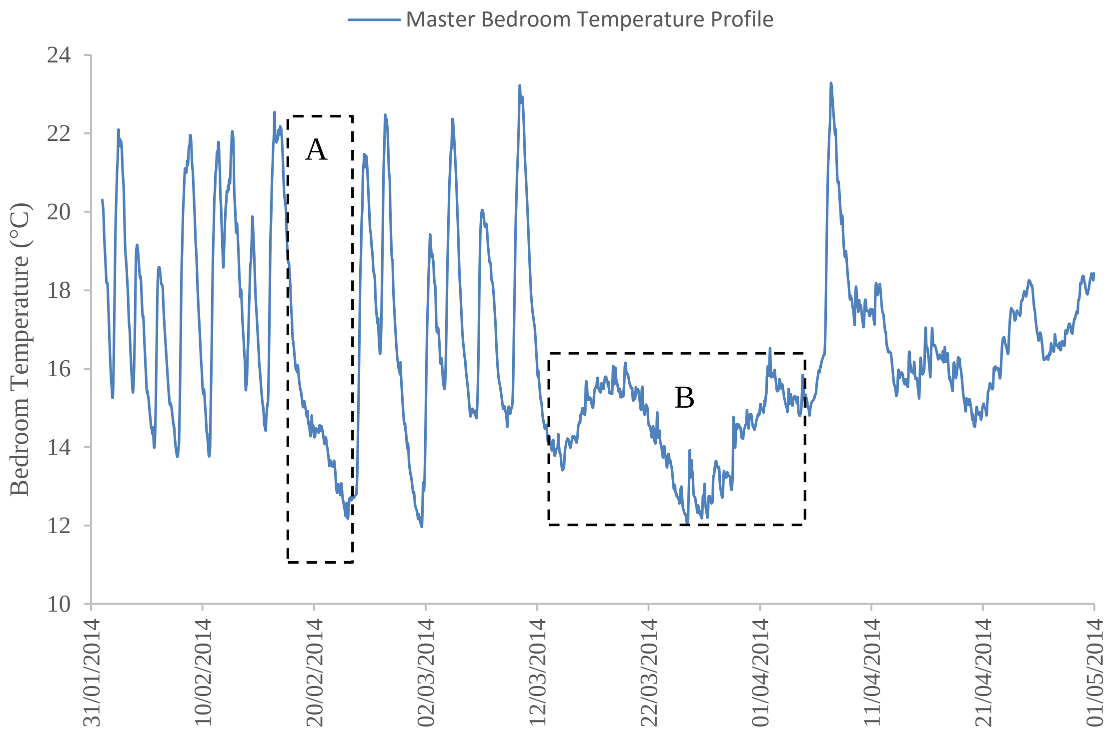

Figure 6.1 Temperature profile for the Master Bedroom from 1 February 2014 until 30 April 2014.

The heating cycle in this room has no distinctive reoccurring pattern for the entire observation period of 1 February 2015 until 30 April 2015. The time between peaks up to interest point A is between 33 and 66 hours. The occupants would leave the heating on until they felt too warm and then turn it off until they felt too cool. This leads to an erratic pattern with significant energy wastage and poor thermal comfort for the occupants.

Interest point A shows a period with a lack of peaks in room temperature. This is due to the heating being turned off in this room for five days when the occupants were out of the home. During this unoccupied period the temperature drops to a minimum of 12.2°C.

Interest point B shows a period where rather than manually controlling the heating and creating the spikes in temperatures seen from 1 February until 12 April the heating was left on a low setting on continuously. A spike in temperature can be seen towards the end of this period where the heating was turned higher. However it was again turned off and the internal temperature trends upwards due to the warming weather so heating was not required.

A comparison between the internal temperature and the external temperature is shown in Figure 6.2 highlighting the effect the external temperature has on the free running temperature of the building.

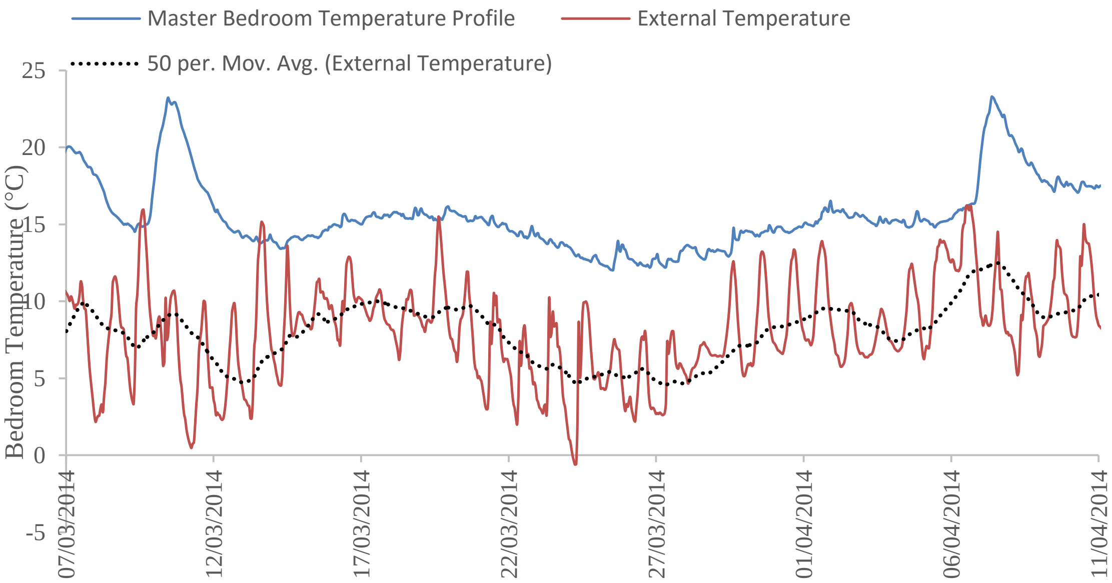

Figure 6.2 Master bedroom internal temperature profile compared to the external temperature profile for minimum heating period.

During the minimum heating period, the internal temperature follows the same general trend as the external temperature. The peaks and troughs of the internal temperature are heavily damped compared to the external temperature which is due to the heavyweight construction of the building which has solid stone walls. These are slow to respond to external temperatures and so provide a much more stable internal temperature.

The minimum temperature measured in the master bedroom was 12.0°C with a maximum of 23.3°C. The average internal temperature was 16.4°C which is close to the minimum CIBSE recommended occupied internal temperature but does not reflect an accurate average as it is skewed by the very large peaks which occur at the start of the observation period.

6.2.1.2 Living Room

Figure 6.3 shows the temperature profile for the living room of the manual control building. There are two points of interest highlighted which show changes in temperature behaviour.

The recommended internal room temperature for a living room as defined by CIBSE is 22°C to 23 °C during occupied hours. The temperature profile along with recommended temperature band is shown in Figure 6.3.

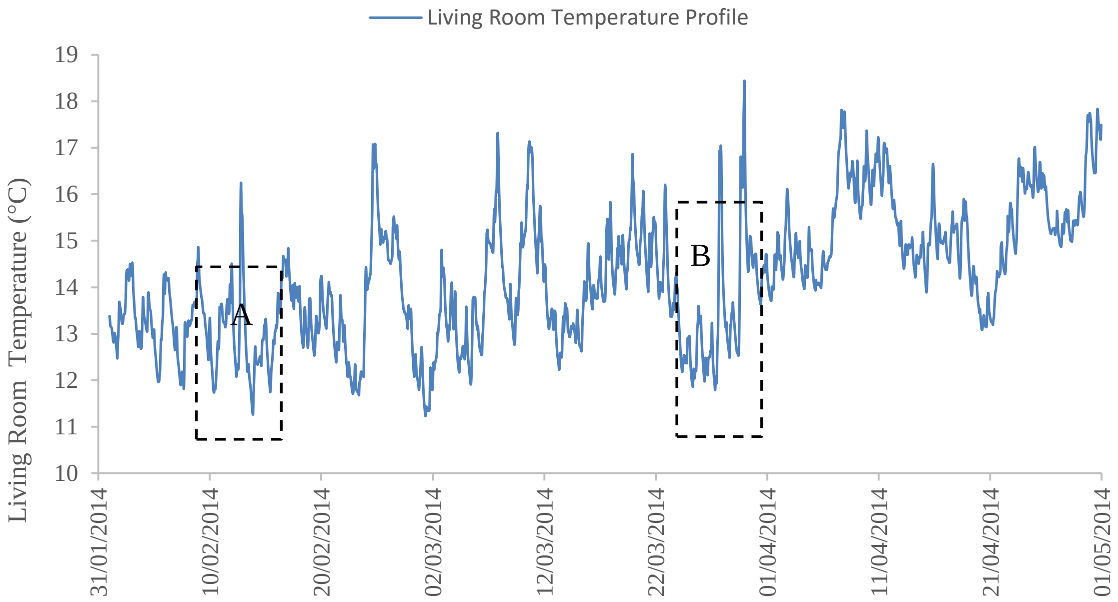

Figure 6.3 Living room internal temperature profile with points of interest highlighted.

Both interest points A and B arise from the occupant using their coal fire in the living room to provide heat. This was only used when the occupants were occupying the living room for a long period of time.

The internal room temperature for the manual controlled room never reaches CIBSE recommended levels and stays significantly under it. The maximum internal room temperature experienced was 18.4°C which is 3.6°C underneath the CIBSE recommendation.

With the adjacency to the kitchen and the door mostly remaining open the heater in the kitchen would have an effect on the temperature of the living room and they follow a similar trend. Figure 6.4 shows the internal room temperature alongside the external temperature demonstrating the influence the external temperature has on the internal temperature.

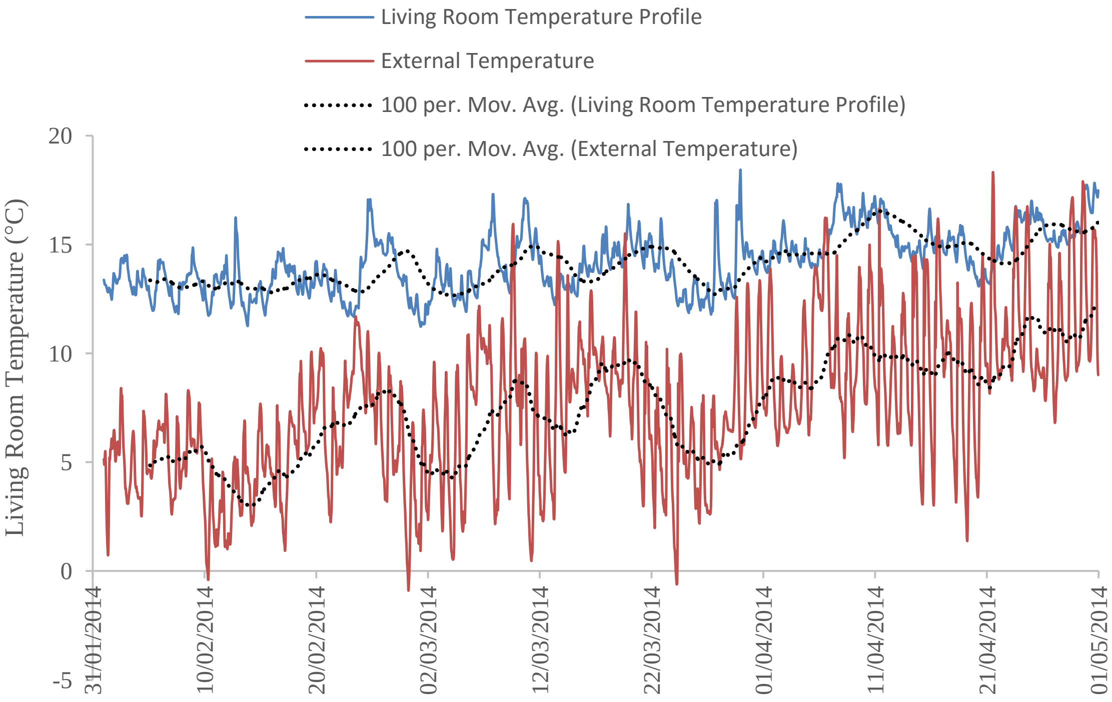

Figure 6.4 Living room internal temperature profile compared to the external temperature profile.

The living room experienced a minimum ambient temperature 11.2°C and an average temperature 14.2°C. During the initial observation period the internal temperature is significantly higher than the external temperature and is not heavily affected by the external fluctuations however later in the observation period the internal temperature is more heavily affected by the external temperature. This is due to the heating having less influence in providing thermal comfort and the external temperature providing a more prominent role.

6.2.1.3 Kitchen

The temperature experienced in the kitchen was low in comparison to CIBSE recommended levels throughout the early stages of the monitoring period.

The recommended internal room temperature for a kitchen as defined by CIBSE is 17°C to 19 °C during occupied hours. The kitchen temperature profile is shown in Figure 6.5.

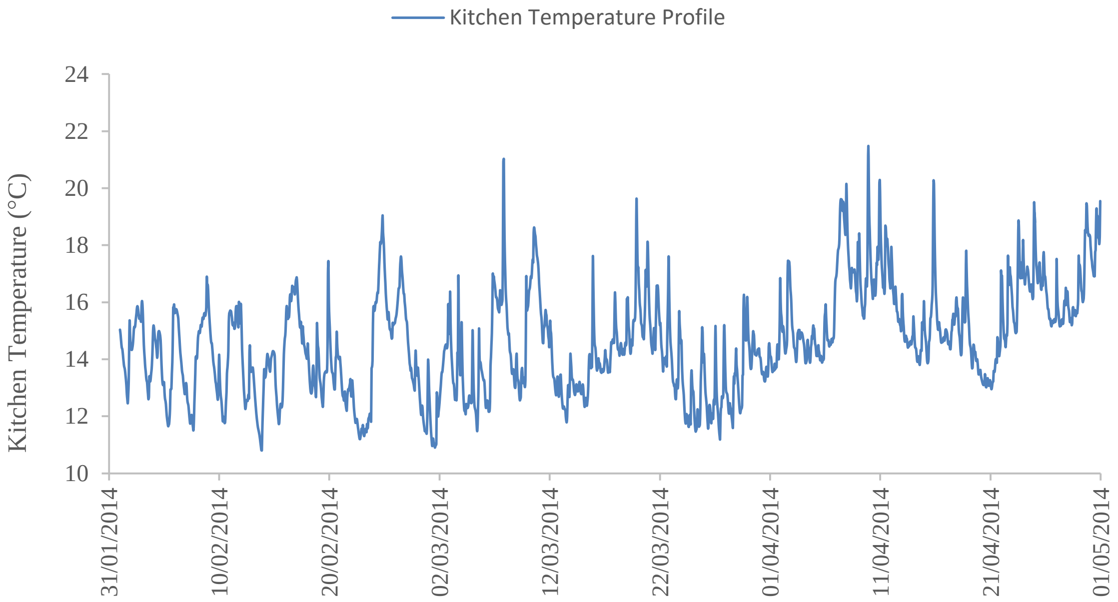

Figure 6.5 Kitchen internal temperature.

The temperature profile for the kitchen is very cool compared to recommended levels but shows no specific points of interest. The large swings in temperature compared to the other rooms in this case study building demonstrate a higher infiltration rate into the kitchen compared to the other observed rooms.

A comparison between the ambient internal temperature and external temperature is shown in Figure 6.6.

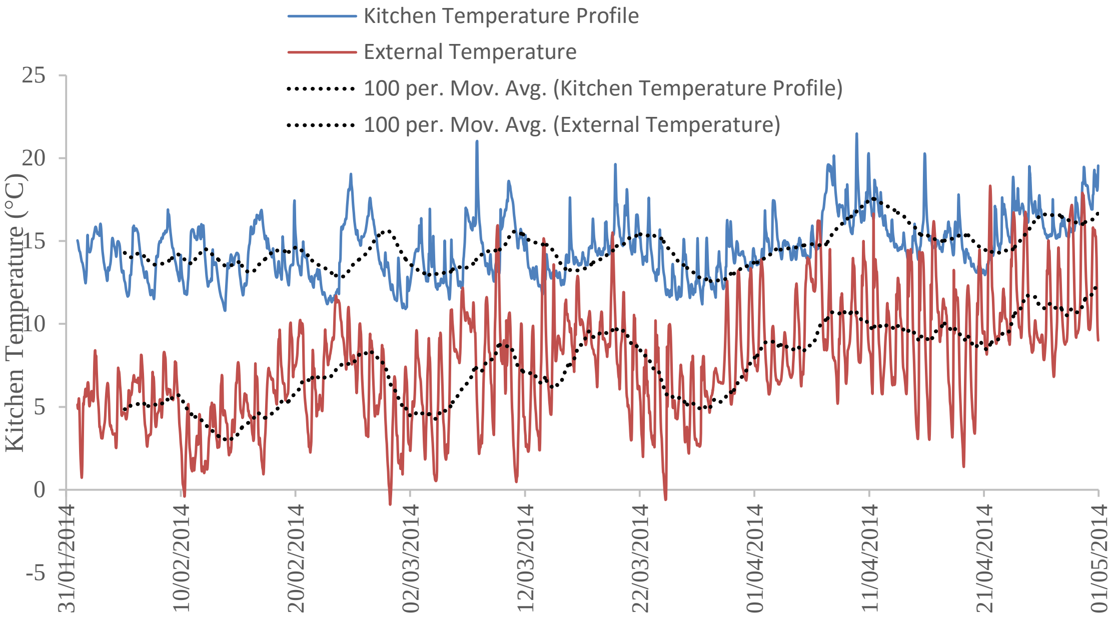

Figure 6.6 Kitchen internal temperature profile compared to the external temperature profile.

The minimum temperature experienced was 10.8°C with a maximum 21.5°C and an average 14.6°C.

Similar to Figure 6.4, during the initial phase of the observation period the internal temperature is not substantially influenced by the external temperature compared to the final period of observation and is much more heavily influenced by the heating system which is to be expected.

6.2.2 Time Control

This building has a timeclock control on the boiler with a power setting for the heat output. Although the timeclock had the ability to create a schedule using the push buttons shown in Section 3.6.3, the occupants used it manually and generally the heating was left on full until the occupants reached uncomfortable levels of warmth and then turned the heating off. Each radiator had a thermostatic radiator valve for some degree of room control.

6.2.2.1 Master Bedroom

Figure 6.7 shows the temperature profile for the living room of the time controlled building. There is a point of interest highlighted which shows a distinct change in temperature behaviour.

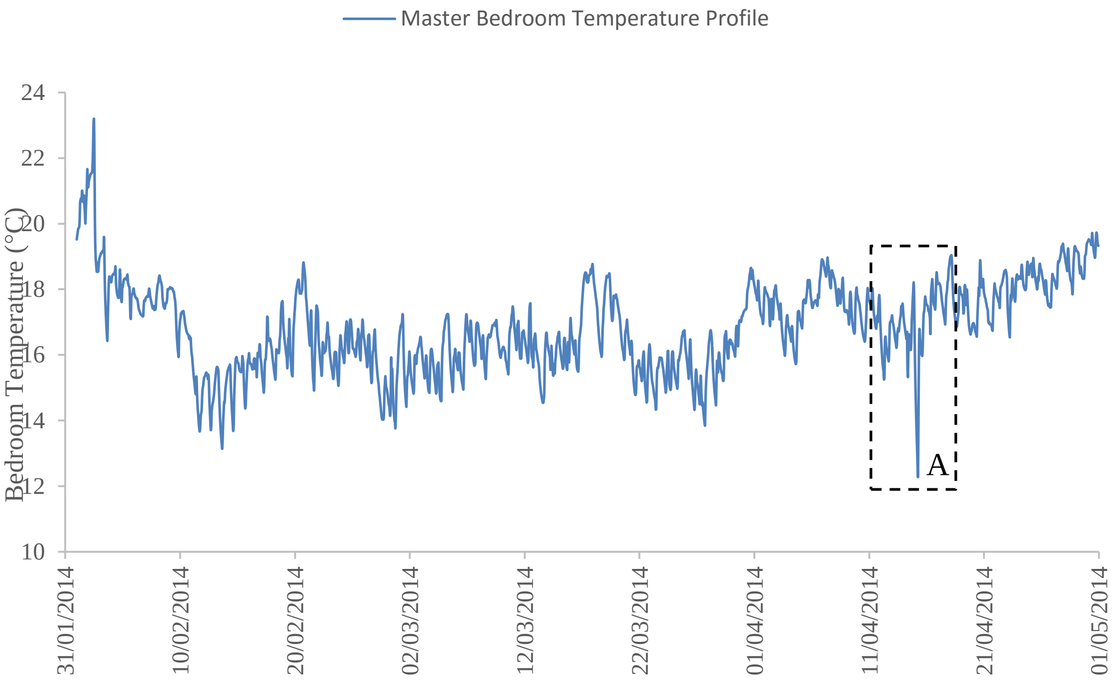

Figure 6.7 Master bedroom temperature profile showing the interest point A.

Interest point A shows a sharp drop in temperature down to 12.3°, a fall of 5.9°C. The sensor quickly recovers which demonstrates this perturbance has no lasting effect to the overall room temperature.

A comparison of ambient internal temperature and external temperature is presented in Figure 6.8.

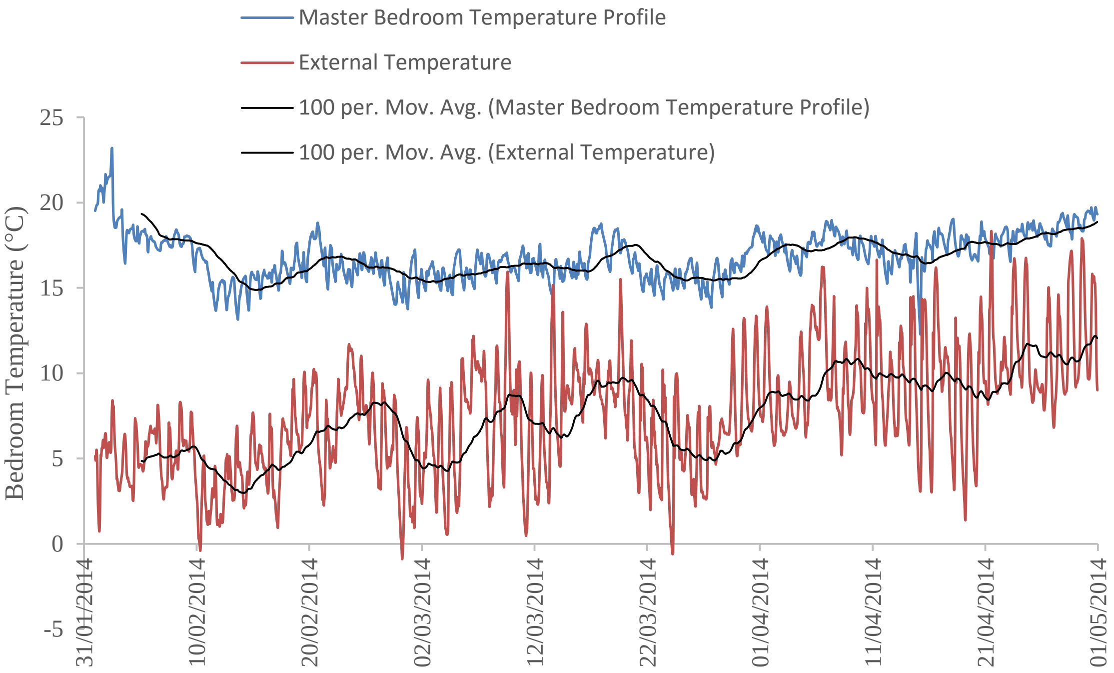

Figure 6.8 Master bedroom internal temperature profile compared to the external temperature profile.

The minimum temperature experienced was 12.3°C, with a maximum 23.2°C which occurred very early in the study. The average temperature was 16.9 °C.

The internal temperature profile is very steady when compared to the fluctuating external temperature which can be attributed to the heavyweight construction of the case study building with thick stone walls which are slow to respond to changes in the external temperature and temper internal fluctuations.

6.2.2.2 Living Room

The living room temperature profile, is shown in Figure 6.9.

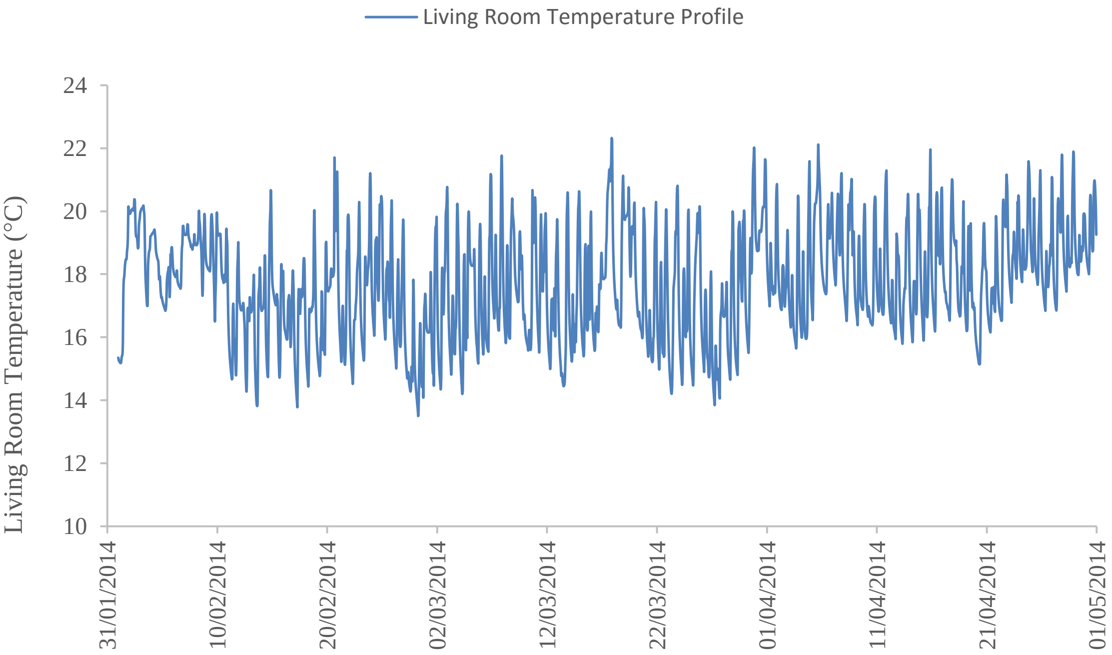

Figure 6.9 Living room internal temperature.

The general trend for the building is to be under heated and the living room follows this trend.

Figure 6.10 shows the temperature profile of the living room compared to the external temperature profile for the same period.

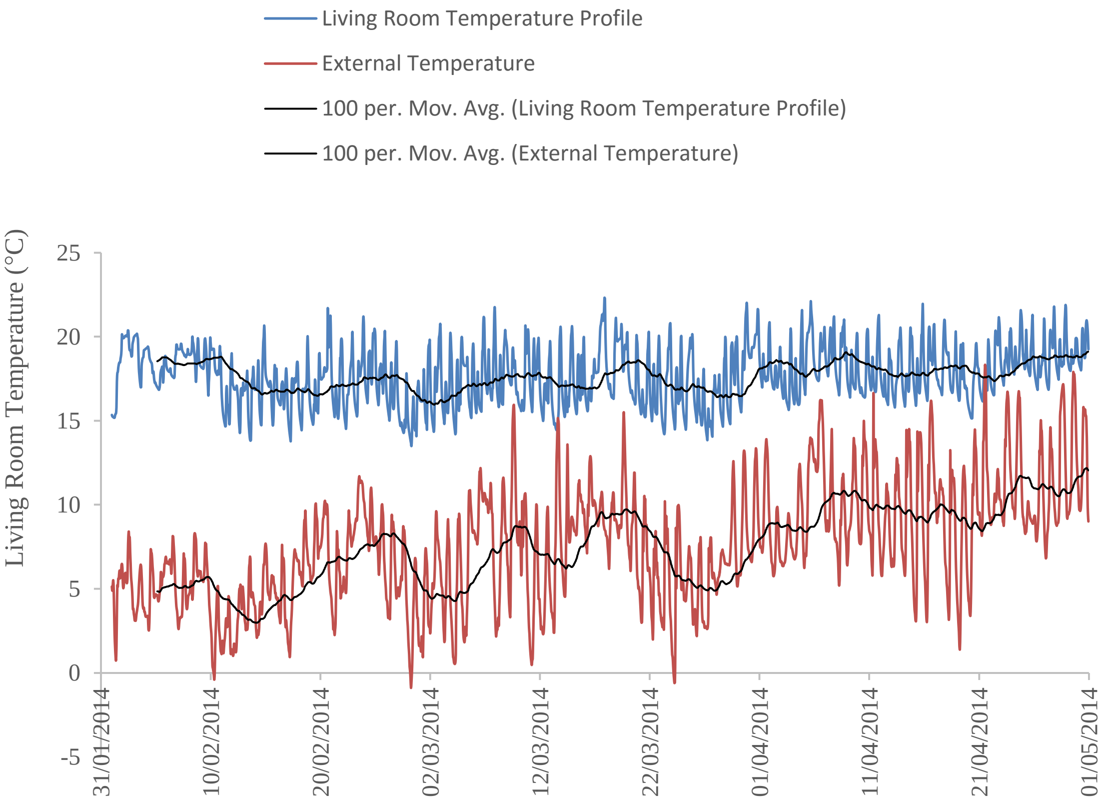

Figure 6.10 Living room internal temperature profile compared to the external temperature profile.

The moving average lines show the peaks in both temperature profiles occurring at similar times follow the same trend.

The minimum temperature experienced was 13.5°C, with a maximum temperature of 22.3°C and the average temperature was 17.7°C. The internal temperature profile does not follow the same trend as the external temperature but generally falls between 15°C and 20°C.

The average internal temperature of 17.7°C was confirmed as comfortable for the occupants and is in line with the thermostat setting for the temperature controlled building.

6.2.2.3 Kitchen

The kitchen room temperature profile is shown in Figure 6.11.

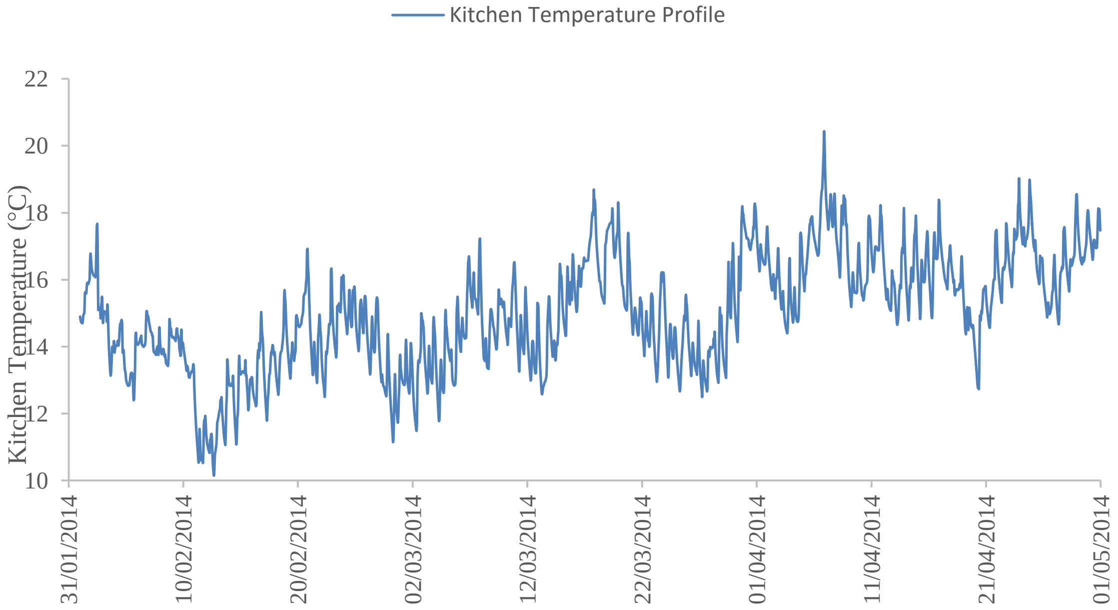

Figure 6.11 Kitchen internal temperature.

The temperature of the kitchen fell outside the recommended operative temperature for a significant amount of time. However the sensor was located away from the cooking appliances and also the radiator whereas the occupants had their seating near the radiator so would benefit from the radiant heat given out by these sources compared to the temperature recorded by the sensor.

A comparison between the ambient internal temperature and the external temperature is presented in Figure 6.12.

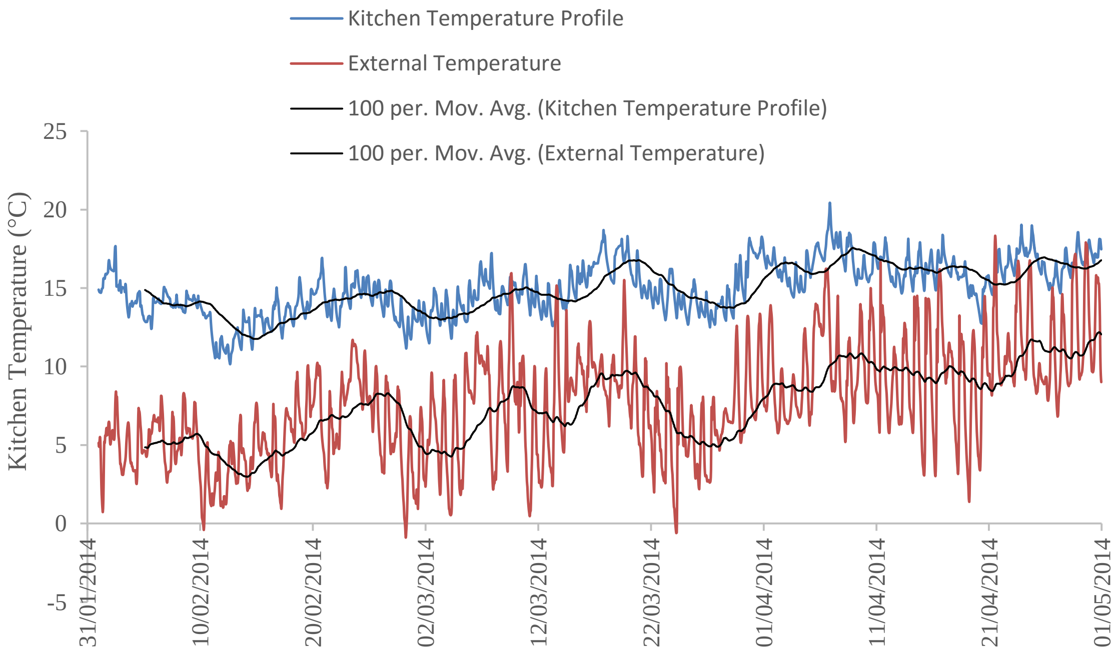

Figure 6.12 Kitchen internal temperature profile compared to the external temperature profile.

The kitchen experienced a minimum temperature of 10.1°C with a maximum temperature of 20.4°C and an average temperature of 15.0°C.

The kitchen internal temperature appears to be significantly effected by the external temperature following the same trend closely at the start of the observation period and this indicates a lack of heating to provide thermal comfort levels.

6.2.3 Temperature Control

This building has a temperature control on a programmable thermostat located in the living room. This has one schedule set for the entire week with no modifications made for weekend heating. When the heating is on, the setpoint is 18°C which matches with the CIBSE recommended operative temperature for the kitchen and bedroom but is low compared to the recommendations for the living room.

6.2.3.1 Master Bedroom

Figure 6.13 shows the temperature profile for the living room of the temperature controlled building. There are three points of interest highlighted which show changes in the temperature behaviour.

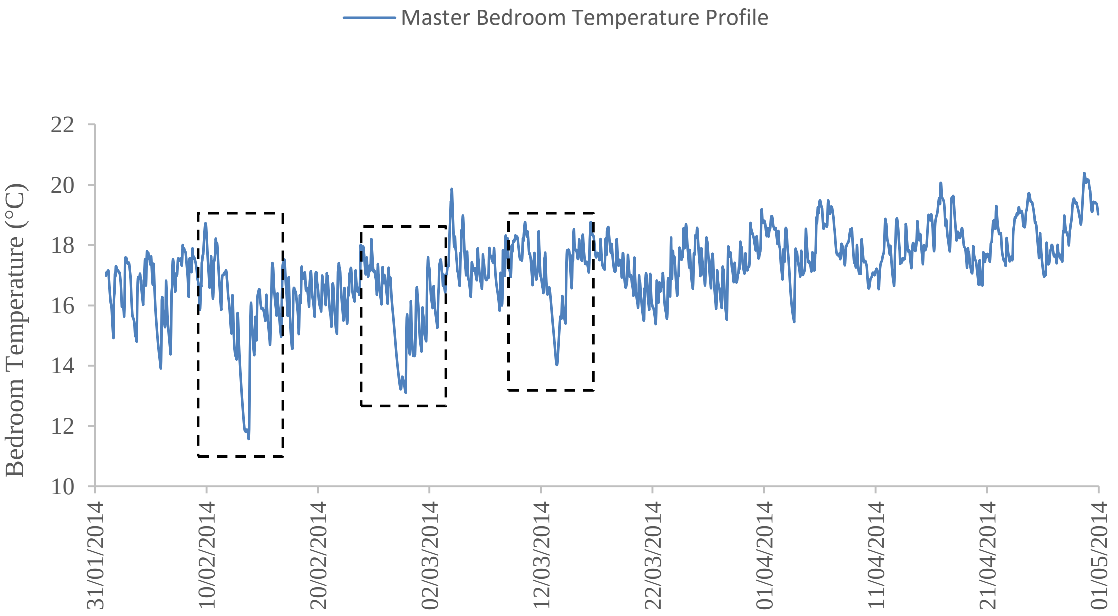

Figure 6.13 Master bedroom temperature profile showing the interest points.

The points of interest are denoted by the dashed boxes and show periods where the temperature dropped significantly in the temperature controlled house. During these periods the occupant switched off the heating system as they were away from the home for an extended period and this was the method they used to provide cost savings.

The time between the first and second off period, as indicated in Figure 6.13, shows a relatively low temperature where the heating system did not manage to bring the room back up to the desired 18°C and this indicates a deficiency in the heating output during the coldest months.

Figure 6.14 compares the internal ambient temperature to the external temperature for the observation period.

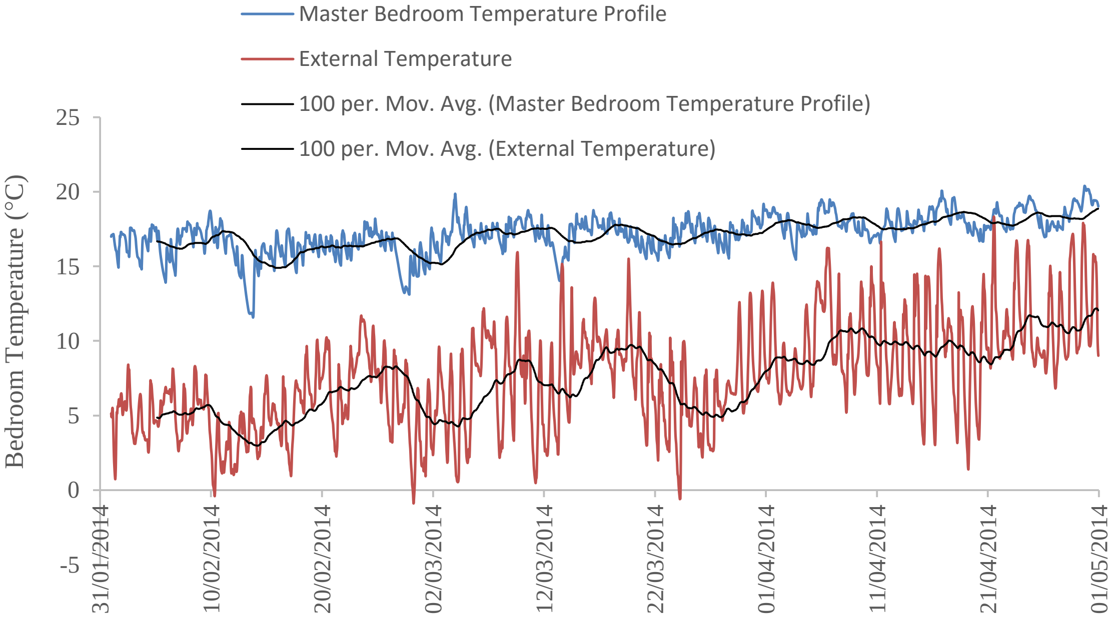

Figure 6.14 Master bedroom internal temperature profile compared to the external temperature profile.

The minimum temperature experienced was 11.6°C, with a maximum 20.4°C and an average 17.2°C.

The trend of the internal ambient temperature is not substantially affected by the external temperature but driven by the heating system controlling the temperature to the thermostatic set point.

6.2.3.2 Living Room

The living room temperature profile, along with the recommended temperature band, is shown in Figure 6.15.

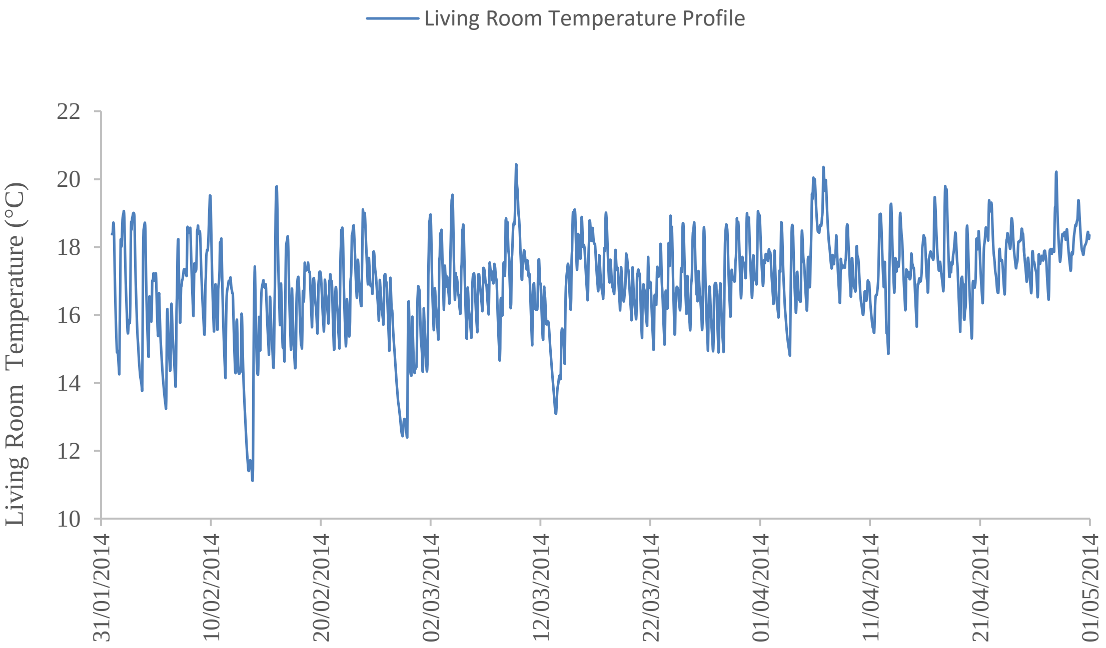

Figure 6.15 Living room internal temperature with recommended operative zone highlighted.

For the living room, the CIBSE internal temperature was under the CIBSE recommended operative temperature for 100% of the time. However the recommendation was between 22°C and 24°C and the occupant had the thermostat set for 18°C as indicated on Figure 6.15.

When the profile is compared to the thermostatic set point of 18°C, and with a deadband 1°C, it falls within this zone for 47.8% of the time which demonstrates a good improvement in the thermal performance compared to the previous case study buildings.

The effect the evening cooking has on the temperature profile of the downstairs rooms in the experimental data of the temperature controlled building is shown in Figure 6.16.

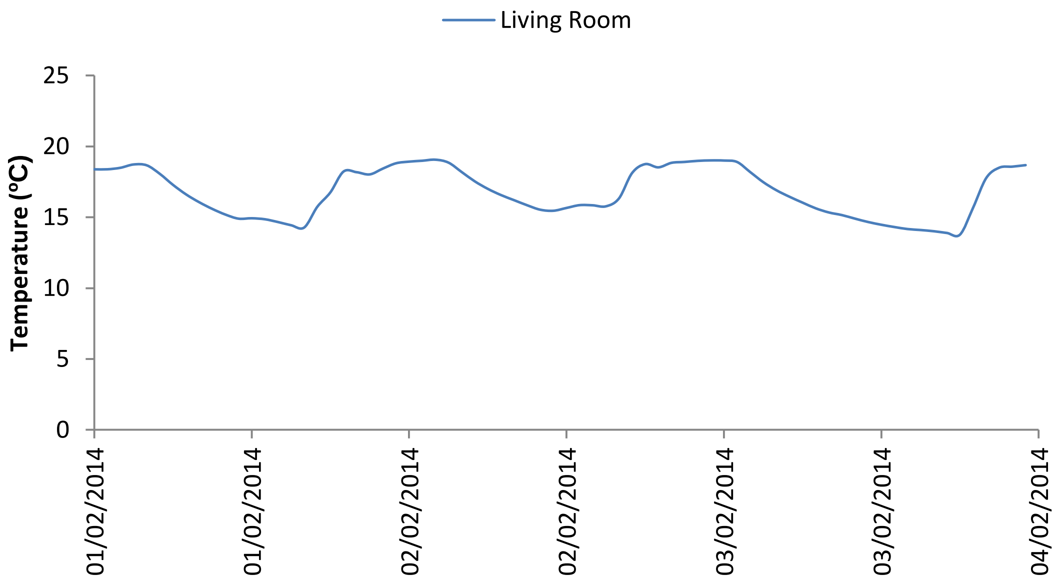

Figure 6.16 Effect of cooking in the kitchen on living room temperature

A peak is clearly seen at the start of the evening heating period each day. The first peak occurs at 19:00 on 2 February with the second peak occurring at 18:00 on 3 February. This highlights the occupant cooked their meals an hour earlier on the second day compared to the first unlike a static schedule the dynamic thermal model would contain.

A comparison between the internal ambient temperature and the external temperature is presented in Figure 6.17.

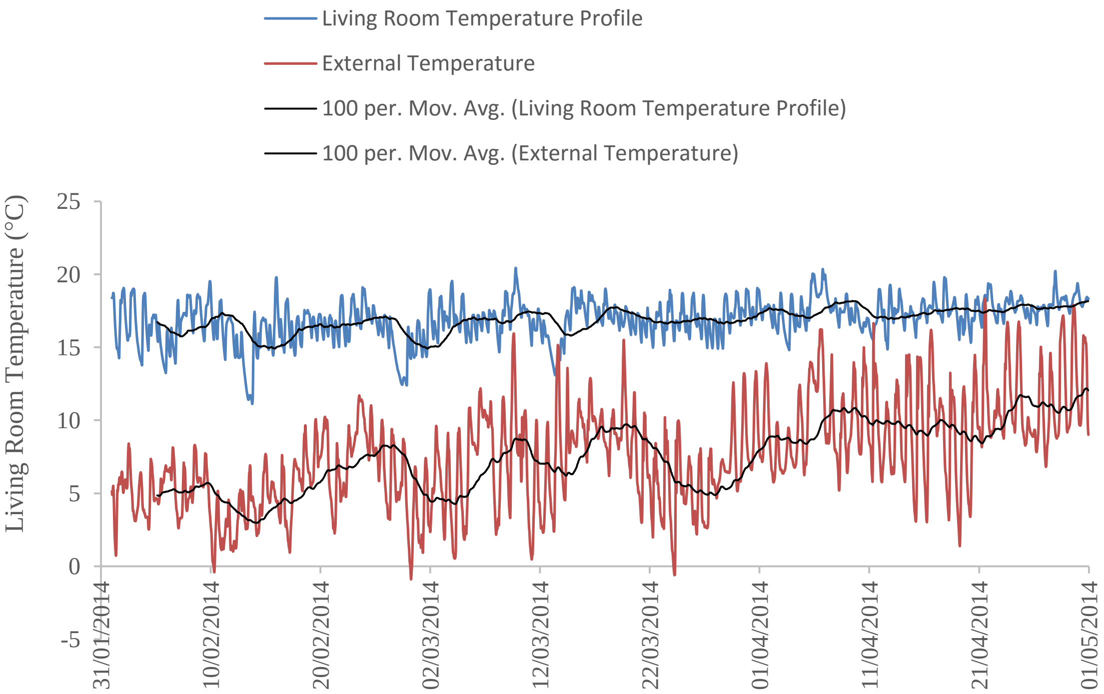

Figure 6.17 Living room internal temperature profile compared to the external temperature profile.

The minimum temperature experienced was 11.1°C with a maximum 20.4°C and an average 16.9°C

The average temperature of 16.9°C is very close to the thermostatic setpoint of 18°C and when periods of no heating are taken into account it demonstrates a good level of control.

6.2.3.3 Kitchen

The kitchen temperature profile, along with the recommended temperature band, is shown in Figure 6.18.

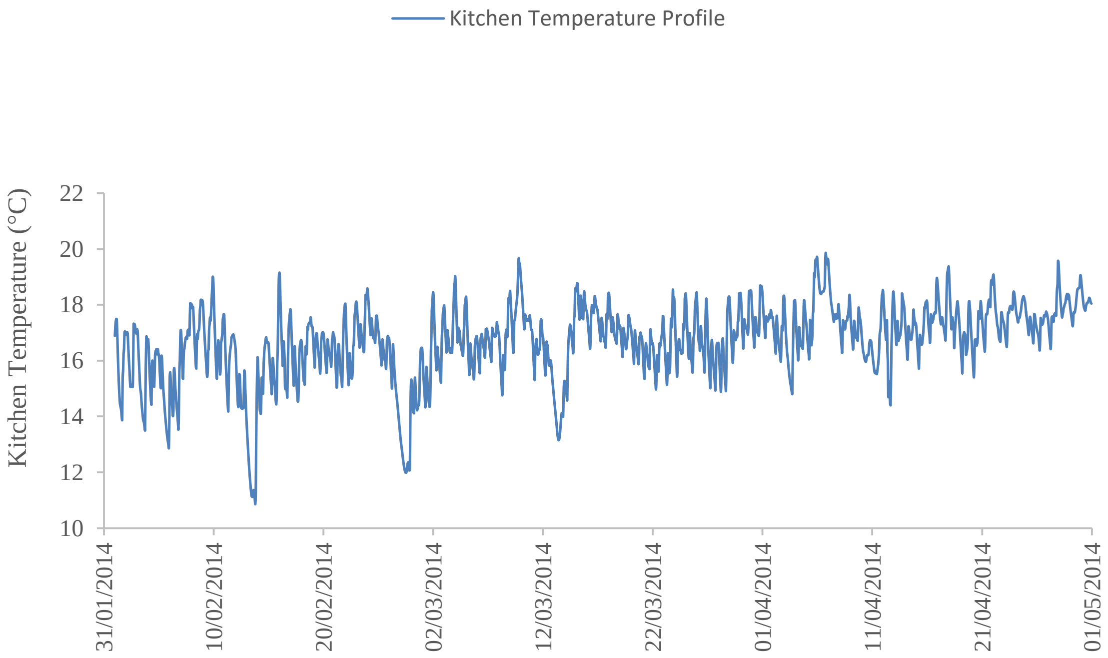

Figure 6.18 Kitchen internal temperature with the recommended operative zone highlighted.

Compared to the living room, the kitchen was a little underheated but the temperature sensor would not pick up on the radiant heat from the cooking and heat source which the occupants would. This is because the thermostat was located within the living room and so we would expect the kitchen to not perform as well thermally.

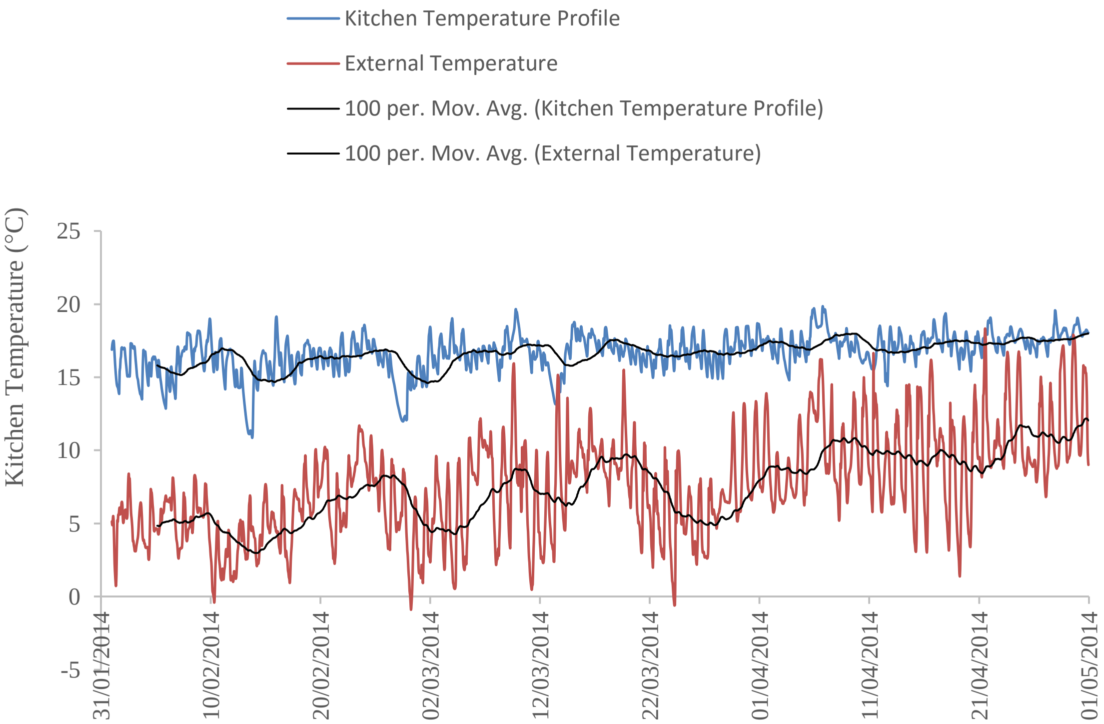

Figure 6.19 Kitchen internal temperature profile compared to the external temperature profile.

The minimum temperature experienced by the kitchen was 10.9°C, with a maximum 19.8°C and an average 16.7°C. The kitchen is not substantially influenced by the ambient external temperature and follows a very similar trend to the living room temperature profile.

In conclusion the results of the experimental observation period of the three case study homes have been presented comparing the internal temperature profiles to the CIBSE recommended operative temperatures and also the recorded external temperature at the time of observation. Observations were made for each room regarding the thermal performance and the reasons for the fluctuations which were outside of expected bounds were highlighted.

The chapter will now move on to the presentation and discussion of the computational results of the dynamic thermal models which were created for each case study building in this study.

6.3 Temperature performance compared to CIBSE recommended guidelines

The results obtained from the experimental study have been discussed in Section 6.2 detailing the actual performance of the case study domestic homes. This was in the form of internal temperature profiles for each of the case study building rooms. Points of interest were noted on the figures which display abnormalities in the expected temperature performance as well as periods in which there was direct human interference with the heating system.

The study will now discuss the expected temperature performance by comparing the experimental data to the CIBSE guidance on recommended internal temperatures for domestic homes. These recommended temperatures are published by CIBSE and the ones relating to the rooms in the experimental study are detailed in Table 6.1.

Table 6.1 CIBSE recommended internal temperatures

Room	**CIBSE recommended internal temperature (°C)**
Bedroom	17-19
Living Room	22-23
Kitchen	17-19

The data provided in Table 6.1 highlights two temperatures ranges which are relevant to the case study building. These temperatures are based on providing adequate thermal comfort for the occupants given the different room usage and occupant requirements.

A comparison between the CIBSE recommended internal temperatures and the average internal temperatures during the heating period for each case study room is plotted in Figure 6.20. The figure details the percentage of time that each rooms spends below, within and above the recommended temperatures.

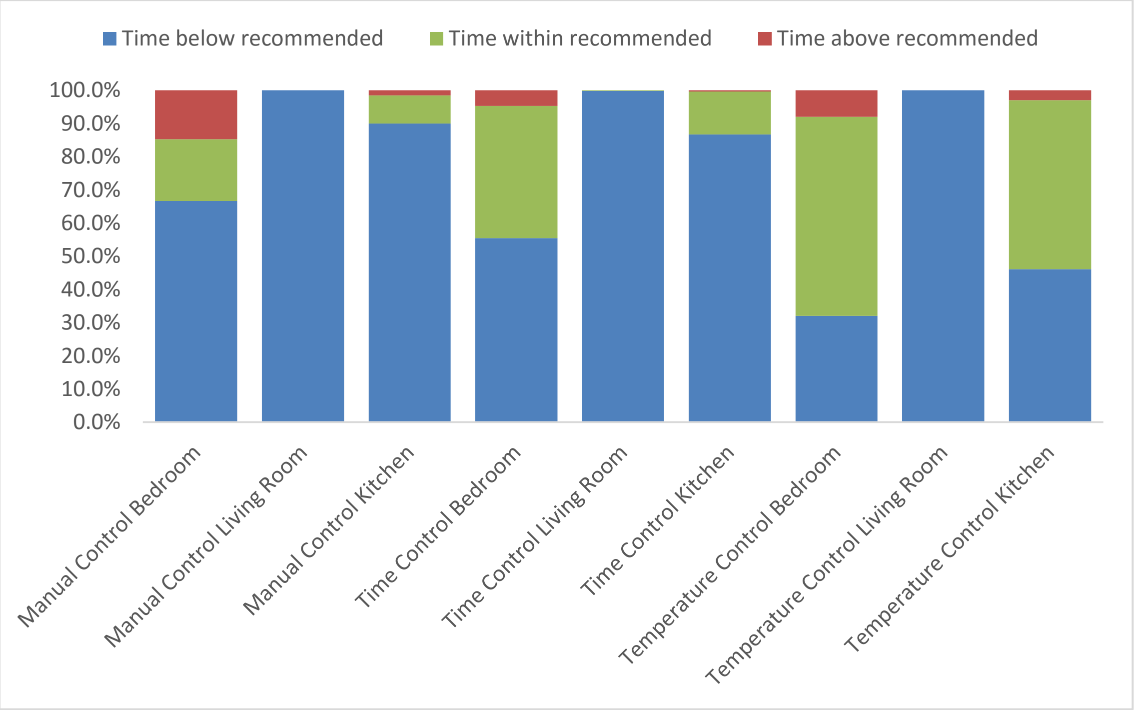

Figure 6.20 Times at which the average internal temperature is within the CIBSE recommended guidelines.

The figure shows a strong bias towards insufficient internal temperature to maintain the CIBSE recommended internal temperatures and this is especially noticeable in the living room for all buildings. The reason for this is the living room recommended temperature is substantially higher than the bedroom or kitchen recommended temperatures and the heating systems are not controlled to provide that much heat to the living rooms.

In all cases the living room spent their entire duration below CIBSE recommended levels which indicates that the CIBSE recommendations of 22°C to 23°C to achieve thermal comfort is too high when compared to the occupants perceptions of warmth and comfort.

6.3.1 Manually Controlled Building

The master bedroom in the manually controlled building spent a relatively short length of time within this recommended temperature band, with a total of 18.6% of the time within this comfort level, 14.7% of the time at temperatures exceeding 19°C and 66.7% of the time below 17°C.

The ambient temperature in the kitchen spent 8.5% of the time within the recommended levels with 1.5% above 90% below. During the first half of the observation period, only spikes in the temperature profiles fall into the recommended occupied temperature with the majority of the time being under heated.

6.3.2 Time Controlled Building

The master bedroom spends a lot more time within the CIBSE recommended operative zone. 39.9% of the time is spent within this zone with only 4.7% of the time being spent above it and 55.4% of the time below During the early part of the study when the external temperature was colder, the master bedroom spent more time below the minimum recommended level when compared with the end of the study period.

The living room spent very little time within the CIBSE recommended operative zone with only 0.2% of the time being within and the remaining 99.8% of the time below the recommended minimum.

The kitchen spent 12.9% of the time within the CIBSE recommended operative zone with the majority of this time being later in the year when the external temperature was higher. The operative temperature was only exceeded for 0.3% of the time and below the recommended levels for 86.8% of the time.

6.3.3 Temperature Controlled Building

The temperature controlled house had a temperature profile which fell into the CIBSE recommended operative zone for a much greater period than the previous two case studies. 60% of the time the bedroom was within these bands, with 8% above and 32% below.

The CIBSE recommended operative zone for the kitchen is between 17°C and 19°C which corresponds to the occupants thermostat set point of 18°C with a deadband of 1°C. 51% of the time the room was within the bounds with only 2.9% above and 46.1% below.

As discussed in section 3.3 the occupants of time and temperature controlled building found their living room to have a comfortable thermal condition. The manual controlled building found theirs cool, which does correspond with the temperature always being below the CIBSE recommended temperature, however they did not have central heating in the living room and relied on a coal fire.

The literature review in section 2.3.2 discusses studies by Oreszczyn *et al.* (2006), Hong *et al.* (2009), Huebner *et al.* (2013a) and Vadodaria *et al.* (2014). The studies conclude that the homes of the occupants surveyed were not heated to the 22-23°C which CIBSE recommends but to a temperature of approximately 19°C which is in line with the experimental results of the temperature controlled case study building.

These observations lead to the conclusion that the CIBSE recommendation of an internal operative temperature of 22-23°C for living rooms is high when compared to both occupant preferences and experimental observations in this study.

6.4 Validation

This chapter compares the results of the experimental and computational elements of the study to establish a validation of the computational models which are used in subsequent chapters.

The experimental test period of 1 February 2014 until 30 April 2014 was used for the computational simulations and this allows for a direct comparison of the building temperatures to establish if the computational model performs within expected error levels.

6.4.1 Criterion of assessment and quantification of uncertainties

The review of existing validation methodologies was undertaken in section 2.7. The most robust and appropriate validation technique is a comparison between the experimental and computational results of the case study buildings. This will take the form of a comparison between measured internal temperatures and computed internal temperatures.

A similar methodology was used by Buratti *et al*. (2013) and Mateus *et al.* (2014) where internal measurements were taken and compared to the results from the dynamic thermal modelling. Mateus used a comparison between the average room temperature over the observation period between the experimental and computational data sets. This same methodology was used by Buratti, who went on the draw conclusions on energy consumption based on a validation of internal room temperatures.

For dynamic thermal simulation typical error results provided by previous studies discussed in section 2.7 (Laouadi and Atif (1998), Mateus *et al.* (2014), Buratti *et al.* (2013)) have fallen with the range of 2-3°C when comparing simulated with experimental results. For normal winter internal temperatures of approximately 20°C, this error rate corresponds to a percentage error of between 10% - 15%.

The chapter takes each case study building in turn, starting with the manually controlled building and compares each of the rooms which contained experimental sensors with the results from that study.

6.4.2 Manually Controlled Building

For the manually controlled building each of the three rooms are taken in turn and the results compared in order to establish the validity of the dynamic thermal model for this scenario.

The degree day calculation for the validation period was undertaken, comparing the heating energy predicted with this method as described in Section 4.3 with the heating energy value provided by the dynamic thermal model. In this case, the average error in the degree day comparison was calculated to be 31%, with the degree day calculation providing a higher required heating load than the dynamic thermal model predicted.

This value is within expected bounds due to the home using auxiliary electric fan heaters which were not included within the dynamic thermal model, along with the internal temperature being below recommended levels. This suggests under heating in the dynamic thermal model compared to the degree day method which assumes recommended internal comfort conditions are maintained.

Figure 6.21 shows a good correlation between the simulation and field data for the bedroom.

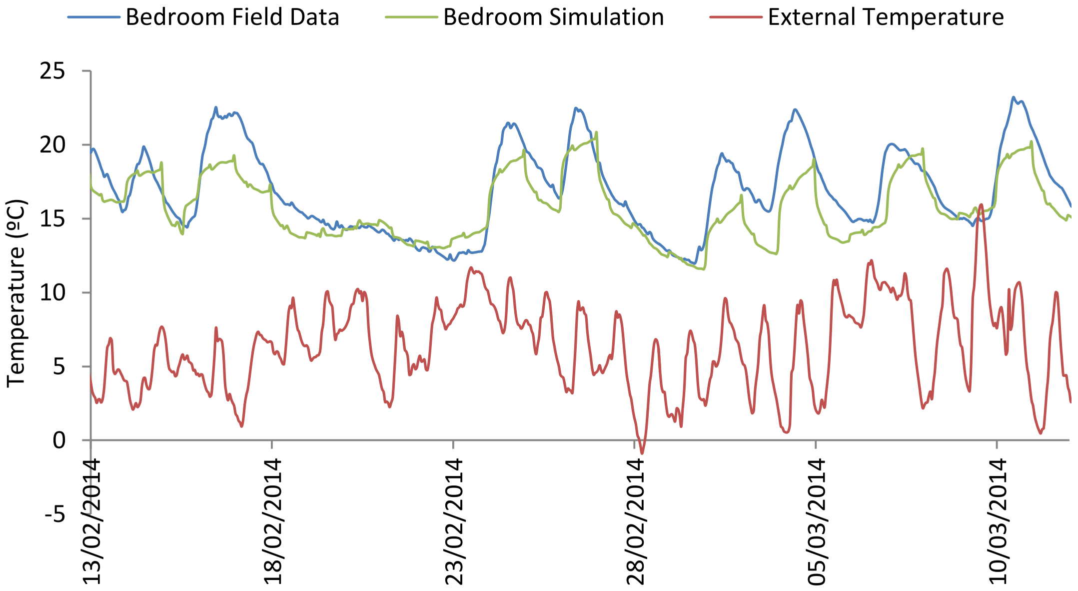

Figure 6.21 Comparison of field data and the simulation results for the heating period in the manually controlled bedroom.

The bedroom simulation data follows a very similar trend to the bedroom field data. However the peaks in temperature for the simulation do not hit the highs of the expected field data with a maximum temperature difference being 2.5°C. This is due to the occupants using a fan heater during particularly cold months at the beginning of the test period due to their changing work schedules this solution was seen as being much more practical than attempting to second guess when their electric storage heaters would need to be turned on to provide heat the next time they were in the bedroom.

The correlation and accuracy of the simulation compared to the experimental data is much better defined in Figure 6.22 where a free running period is shown which corresponds to the occupants not using their heating system due to being away.

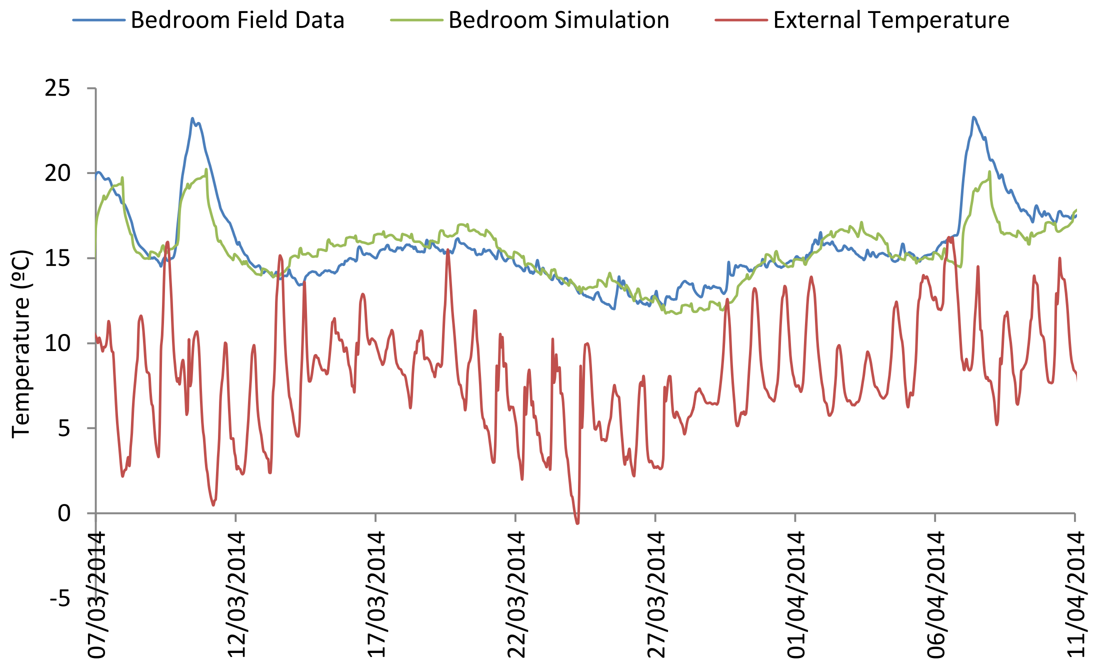

Figure 6.22 Comparison of the field data and simulation results for the free running period in the manually controlled bedroom.

The period between 13 March and 06 April 2014 is the period of free running in the home where the heating system was not used. The correlation between the experimental and simulation data is strong at this period with a maximum difference of 1.6°C.

The data for the bedroom simulation and field data shows a good match in pattern for the whole observation period. The average error for being 7.3%, with a maximum error being 33.5%. In this room a small electric fan heater was used intermittently which accounts for the larger differences in temperature at the beginning of the simulation period and towards the end of the simulation period the bedroom field data was reading a higher temperature than the simulation predicted. The intermittent use of the fan heater again accounts for this difference.

Figure 6.23 shows the comparison of the experimental and computational data for the living room.

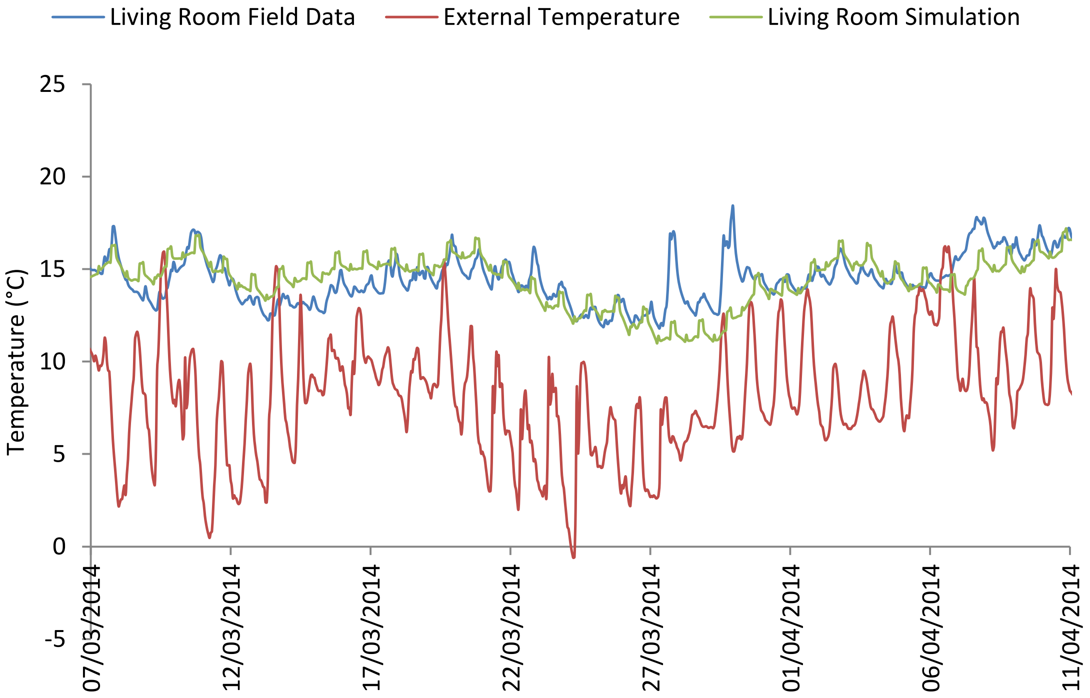

Figure 6.23 Comparison of the field data and the simulation results for the manually controlled living room.

The temperature profile for the living room shows, in general, good with two peaks in the field data on 27 April and 29 April. These are not accounted for within the dynamic thermal model as they are the result of lighting the coal fireplace in the living room and as such are manual interventions which cannot be predicted.

Overall for the whole case study period, the data shows a much stronger correlation than is shown in Figure 6.21 with the pattern following very closely between both data sets. Once again, the simulation overestimates the internal temperature in the period 11 April 2014 to 16 April 2014 and then underestimates it from 16 April 2014 until 28 April 2014.

The average error experienced in this comparison is 5.5%, with a maximum error being 17.9% which demonstrates a very good correlation between the experimental data and the computational data. This provides confidence that the dynamic thermal model is behaving very close to the real world building and data from the model can be used with confidence.

The next room to be considered in Figure 6.24 is the kitchen.

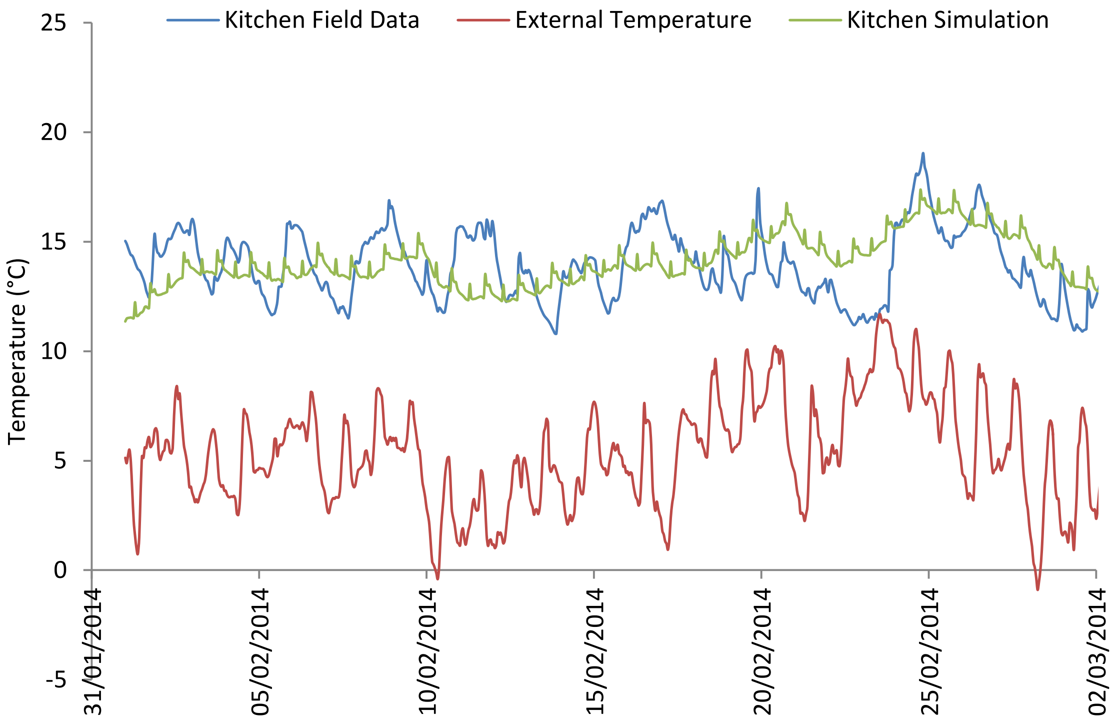

Figure 6.24 Comparison of the field data and the simulation results for the manually controlled kitchen.

The kitchen temperature profile for the manually controlled building shows the least accurate correlation of any of the rooms studied in the manually controlled case study building. The large swings in temperature in the kitchen are over a period of 2-3 days and this does not appear to follow a pre-determined schedule and so was challenging to model using the dynamic thermal modelling software. The internal temperature predicted by the software runs through the centre of the peaks from the experimental data which provides a good approximation for the average internal temperature but fails to account for the large temperature swings.

In the occupant comfort survey, the issue was raised where by the occupants pointed out they found the kitchen to be a room which suffered from drafts of cold air which. This made the room harder to heat than the other rooms in the home when it was particularly windy. An increase in wind speed would cause larger infiltration of outside air, causing sudden changes in room temperature which accounts for the larger discrepencies in this temperature profile. The outdoor wind speeds and directions were unfortunately not recorded in the experimental phase of the study and the computational wind data is based on a historical average from the weather file.

The same general trend as observed in Figure 6.21 and Figure 6.23 is present in this case. This is to be expected since in general, the building was very open between the kitchen and the living room and so follow a similar temperature profile with a heavy thermal influence between the two, with an open doorway which was simulated with the real time air transfers in the dynamic thermal model.

The average difference between the experimental data and the computational data for this room resulted in an average error rate of 7.6% which demonstrates a very good correlation between the experimental data and the computational data from the dynamic thermal models.

6.4.3 Time Controlled Building

The time controlled building is discussed and a comparison between the experimental and computational results for each of the rooms in the experimental study is presented.

A degree day method calculations was undertaken to predict the energy consumption of the timed controlled building over the course of the experimental observation period as outlined in Section 4.3. The error in this comparison is 24%, with the degree day calculation reporting a higher energy consumption. This value is within the expected bounds and it is expected to be higher than the simulation as the building was generally below the recommended comfort levels in the simulation and the experimental observation compared to the degree day method which would assume the building was at a recommended indoor temperature.

Each room is taken in turn and a comparison conducted to establish the accuracy and validity of the dynamic thermal model and the computational analysis compared with the experimental observation data.

Figure 6.25 shows a comparison between the computational and simulation data for the bedroom.

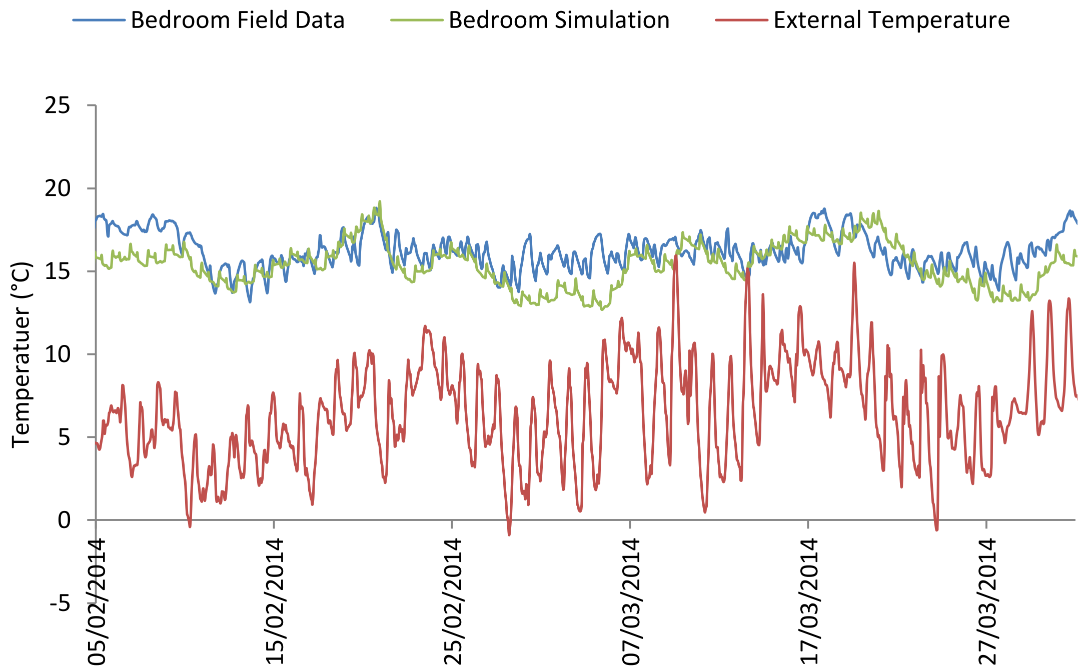

Figure 6.25 Comparison of field data and the simulation results for the timed control bedroom.

For the bedroom of the time controlled building, the temperature profile of both the experimental and simulation results follow a very similar trend as shown in Figure 6.25, with the main oscillations in the temperature being picked up by the dynamic thermal model.

The trend of the experimental data compared to the simulation data, is again very close for the bedroom in the time controlled building. Noticeably between 16 April 2014 and 27 April 2014, the dynamic thermal model underestimates the temperature in the bedroom compared to the actual internal temperature recorded in the experimental study. This could be due to an intermittent factor which was not predicted in the dynamic thermal model, such as human intervention in the opening of a window or the heating being reduced in that room due to no-occupancy.

The overall error in this room temperature during the observation period is still within expected bounds, with an average error between the internal temperatures of the computational study and experimental study of 10%.

Figure 6.26 shows a comparison between the living room temperatures for the simulation and experimental data.

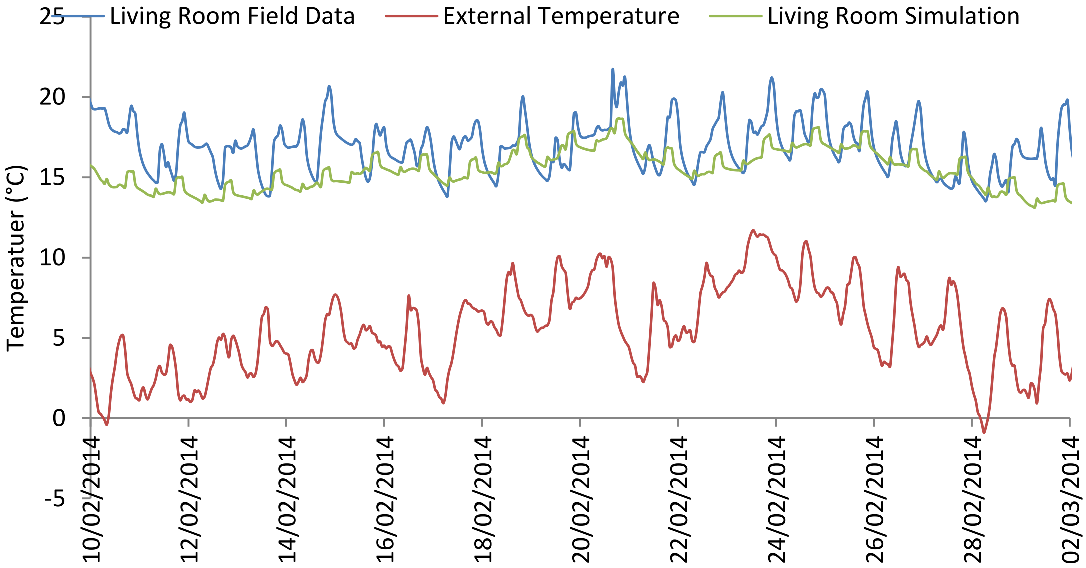

Figure 6.26 Comparison of field data and simulation results for the timed control living room.

The living room shows a much less correlation than does the bedroom in Figure 6.25 with larger peaks being recorded in the internal temperature compared with the dynamic thermal model. During this period of time, extensive use of the coal fire was noted by the occupants which accounts for these large peaks in temperature which are not recorded in the model. Later in the reporting period, when the fire is lit less, the peaks reduce and the temperatures show a stronger correlation.

The same general trend in the temperature profiles exists here as with Figure 6.26. A temperature dip between the same dates can be observed in the living room in the simulation compared to the experimental data. The lower diurnal temperatures are shown in the simulation data compared to the field data. This is because the simulation consists of an average zone temperature for the room where as the field data is a point temperature and therefore is more susceptible to larger swings in temperature due to the sensor location and the effect of the local environmental conditions, such as drafts or radiant effects from the wall. The magnitude of the temperature will be affected to a much larger degree than the trend in the temperature profiles.

The connection between the kitchen and living room is through an open passage and so the drafts which affected the kitchen in Figure 6.24 would also have an effect on the living room in Figure 6.26,

The differences in the average internal temperature comparison between the experimental data and the computational data is calculated to be 11.6% which is within expected bounds.

Figure 6.27 shows a comparison between the kitchen temperatures for the simulation and experimental data.

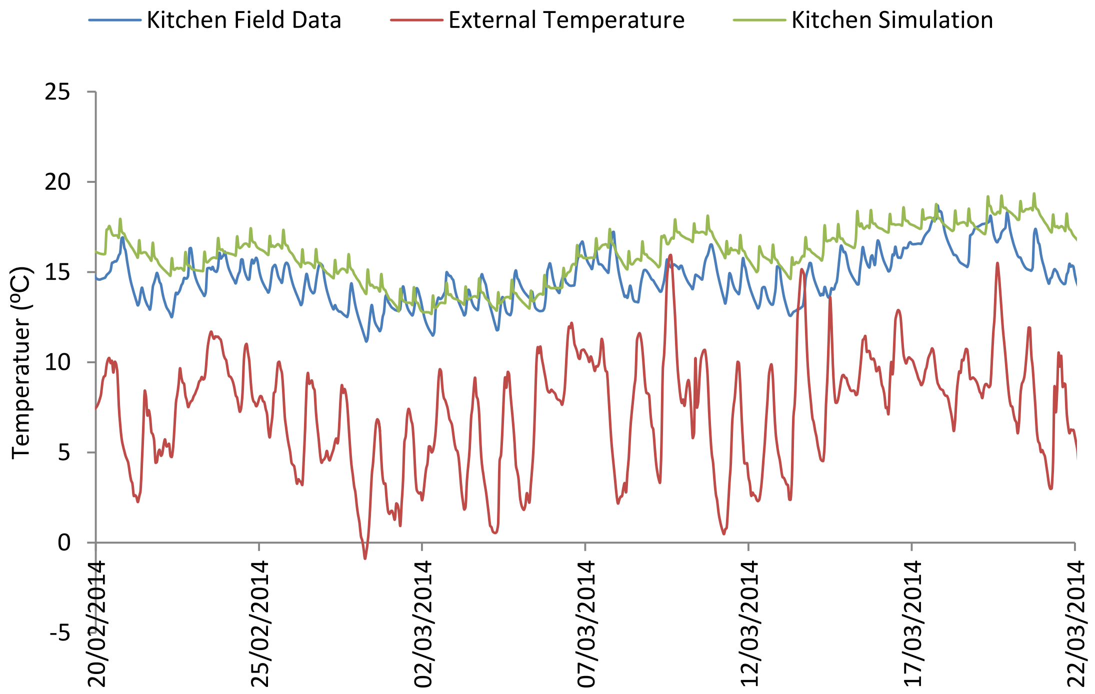

Figure 6.27 Comparison of field data and the simulation results for the time controlled kitchen.

In the kitchen the peaks of the simulation data are of a similar magnitude as the experimental data and the trends in the temperature profile match. However for this period the simulation is running slightly warmer compared to the kitchen. Although this case study has central heating with a timeclock, the heating was operated manually with the residents leaving the heating on for the whole home and only turning it off when they felt too warm which made the simulation a little more challenging.

The temperature profile of the computational data compared with the simulation data shows a much closer trend than the previous two figures with the peaks and troughs matching between the two data sets and an average error between the internal temperatures being 9.4%.

The errors experienced in the timed controlled building are of a similar magnitude to the manually controlled building due to a high degree of manual control being used here too. The error rate is within the expected bounds, however it shows a good correlation between the experimental and computational data which provides confidence that the dynamic thermal models behaves as would be expected when responding to internal and external environmental influences.

The temperature controlled building is now discussed in detail, thus establishing the final validation of the experimental data sets and establishing the quality of the dynamic thermal models in all three case study buildings to simulate and predict the buildings thermal response.

6.4.4 Temperature Controlled Building

The temperature controlled building is thermostatically controlled by a centralised thermostat in the living room. This building has minimal manual control aside from a heating boost for one hour which was used when the occupant felt cold when going to bed.

Initially a degree day calculation was performed on the case study building in order to compare the predicted energy consumption with the actual energy consumption. The average error experienced in these was much higher than that in the previous two case study buildings being71% which equates to an average difference of 2.8 kW which is reasonably significant.

Figure 6.28 shows a comparison of the boost periods compared to the error experienced between the energy consumption of the dynamic thermal model and the experimental data.

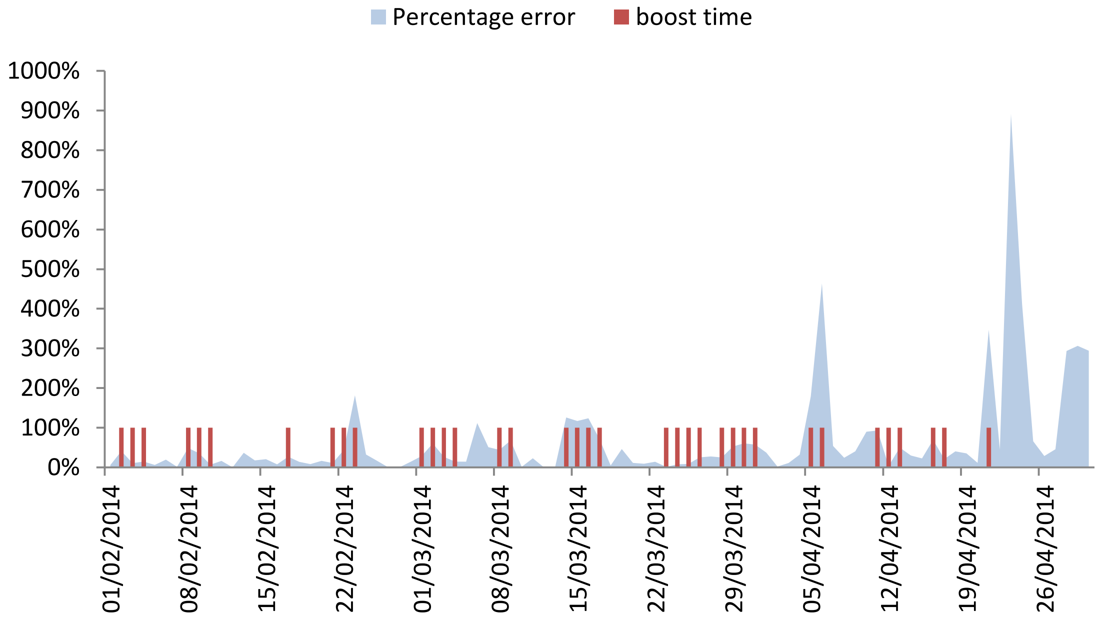

Figure 6.28 Comparison of boost periods and the percentage error in the degree day calculations.

The figure clearly shows a correlation between the boost period for the heating and a rise in the error rate for the comparison of the energy consumptions. This is because the degree day method works on an averaged internal temperature which does not take into account the manual overrides such as boost periods which occurs in the experimental data set.

It should be noted that at the end of the test period, very large percentage errors are present. This is because the external temperature is increasing towards the free running temperature of the building and so with lower heating requirements this artificially raises the percentage error.

These manual boosts, which cannot be predicted by the degree day method introduce heating energy gains into the dynamic thermal model which are not accounted for and this increases the error rate.

The larger error peaks are observed on 6, 21, 23, 30 April 2014 are due to the heating requirement being low due to the increasing outdoor temperature approaching the building base line free running temperature and so small actual energy differences result in very large percentage differences.

Each room is now taken in turn and the internal temperature for them compared between the computational model and the experimental data to establish the accuracy and validity of the computational model compared to the experimental data.

Figure 6.29 shows the computational data compared to the simulation data for the bedroom in the temperature controlled house.

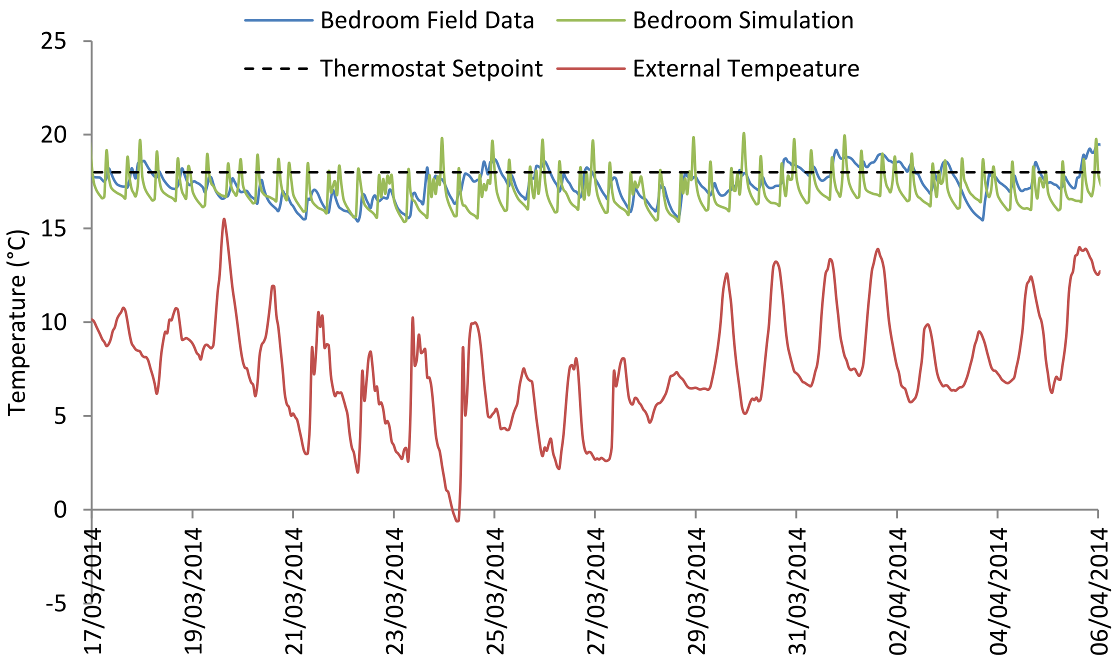

Figure 6.29 Comparison of the field data and the simulation results for the temperature controlled bedroom.

The bedroom temperature profile for the temperature controlled building shows a very strong correlation between the experimental and the computational data sets. The peaks and troughs for each data set follow the same pattern.

The trend of the simulation and computational data shows a high degree of correlation for the observation period. The periods in which the heating was turned off can be seen clearly on 14, 27 February and 14 March and in these cases the response of the simulated building is in line with the response of the experimental data.

The thermostat set point is not exceeded significantly, aside from boost periods until 17 March 2014, which demonstrates a slight underheating in the bedroom compared to the living room where the thermostat is located. This necessitates the use of the boost period to establish the thermal comfort for the occupant when they go to bed.

The average error rate between the experimental temperature data and the computational temperature data is low at 6.3% and this provides confidence in the dynamic thermal model is performing adequately.

Figure 6.30 compares the internal temperature of the living room for the computational and experimental study.

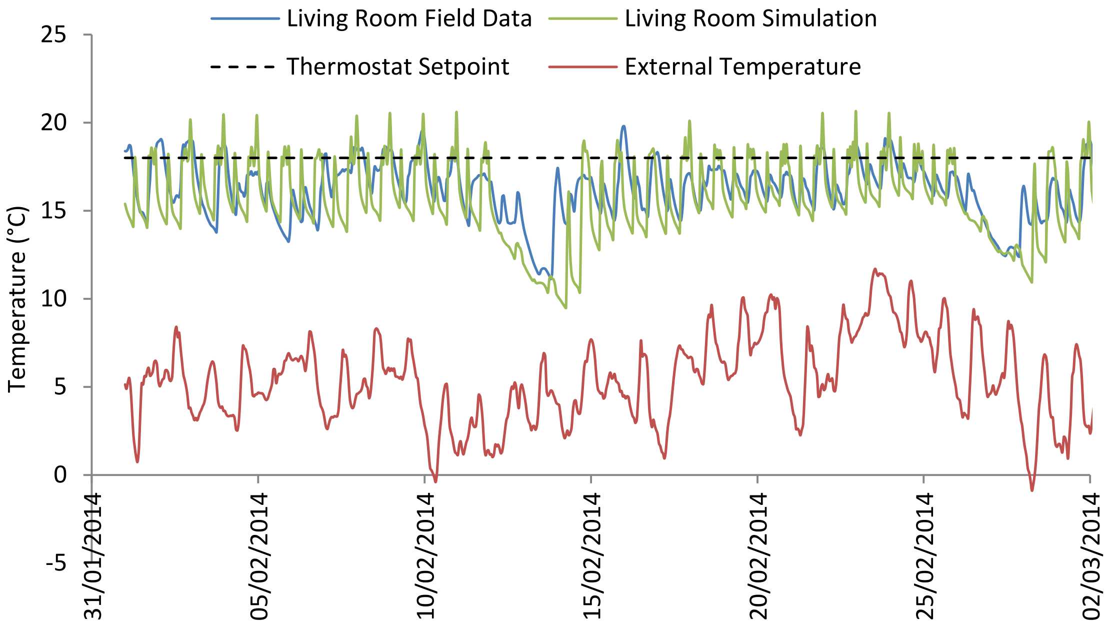

Figure 6.30 Comparison of the field data and the simulation results for the temperature controlled living room.

The living room also shows very good correlation with the magnitude of the peaks and troughs in the temperatures, thus showing good agreement between the experimental and computational results. The computational results do reach and exceed the temperature set point at times which the experimental data does not and this shows the heating system for the living room may have been slightly undersized compared to the dynamic thermal model. Two periods are shown where the heating is turned off and the computational results behave in a similar manner to the experimental results, with the minimum temperature for the experimental data being 10.8°C compared to the computational minimum 9.5°C.

The average internal temperature experienced in this room is higher than the bedroom and this is because of the location of the thermostat and therefore will fluctuate closer to the thermostat set point.

The living room still experiences the peaks in temperature related to the evening boost even though the reason for the boost is to raise the temperature of the bedroom only. This is because the whole heating system is controlled from a single thermostat and is a single zone system rather than a multi zone system. Therefore in order to raise the bedroom temperature then the entire house heating must be boosted and this raises the temperature in unoccupied rooms, thus resulting in energy wastage.

The average error between the computational and experimental data is 6.9% which shows a strong correlation between the two sets of data and provides validation that the dynamic thermal model approximates the performance of the building with a high degree of accuracy.

Finally the kitchen temperature data for the experimental and computational studies is compared in Figure 6.31.

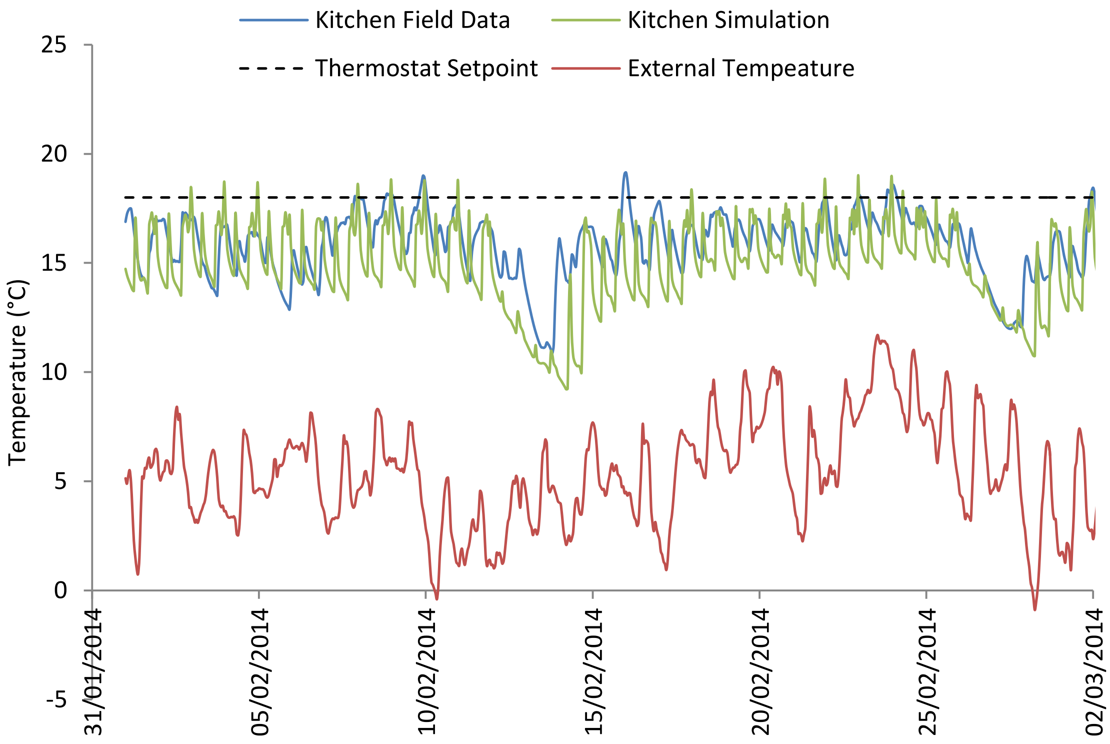

Figure 6.31 Comparison of the field data and the simulation results for the temperature controlled kitchen.

Similar to Figure 6.30, the period in which the heating is switched off shows a good similarity between the experimental and simulation data sets. However, unlike Figure 6.30 the simulation data does not show a tendency to increase to higher temperatures unlike in the living room which shows the heat emitter simulated in this room is closer in operational performance to the emitter installed in the case study home. Once again, the peaks in the temperature for the system boost are present in both data sets and occur at similar times.

The trend in the data from the experimental and computational studies follows the same pattern as for the kitchen, picking up again when the heating is turn off and the buildings response to the heating being turned back on again. Similar to the bedroom, see Figure 6.29, the kitchen is under heated compared to the living room where the thermostat is located. Later in the observation period as the external temperature increases the room begins to maintain the comfort setpoint of 18°C.

An average error rate of 7.5% was calculated for the kitchen and this demonstrates a very good correlation between the two sets of data and provides a high degree of confidence that the dynamic thermal model for the temperature controlled house estimates the performance of the building with a high degree of accuracy.

To summarise, Section 6.4 has discussed the validation of the dynamic thermal models compared to the experimental data for each case study house. The minimum average error rate was given as 5.5% with a maximum error rate of 11.6%. These two boundaries provide confidence that the dynamic thermal models are providing a very good estimation of how each case study building performed under the external climatic and internal conditions during the observation period.

The results produced by the dynamic thermal models provide us with confidence that the modelling procedure is sound and the results can be relied upon to draw accurate conclusions from for the remainder of this study. Thus we are able to evaluate with confidence modifications made to the heating systems and their effect on the internal conditions in the building as well as the energy consumption.

In Section 6.6 we will now discuss modifications made to the heating control system of the temperature controlled building which was selected because it showed the lowest overall error rate and represents a typical modern thermostatic controlled system which is known as the current best practice. The section begins by identifying the comfort and energy impact of using a 2 – zone temperature control system on the building followed by increasing the complexity of the control system to a true multi-zone system and investigating the effect that this has on the thermal comfort and energy consumption of the building.

6.5 Building Energy Performance.

The building temperature performance, compared to the CIBSE current best practice will be established followed by the calculation of the energy required for each building to raise the internal temperature to meet the CIBSE standards.

When comparing the observed building temperature levels, it is clear they are underperforming compared to the CIBSE recommendations detailed in Table 6.1. Table 6.2, Table 6.3 and Table 6.4 compare the observed temperatures during the building monitoring period to the CIBSE recommendations in order to establish the range of differences experienced between these temperature.

Table 6.2 Temperature deficiencies for the manually controlled house.

	Observed Temperature (°C)	CIBSE Recommended average temperature (°C)	Difference in Temperature (%)
Bedroom	16.4	18	8.9
Livingroom	14.2	22.5	36.9
Kitchen	14.6	18	18.9

The manually controlled house shows a temperature difference range of 28% between the values of least and most deviation. This is a considerable difference and demonstrates a large degree of undereating, notably the living room.

Table 6.3 Temperature deficiencies for the time controlled house.

	Observed Temperature (°C)	CIBSE Recommended average temperature (°C)	Difference in Temperature (%)
Bedroom	16.9	18	6.1
Livingroom	17.7	22.5	21.3
Kitchen	15.0	18	16.6

The temperature difference range in the time controlled house is smaller than that of the manually controlled house being 15.2% between the least and highest temperature deviation. The largest deviation is again in the living room but this value is closer to that of the kitchen but overall it is still under heated and thus not achieving the recommended comfort conditions.

Table 6.4 Temperature deficiencies for the temperature controlled house.

	Observed Temperature (°C)	**CIBSE Recommended average temperature (°C)**	**Difference in Temperature (%)**
Bedroom	17.2	18	4.4
Livingroom	16.9	22.5	24.9
Kitchen	16.7	18	7.2

The temperature controlled house shows a temperature difference range of 20.5% which is higher than that for the time controlled house. However the actual observed temperature deviation is 0.4 °C, compared to 2.7°C, in the time controlled house and 2.2°C in the manually controlled house. As these are single zone systems, this shows a higher degree of temperature controlled for the temperature control house when compared to the other two houses.

If the homes were to be heated to CIBSE standards, the required increases in energy consumption for each control strategy are presented in Table 6.5, Table 6.6 and Table 6.7. These increase in consumption have subsequent implications in fuel costs as a consequence.

Table 6.5 Energy increase for the manually controlled house to reach the CIBSE recommended comfort levels.

	Calculated Energy Consumption (kWh)	**Temperature difference (%)**	**Increase in energy (kWh)**
Bedroom	603.6	8.9	53.7
Livingroom	-	-	-
Kitchen	475.2	18.9	89.8

For the manual control building, it would require 143.5 kWh of additional energy during the observation period to bring the building up to the CIBSE recommended temperature levels, which is an energy increase of 13.3%. It should be noted that the living room had no central heating installed and so was not included in this calculation.

Table 6.6 Energy increase for the time controlled house to reach the CIBSE recommended comfort levels.

	Calculated Energy Consumption (kWh)	**Temperature difference (%)**	**Increase in energy (kWh)**
Bedroom	260.8	6.1	15.9
Livingroom	1012.8	21.3	215.7
Kitchen	156.5	16.6	26

The time control house requires an additional 257.6 kWh of additional energy during the observation period to bring the internal temperature up to the CIBSE recommended internal temperature conditions. This represents is an energy increase of 18%

Table 6.7 Energy increase for the temperature controlled house to reach the CIBSE recommended comfort levels.

	Calculated Energy Consumption (kWh)	**Temperature difference (%)**	**Increase in energy (kWh)**
Bedroom	188.7	4.4	8.3
Livingroom	360.9	24.9	89.9
Kitchen	191.0	7.2	13.8

The temperature controlled house requires an additional 112 kWh of additional energy during the observation period to bring this up to the CIBSE recommended levels. This represents an increase in energy consumption of 15%.

Whilst the additional energy required to bring the internal temperatures up to CIBSE recommended levels varies from building to building by over 50%, the percentage increase in energy considerably more consistent with the difference in required energy varying by 4.7% between the highest and lowest energy values. This demonstrates a consistent under heating of a similar degree in each home and this allowed us to modify the building heating control systems in order to study the temperature impact performance by using a zone control strategy.

The impact of increasing the heating energy consumed to raise the comfort conditions to meet CIBSE recommendations would be an average household energy increase of 15.8% which corresponds to a country wide increase of 42.66 TWh which is a significant increase if only the energy consumption were increased without taking other energy saving measures.

Section 6.6 details the modification of these heating schedules and presents the effect these that modifications have on the energy performance of the buildings.

6.6 Modification of dynamic thermal models

In section 6.4, the results from the experimental and computational research provided a validation and this ensures that the dynamic thermal models are suitably accurate to use in such studies in providing conclusions on the modifications of the models and the associated energy repercussions.

A benchmark model, based on the temperature controlled house, was established and the energy performance is presented in this section. The control algorithm is discussed, detailing how the model runs to simulate the performance of the control system and predict the thermal and energy results of the computational buildings. This is followed by modifications to the control scheme in order to demonstrate the effect of using a multi zone control approach has on the energy performance of the building.

6.6.1 Logic flowcharts for modelling control in zonal heating systems

The algorithm which controls the simulation and reporting of the dynamic thermal models is shown in Figure 6.3. This process is undertaken at each timestep within the dynamic thermal model

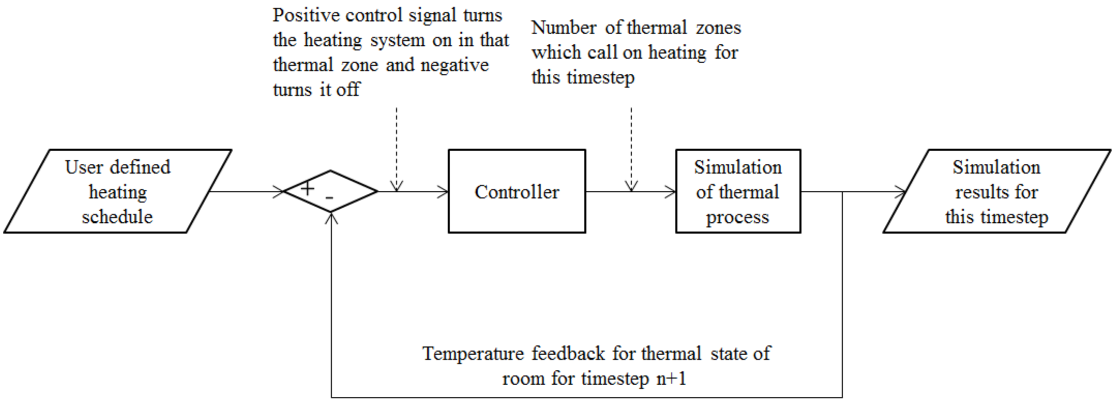

Figure 6.32 Logic flowchart for model simulation

The user defined heating schedule is used as an input to determine the room setpoint with the temperature feedback from the previous step being used to determine if heating is required in the next time step. This positive or negative, meaning heating is required or not required for that zone is fed into the controller.

The controller aggregates the control signals from each zone to determine how much overall heating is required in the building and sends this control signal to inform the dynamic thermal model which zones to activate in the simulation. This simulation methodology is discussed in Chapter 4.

The temperature output from the simulation is fed back to the decision process to generate a control signal for the controller to determine if heating is required in the following time step and results are available for all simulated parameters.

This algorithm is followed until the end of the simulation is reached. The same algorithm is used for single zone control, two zone control and multi zone control with the difference being the number of control signals fed into the controller. These are illustrated in Figure 6.33, Figure 6.34 and Figure 6.40 respectively.

The modification of the control strategies for the single, two zone and multi zone control strategies will now be discussed.

6.6.2 Heat input to thermal zones

The heat input available in each zone for the investigation into the performance of the multi zone heating system is controlled by the physical definition and maximum heat output of each radiator within the dynamic thermal model. Measurements were taken during the experimental investigation with the physical dimensions and type of radiator recorded for each room in the home along with the setting on the TRV.

These radiators were modelled within the dynamic thermal modelling software as they were installed in the case study building to ensure more heat than the system is capable delivering was not included within the dynamic thermal model results.

6.6.3 Single Zone Control

Initially it is important to look at the single zone system in order to establish a benchmark for each type of occupancy which are being investigated in this study. These are sample schedules based on traditional types of occupancy patterns with a 9-5 working week, a scenario where the occupants are at home all day and a shift work pattern in the form of a nightshift.

Each occupancy pattern will in turn be applied to the single zone building in order to establish benchmark figures. It is important to note that an internal setpoint temperature of 18°C was used throughout all the subsequent control scenarios. This is in order to provide an accurate representation of the comparison between the performance of the system rather than realising energy changes from the modification of the setpoint temperatures.

A schematic representation of the single zone control strategy is provided in Figure 6.33 and this highlights the single heating zone Z.a and is controlled by a thermostat located in the living room.

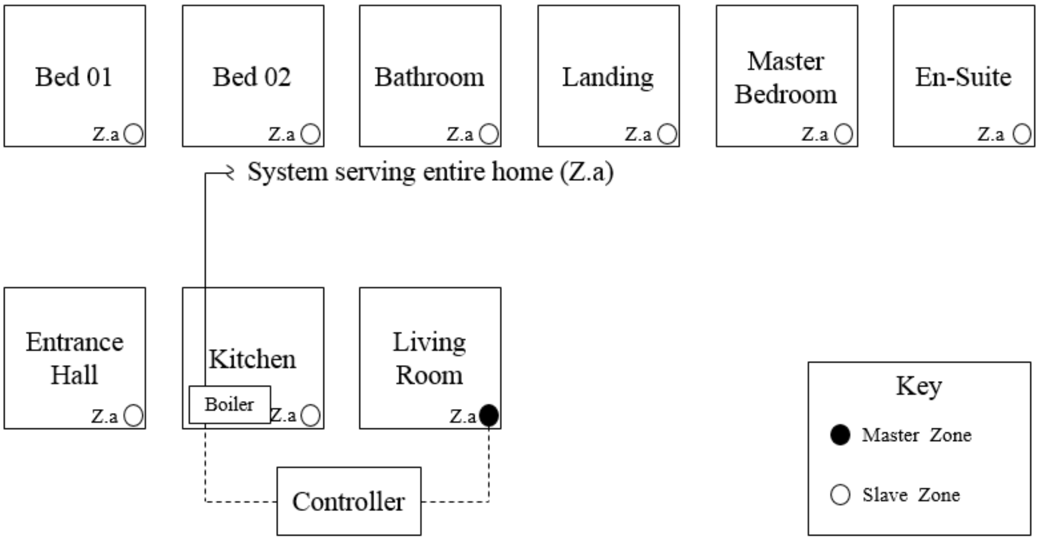

Figure 6.33 Schematic representation of the single zone control.

The figure illustrates the single master zone being the living room with all other zones in the home are slaves. There is one control signal to the controlled which controls the firing of the boiler.

Each control scenario will now be outlined in turn for the single zone system with an outline of the heating schedules for their respective energy consumptions. The first scenario to be discussed which provides a worst case value, is the always on scenario where the heating is never turned off.

6.6.3.1 Always on Setting

In this scenario the heating system is always left on for 24 hours a day and simulates the worst case heating scenario for the building using the temperature control system already installed. The annual consumption of energy in this case is 4487 kWh. Every subsequent heating configuration will provide savings on this value.

6.6.3.2 Current Settings

With the current heating settings, as described in Chapter 4, the annual energy consumption for providing space heating is 3618 kWh. This value represents the current benchmark at which the house is operating and the occupant feels comfortable. It should be noted that whilst for the observation period 1 February 2014 – 30 April 2014, an evening boost was used and this is not used at any other point outside that time period. This is due to the occupant using this procedure as their own preferences and not as part of the schedule by the programmable thermostat.

The first scenario to be investigated is the 9-5 working day in Section 6.6.3.3.

6.6.3.3 9-5 Working Day Setting

The 9-5 working day is made up of two schedules with 18°C setpoints. During the week days the heating activates between 0700 and 0830 and then turns off for the duration of the day. In the evening the heating is on from 1700 until 2300. This schedule simulates a morning heating period when the occupants are eating breakfast and readying for work. The evening is when the occupants return from work and stay in the house until they go to bed at about 2300.

The weekend has a different schedule due to the fact that the occupants do not leave in this period for work. This heating schedule is set from 0700 until 2300 and is on continuously. It is assumed that the occupants never alter the weekend schedule even when they are not present in the house as this was the assumption made for the benchmark figure.

The overall heat consumption for this control scenario is 3790 kWh, which is 4.8% increase in energy consumption over the benchmark figure. This is due to the weekend profile on the 9-5 working day being on all day whereas the current settings retains the daytime setback at this time and any additional heating to maintain comfort would be made manually.

6.6.3.4 Always Occupied Setting

The always occupied scenario assumes constant occupancy and heating requirement in the house such as when people work from home. The schedule in this case is the same as the weekend setting for the 9-5 working day with heating provided from 0700 until 2300 7 days per week. The energy consumption for this scenario is 4148 kWh which is an increase of 14.7% over the benchmark. This larger increase is expected as there is no daytime setback for the heating system given the continuous occupancy and so it would be expected that no energy savings are realised.

6.6.3.5 Nightshift Setting

The shift work pattern or nightshift scenario has the occupants working for 4 days per week with 3 days off. During the working days the heating is on from 0600 until 1100 and then in the evening it is on from 1900 until 2030. This represents the occupant sleeping during the day and waking up at 1900 to leave for work. The occupant then returns from work at 0600 and remains awake for some time before going to sleep at 1100. The days in which the shift working are not working are set the same as the weekend occupancy schedules used in the previous two examples which are on from 0700 until 2300.

The domestic heating energy consumption for this scenario is 3897 kWh for the year which is an increase of 7.71% over the benchmark case. The increase in consumption is to be expected as there are three days in which the heating is on from 0700 until 2300 which had no setback compared to the benchmark case.

6.6.4 2 Zone Control

Now that the energy performance for the scenarios have been established for a single zone control system, the energy performance of the building will now be investigated with a modified 2 zone heating control system. This will control the upstairs separately from the downstairs. This split is used as it is a natural divide of usage patterns in the home with the downstairs being used primarily during the day for eating, living and socialising with the upstairs being used overnight for sleeping.

A schematic representation of the 2 zone control strategy is provided in Figure 6.34 and it details the two thermostatic zones Z.a and Z.b.

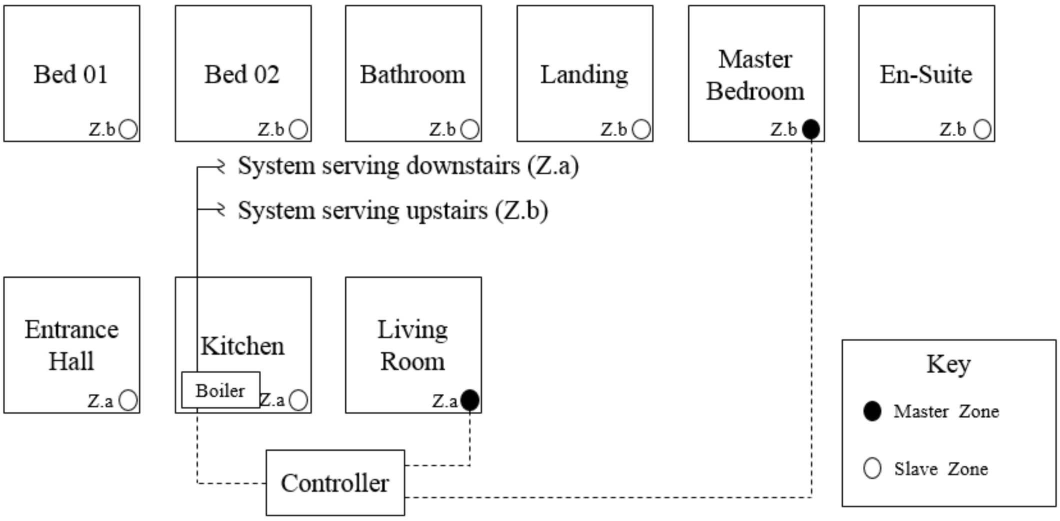

Figure 6.34 Schematic representation of the 2 zone control strategy.

The schematic shows the two master zones for the downstairs and upstairs, Z.a and Z.b, respectively. Here two control signals come to the controller which controls the boiler which serves the two zones.

Automatic valves are located on the two branches which serve Z.a and Z.b and these can modulate open and closed depending on the heating requirement from that zone.

The zone strategy was selected as upstairs and downstairs as this provided the most logical split in the building usage with the downstairs being primarily used during the day and the upstairs primarily being used during the night.

The first scenario to be investigated in Section 6.6.4.1 is the 9-5 working day.

6.6.4.1 9-5 Working Day Setting

In this scenario the upstairs zone was set to provide heat from 0630 until 0730 to provide time for the occupants to get up and conduct morning ablutions and an evening heating period was set from 2200 until 2400 which is when the occupants would typically go to bed. Downstairs, the heating was on from 0700 until 0830, thus simulating the period in which the occupants would eat breakfast and conduct their morning tasks before leaving for work. In the evening, the heating was set from 1700 until 2300 when the occupants would be cooking dinner and in their living room. On a weekend the upstairs retained the same heating profile but the downstairs was set to provide heat from 0700 until 2300, which is in line with the weekend heating schedule used previously.

The heating value for the two zones is compared to the same zones in the single zone heating system and presented in Table 6.8.

Table 6.8 Comparison of the heating energy consumption between the single zone and 2 zone heating systems.

Scenario	Upstairs (kWh)	Downstairs (kWh)	Total (kWh)
Single Zone	1709	2080	3790
2 Zone	1377	2253	3630

Table 6.8 shows a decrease in the energy consumption for the two zone system compared to the single zone system of 4.4%. The downstairs sees an increase in the energy consumption of 8.3% while the upstairs sees a decrease of 19.4%.

This decrease in consumption for the upstairs zone is expected as the duration of the heating is reduced for that zone, as previously the upstairs was being heating during unoccupied periods due to the single zone approach. This decrease in heating duration has the subsequent effect of slightly increasing the heating requirement for the downstairs zone since there is now a larger temperature differential between the two thermal zones, more heat transfer occurs away from the living room and thus more heat is required to keep the room at an acceptable temperature.

This is graphically highlighted in Figure 6.35 by comparing the heat transfer through the ceiling into the living room between the single zone and 2 zone systems on 27 December 2014.

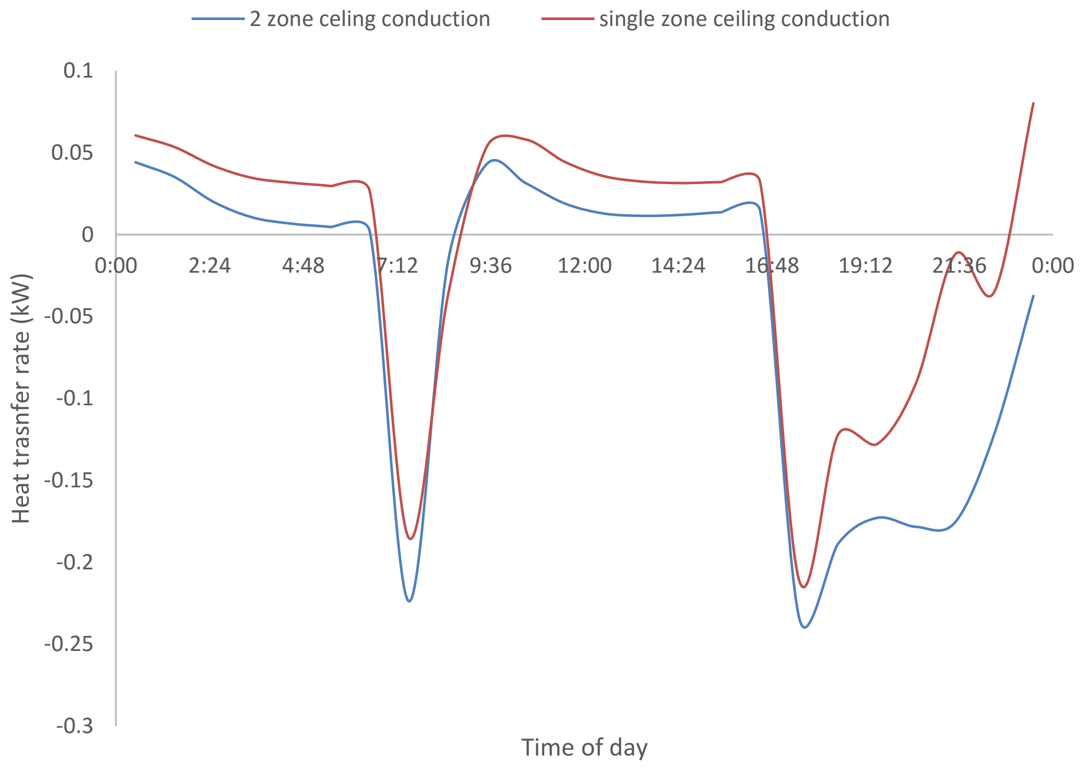

Figure 6.35 Comparison between the heat transfer rate of the living room through the ceiling between the living room single zone and 2 zone control scenarios.

A positive conduction value denotes heat entering the room where the negative value indicates that heat is leaving the room. From Figure 6.35 it is clear when there is no heat applied to the upstairs and downstairs, there is a similar temperature profile between the two control strategies. However in the evening there is a large difference in conduction rates between the two strategies because there is a reduced heating duration in the bedroom during the for the two zone control strategy evening which is resulting in more heat leaving the living room into the bedroom and thus the heating system in the living room must make up this difference.

Also the conduction rate is slightly higher in the single zone situation at other times which is due to a difference in temperature as shown in Figure 6.36 where the same date of 27 December 2014 was selected.

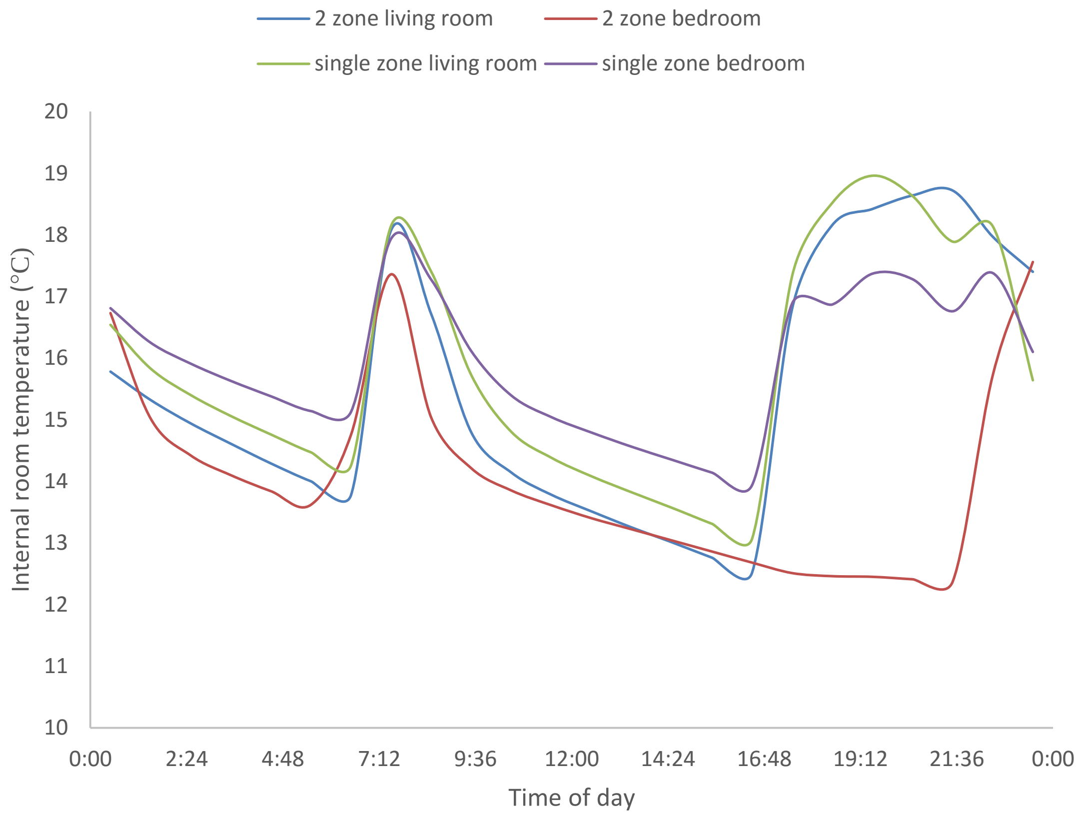

Figure 6.36 Comparison of the internal room temperatures for the single zone and 2 zone heating strategies.

With the single zone heating strategies, the bedroom maintains its heating setpoint in line with the living room. However with the 2 zone strategy, the bedroom does not reach the ideal comfort temperature of 18°C.

It is clear that as a result of the evening heating regime, only raising the internal bedroom temperature to 17.5°C and not maintaining a setpoint of 18°C for a period that this has a subsequent effect on the morning heating regime as the room cools at a much more rapid rate and to a cooler temperature than the other heating scenarios the morning comfort conditions are not achieved either.

The always occupied scenario will now be investigated to establish the effect of moving to a 2 zone control system will have on the performance of the heating system.

6.6.4.2 Always Occupied Setting

In the always occupied schedule the upstairs heating is set at 0630 until 0930, thus allowing a period for tidying the upstairs as it was assumed in this scenario there were children present. The evening heating is set at 1600 until 2300 allowing for the scenario in which the children would play in their bedroom during the evening and so heating would be required. The upstairs weekend heating is set on from 0700 until 2300. The downstairs retains the same schedule as the upstairs from 0700 until 2300.

The heating energy consumption is laid out in Table 6.9 comparing the single zone to the 2 zone system for the always occupied scenario.

Table 6.9 Comparison of heating energy consumption between single zone and 2 zone heating system

Scenario	Upstairs (kWh)	Downstairs (kWh)	Total (kWh)
Single Zone	1878.4	2270.8	4149
2 Zone	1862.4	2279.4	4142

Table 6.9 shows no significant difference between the energy consumptions of the two heating systems. This is unexpected as the duration of heating for the upstairs zone in the 2 zone control scenario is reduced compared to the single zone scenario.

However when investigating the internal temperatures achieved in the upstairs zone it is evident that the 2 zone system is in fact yielding a greater degree of comfort for the occupant compared to the single zone system and so performing much closer to how we would require. This is illustrated in Figure 6.37, where the internal temperatures for the bedroom and living room are compared between the single zone and 2 zone control strategies on 27 December 2014.

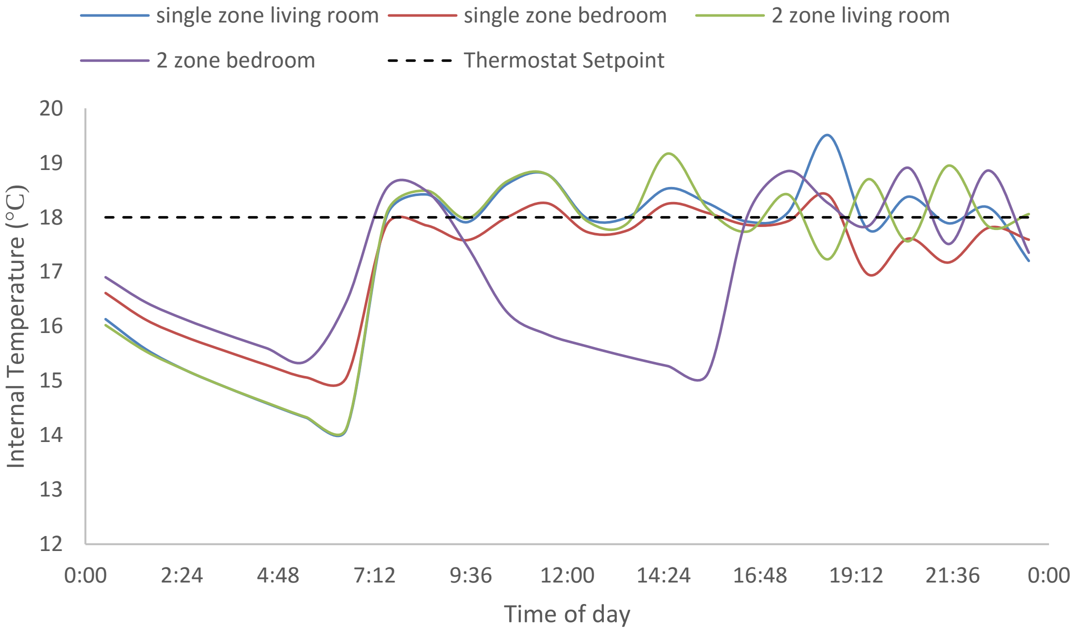

Figure 6.37 Comparison of the living room and bedroom heating between the single zone and 2 zone heating strategies.

It is clearly seen in Figure 6.37 that the temperature of the bedroom in the 2 zone system falls to 15°C during the day when no heating is supplied whilst the bedroom in the single zone scenario remains fluctuating around 18°C. However during the evening when the external temperature falls the bedroom cannot maintain the desired comfort condition of 18 °C due to the heating system not firing for enough time as it is controlled by the living room thermostat. However the 2 zone system is able to maintain comfort conditions for the duration of the evening period with the two zones calling for the boiler to fire at opposite times. Whilst the two systems use a very similar total heating energy, the 2 zone system is able to maintain more desirable comfort conditions for the occupants.

The 2 zone control strategy did not have a significant impact on the overall heating energy consumption compared to the single zone strategy, however it did increase the thermal comfort of the occupants by maintaining the required indoor temperature. The nightshift heating strategy is now discussed in Section 6.6.4.3.

6.6.4.3 Nightshift Setting

In the nightshift case study, the downstairs heating is on from 0600 until 1100 and then at 1930 until 2030 for Monday, Tuesday, Thursday and Friday with the remaining days using the 0700 until 2300 heating schedule to simulate the days off. The upstairs zone for the night shift is on from 1000 until 1100 and 1900 until 2030 on a working day and then 0630 until 0730 and 2200 until 2400 for a day off.

In this case study example, it is assumed that the occupant will maintain his nightshift pattern for the working days and then attempt to keep a normal sleeping pattern during his days off. The duration of heating is very similar to the 9-5 working day, however there is one extra day spent at home with a full day of heating downstairs.

A comparison of the energy performance for this scenario between the single zone and 2 zone control method is presented in Table 6.10.

Table 6.10 Comparison of the heating energy consumption between the single zone and 2 zone heating systems.

Scenario	Upstairs (kWh)	Downstairs (kWh)	Total (kWh)
Single Zone	1755	2142	3897
2 Zone	1318	2356	3675

The 2 zone control strategy provides an overall energy reduction of 5.7% for the nightshift scenario. Similar to the 9-5 working day control, the upstairs sees a reduction in energy consumption whereas the downstairs sees an increase in energy consumption. This is due to the same reason as experienced in the 9-5 working week scenario where a reduction in the period of heating results in a larger temperature differential between the living room and bedroom and this results in more heat transfer out of the living room whilst the bedroom is not heated. This is illustrated in Table 6.10, where the conduction gain through the ceiling is compared between the 2 zone control scenario and the single zone control scenario on 27 December 2014.

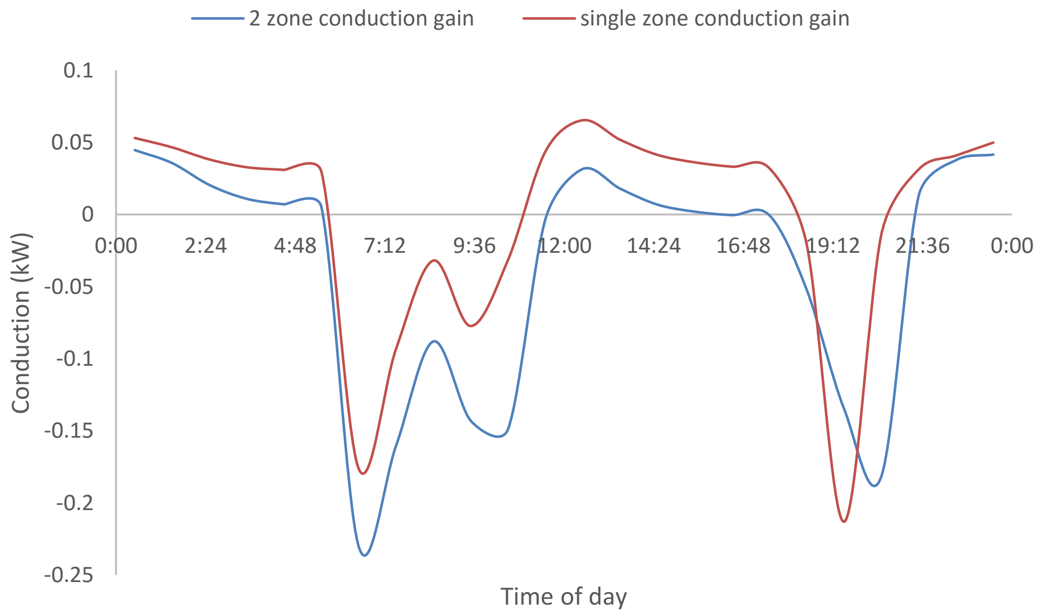

Figure 6.38 Comparison of the ceiling conduction gain for the living room between the single zone and 2 zone heating scenarios.

The figure shows an increased conduction rate into the living room through the ceiling for the single zone control scenario compared to the 2 zone control scenario. This is again due to the increased temperature in the bedroom for the single zone scenario compared to the 2 zone scenario.

Figure 6.39 shows a comparison between the internal room temperatures for the single zone and 2 zone systems.

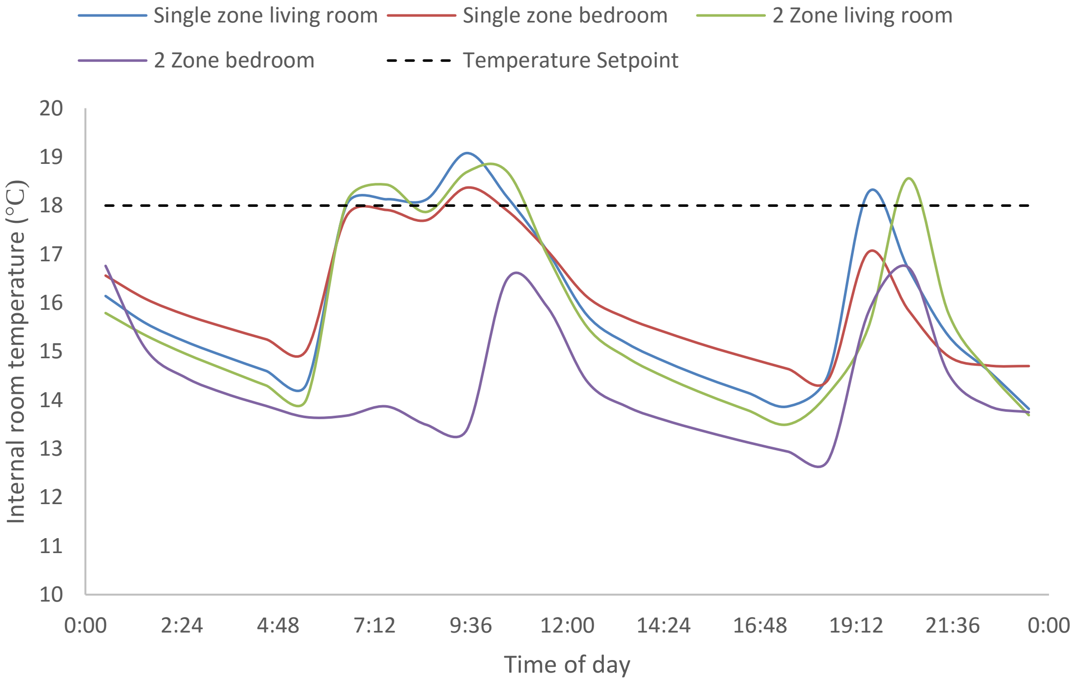

Figure 6.39 Comparison of the living room and bedroom heating between the single zone and 2 zone heating strategies.

In the 2 zone control system, the bedroom does not reach the comfort conditions but instead reaches a maximum temperature of 16.5°C in both the morning and evening heating periods. For the single zone strategy, the master bedroom reaches comfort conditions in the morning whereas it does not reach them in the evening.

Each of the scenarios have been compared for the 2 zone control strategy. The 9-5 working day has been selected as the typical control scenario which the majority of the population work under and this will be further investigated using a multi zone control system.

6.6.5 Multi Zone control

The control system is now developed from a 2 zone control system to incorporate a multi zone system where the temperature in each room is controlled individually with the aim of providing a higher degree of thermal comfort and to save energy.

The control system is schematically illustrated in Figure 6.40, detailing each thermal zone Z.a – Z.g and how these are controlled.

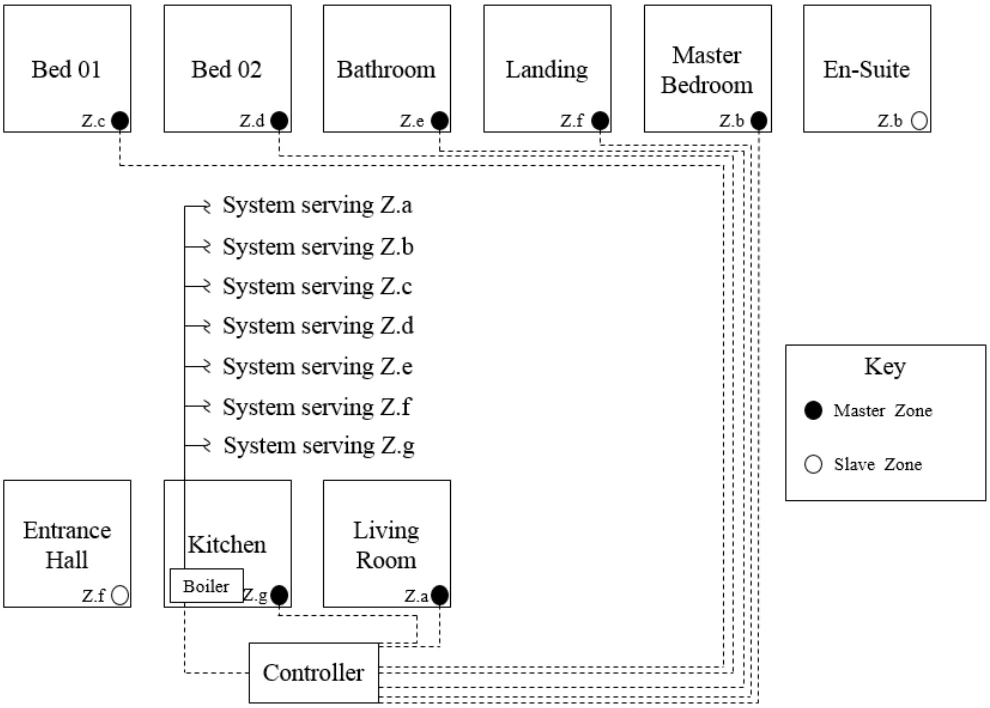

Figure 6.40 Schematic representation of the multi zone control system.

There are two slave zones present in this system, the first is the entrance hall which is controlled as a slave to the landing as the two zones are open to each other and are transient spaces so therefore there is a greater temperature tolerance here. The second slave zone is the en-suite bathroom attached to the master bedroom. This is a slave zone as it is also a transient space and will be used at the same time as the bedroom for ablutions and then clothes changing.

Every other zone within this system has its own individual thermostatic control and associated schedule. The performance of the multi zone system is now discussed with each room in turn investigated to evaluate the performance of the multi zone system over a single zone system.

6.6.5.1 9-5 9-5 Working Day Setting

The multi-zone control strategy in Figure 6.40 above was applied to the case study building and the energy performance was established for this case. The overall heating energy consumption is presented in Table 6.11.

The schedules were modified for the multi zone building taking into account the greater degree of control. The living room is only heated on a work day in the evening from 1800 until 2300 with the kitchen being heated 0700 until 0830 in the morning and 1700 until 2000 in the evening. This is to better simulate the cooking and eating patterns of the residents during these times and not to heat the living room on a morning when they will not be present in it. On a weekend the living room receives heat from 0700 until 2300 in line with other simulations. However the kitchen remains the same as the rest of the week.

For the upstairs zones, the timing remains the same for the entire period with heat from 0630 until 0730 and then again from 2200 until 2400. Z.f is controlled to the same schedule assuming the occupants will be moving around at the same time as they are going to bed. The difference in this scenario to the 2 zone control is that although each upstairs zone is controlled to the same schedule, they all have their own thermostat and so the individual zone control is more accurate.

Table 6.11 Comparison of the heating energy consumption between the single zone, 2 zone and multi zone heating system

Scenario	Upstairs (kWh)	Downstairs (kWh)	Total (kWh)
Single Zone	1709	2080	3790
2 Zone	1377	2253	3630
Multi Zone	1585	2244	3830

In the case of the multi zone system, it results in a 1% energy gain over the single zone system and a 5.51% gain over the 2 zone system. Whilst no significant energy consumption difference is present between the single zone and multi zone scenarios, it is important to establish the effect on the occupant thermal comfort.

A comparison between the internal temperatures of the living room for all three control strategies is shown in Figure 6.41 with the thermostat setpoint temperature of 18°C.

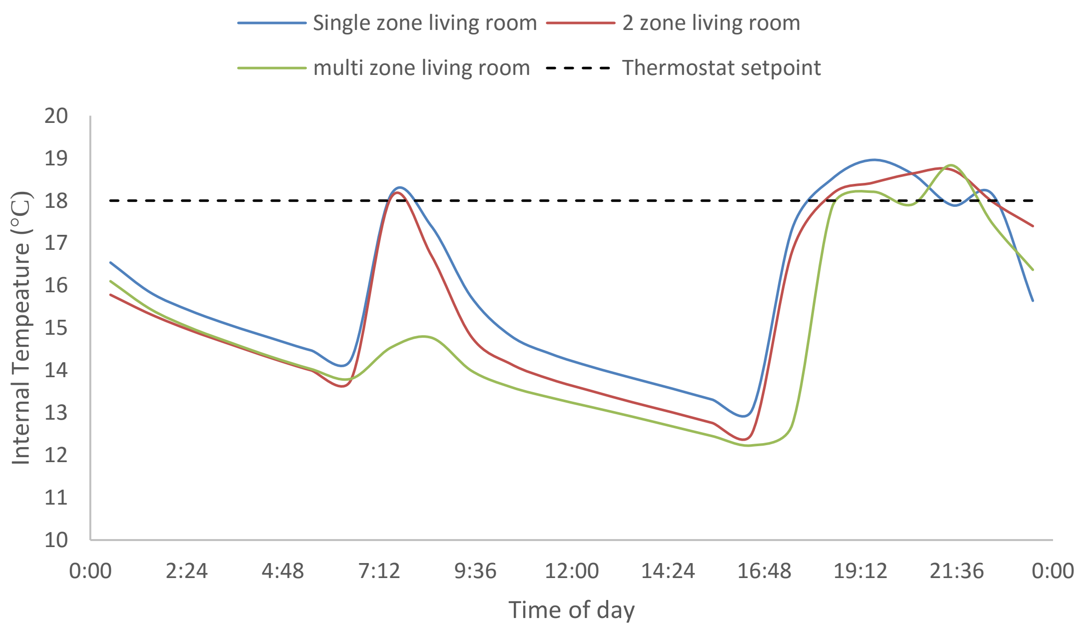

Figure 6.41 The living room internal temperatures for all three control strategies.

The morning and evening temperatures are achieved for the living room in all three scenarios and this is to be expected as in all three cases the living room is a master control zone which controls when the heating is available to the thermal zones.

In the case of the multi zone control, the morning heating period has a much lower temperatures compared to the single zone and 2 zone control by design as there is no heat supplied directly to the living room, there is however a small peak in temperature due to the heat transfer from the adjacent zones which are heated in the mornings.

On investigating the master bedroom, which is a slave zone in the single zone strategy but a master zone in the 2 zone and multi zone strategies. A comparison of the internal temperatures for the master bedroom for each of the control strategies is provided in Figure 6.42 including the thermostatic setpoint of 18°C.

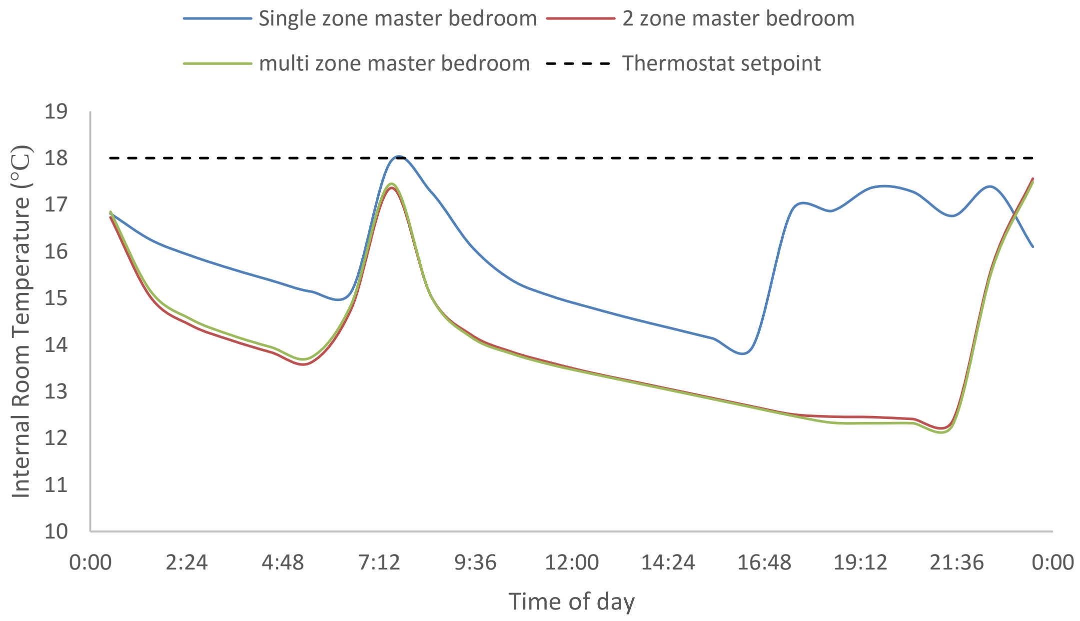

Figure 6.42 The internal temperatures in the master bedroom for each control strategy.

The figure illustrates a better temperature performance in the single zone strategy for the morning due to the other strategies not providing sufficient heating during the morning to reach the required temperature where it reaches 17.5 °C rather than 18°C.

However in the evening this is where the energy savings are recognised since the master bedroom receives heat from 1800 until 2300, in line with the rest of the house, but in this period the room is unoccupied so the multi zone system is saving energy for the building as a whole.

It is important to understand how a slave room in the multi zone scenario performs compared to the single zone scenario. The internal temperature for bedroom 02 is provided in Figure 6.43 with a comparison for each control system.

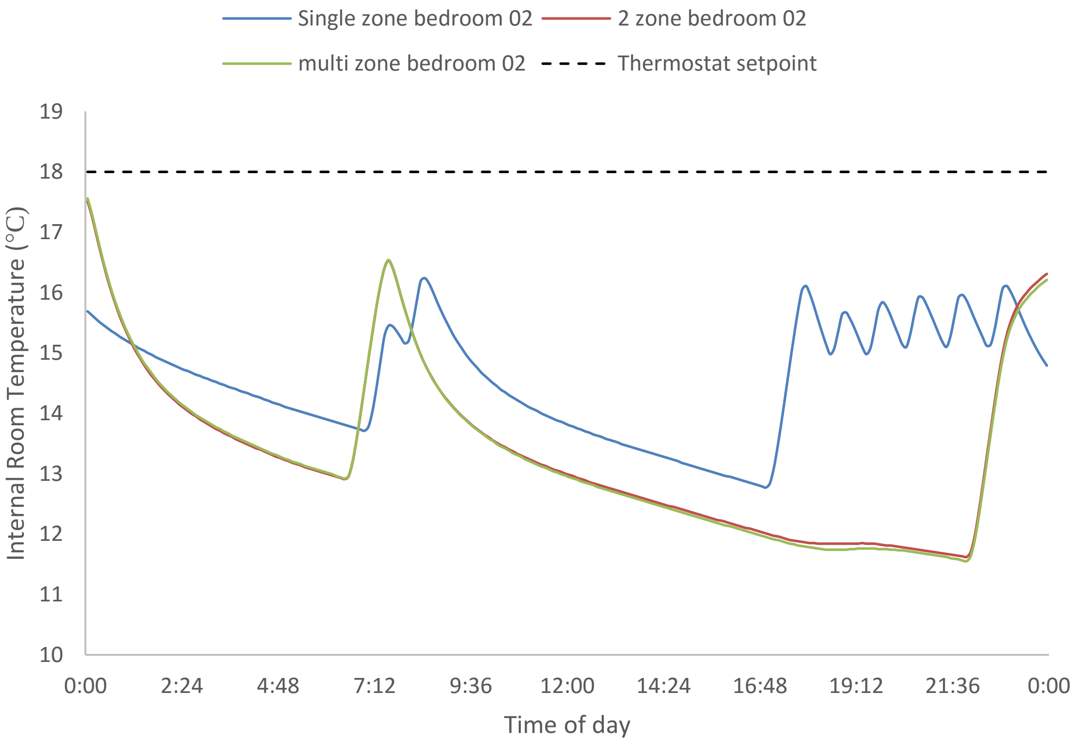

Figure 6.43 The bedroom 02 internal temperature from each control system.

In the evening the bedroom 02 heating period for the single zone control shows that the radiator is inadequate currently in maintaining the comfort conditions and underheates the room. The period of heating is also outside that which is required for a normal 9-5 scenario as it is heated from 1700.

The temperature profile for the multi zone and 2 zone heating systems are almost identical. This is because the room is being underheated and as they have the same heating schedule with the multi zone system then the room calls for heat all the time and this is the same as if the room was a slave in the 2 zone system but heating was supplied all the time.

6.6.5.2 Always occupied Setting

The multizone strategy outlined in Figure 6.40 has been applied to the always occupied control strategy to determine the impact on the building energy performance.

The heating pattern for the multi-zone control follows a very similar trend to the two zone control strategy. A comparison between the single zone living room and multi zone living room is shown in Figure 6.44.

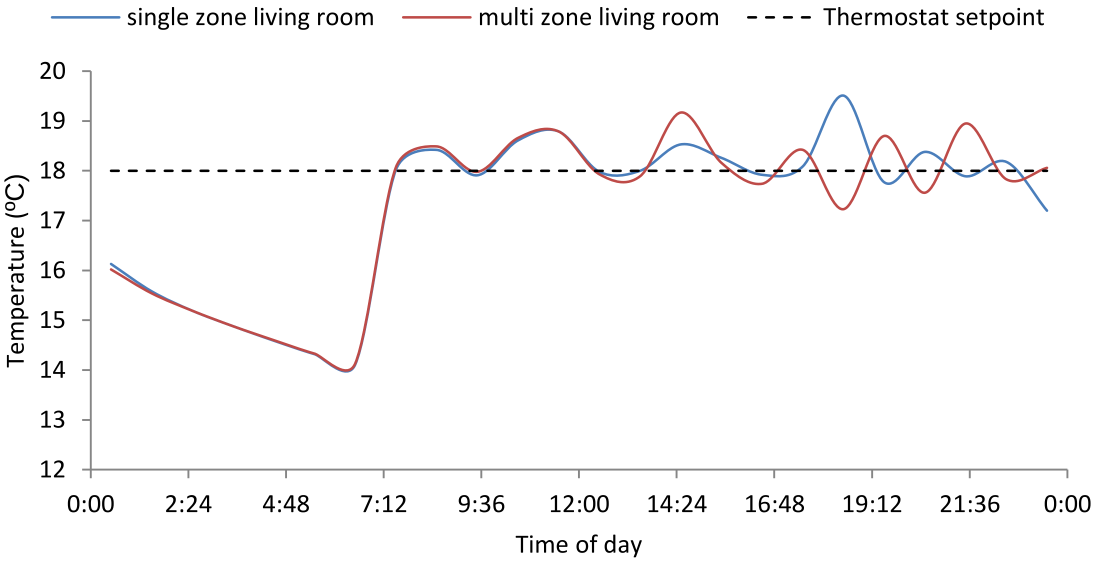

Figure 6.44 Comparison between single and multi zone living room temperature profiles

The initial period of heating are identical up until approximately 12:30. After this the multi zone and single zone temperature profiles become desynced. This is due to the upstairs heating in the multi zone system not turning on which results in a larger rate of heat transfer out of the zone, as such the heating profile and temperature profile change. This change in conduction for the two zone system is shown in Figure 6.35 and is the same for the multi zone case. The magnitude of the peaks remains constant due to the heating in the living room being sized appropriately to cope with the demand.

The reduction in bedroom heating is illustrated in Figure 6.45.

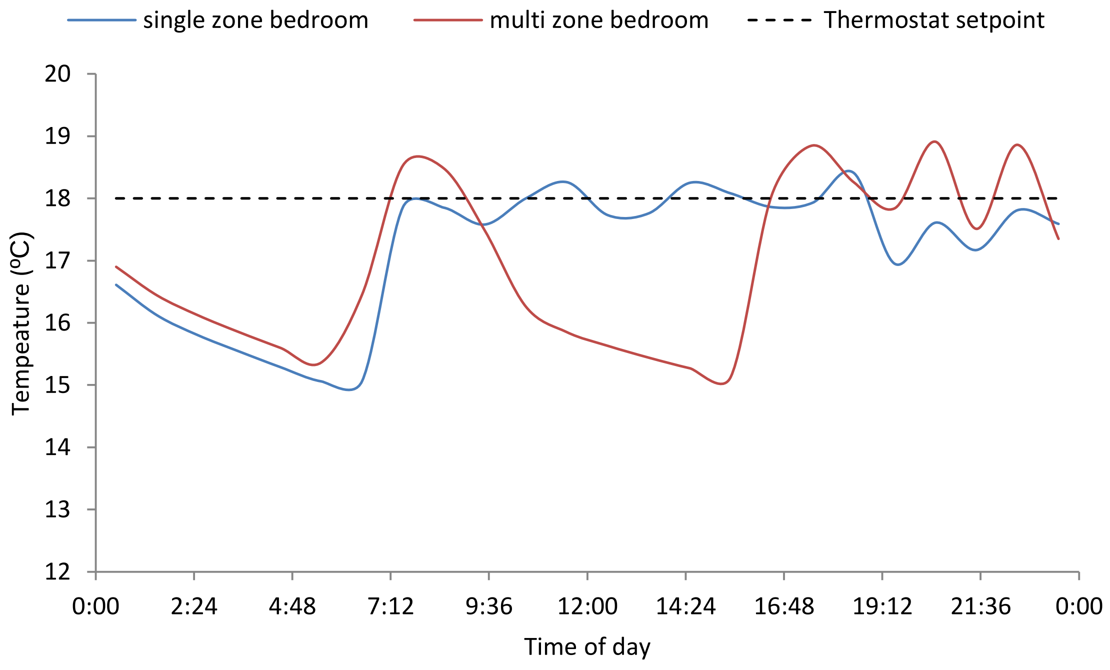

Figure 6.45 Comparison between single and multi zone bedroom temperature profiles.

Unlike the single zone bedroom which receives heat for the entire day even when unoccupied, the multi zone system results in a temperature decrease due to the heating turning off during the middle of the day when the room is unoccupied. The changing oscillations in heating start occurring in Figure 6.44 at 12:30 which corresponds with a temperature in the bedroom of 15.6ºC. This lag in influence between the bedroom and living room is caused by the thermal mass of the build fabric between the two rooms unlike the influence between the living room and kitchen as discussed in Figure 6.47 where a direct connection occurs between the kitchen and living room.

The energy consumptions for each control strategy are detailed in Table 6.12.

Table 6.12 Comparison of energy consumptions for the always occupied schedule between the three control strategies.

Scenario	Upstairs (kWh)	Downstairs (kWh)	Total (kWh)
Single Zone	1878	2271	4149
2 Zone	1862	2280	4142
Multi Zone	1993	2889	4882

When compared to the single zone strategy, the multi zone system causes an increase in the overall energy consumption by 17.7%. There is a significant increase in the downstairs energy consumption and a small increase in the upstairs energy consumption. This is because the previously underheated bedroom 1 and 2 are able to call for more heat compared to the two zone strategy. However the decrease in heating period results in more heat lost from downstairs to upstairs of the building which increases the heating load of the living room and kitchen considerably.

6.6.5.3 Nightshift

The multizone strategy has been applied to the nightshift control strategy to determine the impact on the building thermal and energy performance. For the nightshift controlled building the main heating period occurs during the early period of the day as shown in Figure 6.46.

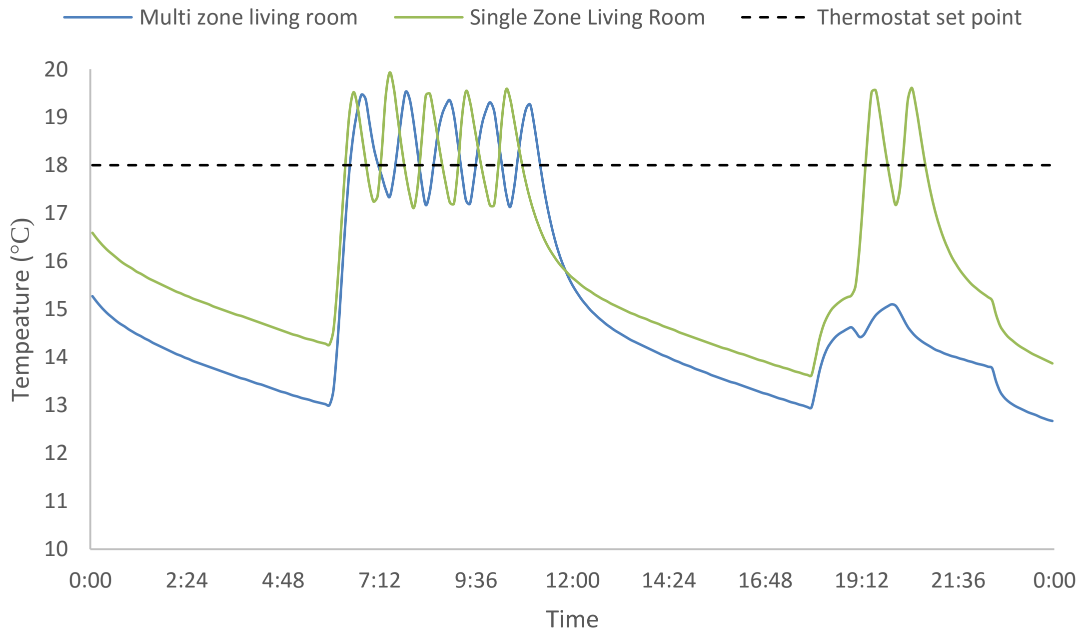

Figure 6.46 Comparison of living room temperature performance for the multi zone living room compared to single zone living room

The second heating period is when the occupant consumes their breakfast and does not enter the living room. The single zone heating system continues to heat during this period which results in energy wastage. The multi zone system however only heats during the morning period in the living room as requested by the heating schedule.

The temperature during unheated periods is lower in the multi zone heating strategy because the building fabric has less time to absorb the heat and thus the effect of heat storage is lessened, leading to a faster cooling of the space. This response by the building fabric means the multi zone system requires more energy to bring the room up to the desired temperature compared to the single zone heating strategy.

The same principal is seen in Figure 6.47 within the kitchen of the nightshift occupancy pattern.

Figure 6.47 Comparison of kitchen temperature performance for the multi zone kitchen compared to single zone kitchen

For the multi zone system a peak in the kitchen temperature can be seen at the same time at 07:00 where the occupant cooks their main meal of the day. The kitchen temperature in the multi zone system then falls compared to the single zone system. There are still peaks in the multi zone system due to the passive effect of the living room heating causing an increase in temperature in the kitchen.

In the evening the kitchen fails to reach the set point temperature. The trend again follows the same pattern with the passive heating from the living room causing a temperature increase which is closed off at 20:00 when the occupant closes the door joining the two spaces. Without this additional source of passive heat from the living room, the kitchen fails to reach the set point temperature for heating which would necessitate increasing the setting on the TRV in order to reach the setpoint.

The energy consumptions for each strategy are detailed in Table 6.13.

Table 6.13 Comparison of the energy consumptions for the nightshift schedule for the three control strategies.

Scenario	Upstairs (kWh)	Downstairs (kWh)	Total (kWh)
Single Zone	1755	2142	3897
2 Zone	1318	2356	3675
Multi Zone	1424	2501	3925

Similar to the working day control strategy presented in Table 6.11 the difference in energy consumption is less than 1% between the single zone and multi zone control strategies but a gain of 6.8% over the two zone strategy. The effect of the multi zone control system has on the nightshift building performance is of a similar order to the working day control strategy by increasing comfort during occupied hours in rooms but at the cost of a slightly increased energy consumption.

Chapter 7 Conclusions and future work

7.1 Conclusions

The research has made a number of advances in the understanding of the effect heating control zoning has on the performance of a domestic heating system. The conclusions are made to draw a direct comparison to the research objectives of the study defined in Chapter 1. The study achieved the objectives through numerical and experimental investigations.

A summary of the objectives met are as follows:

1. The experimental observation of three case study buildings established current benchmarks for the energy and thermal performance of three typical UK domestic homes. The study demonstrated that a wide variety of heating control systems are currently in use within UK domestic homes. The three benchmarks each had a different control strategy with one having manual control, a second having timed control and the third having temperature control.

2. The experimental temperature results were used to validate the dynamic thermal models in the numerical investigation. The temperature results from the observation period 1 February 2014 until 31 April 2014 of the experimental data and dynamic thermal models were directly compared and the average error rates for each case study building were 6.9%, 9.5% and 11.7% for the temperature controlled, manually controlled and time controlled systems respectively. These are within the expected error range of 10% - 14% which has been noted in other similar studies using a similar methodology as outlined in 4.6 Quantification of the Uncertainties.

3. The thermal performance of each case study building was compared to recommended CIBSE guidelines for thermal comfort in UK domestic homes. The benchmarks show that the rooms on average spent between 37.5% and

100% of their time below recommended temperature levels which demonstrates a clear trend towards underheating. In each case the living room spent their entire period below the CIBSE recommended temperature of 22°C - 23°C which suggests that the CIBSE recommendations for internal comfort conditions are set too high when compared to occupant expectations of warmth. A limitation in this study is the number of buildings which were selected for the experimental observation due to the duration of the study and the available finances.

The computational study in Section 6.5 provides concludes that it would require 15.8% more heating energy consumption to provide domestic homes with comfort conditions at CIBSE recommended standards which on a country wide scale is an increase of 42.66 TWh based on 2011 levels of heating.

4. Three occupancy scenarios were modelled using the validated dynamic thermal model for the 2 zone control strategy which were a 9-5 working day, always occupied and nightshift working scenario. The implementation saw a decrease in energy consumption of between 0% and 5.7%. The 2 zone strategy allowed the building to have a separate heating schedule for the downstairs and upstairs which are occupied at different times but are heated at the same schedule for a single zone system. The always occupied scenario saw no noticeable effect with the implementation of the 2 zone system as the benefits of altering the heating schedules to suit occupancy during a working day could not be realised. The range of occupancy scenarios simulated is a limitation in this study as there are a very wide range of possibilities, however time constraints meant a small number of sample occupancy patterns had to be selected which covered a wide range of scenarios.

5. The same three occupancy scenarios were modelled in a multi zone control system. The heating energy consumption in the 9-5 working day and nightshift working scenarios increased by 1%. The always occupied scenario increased by 17.7% which is a significant increase. This is due to rooms which were previously underheated in the single zone and 2 zone strategy were now calling for heating energy for increased durations rather than the rooms acting as slaves to the thermostat located in adjacent rooms.

7.2 Contributions to knowledge

This study used the numerical and experimental techniques identified in Chapter 2 to address the research gap identified. The following will summarise the contributions to knowledge this study has made in the effect smart control systems have on the energy performance of domestic homes.

- Experimental data has been gathered on the temperature performance of three domestic homes in the UK over a three month period 1 February until 31 April 2014.
- Subsequently numerical data from dynamic thermal models has been provided on the energy performance of these domestic homes over the same time period, 1 February until 31 April 2014.
- Experimental and numerical investigations demonstrated that homes in the UK are underheated compared to the CIBSE recommendations.
- The data supports the conclusion that the CIBSE recommendation for living room temperature of 22°C - 23°C is high compared to the occupants requirements.
- Numerical simulation data has been provided on the effect that a 2 zone and multi zone domestic heating control system has on the energy performance of a domestic home.
- A 2 zone control strategy has been shown to have a negligible impact on the heating energy performance on homes which are occupied extensively.
- A 2 zone control strategy has been shown to have a positive impact on energy consumption in UK domestic with an occupancy pattern that follows a 9-5 working day.
- A multi zone control strategy has been shown to have a negative impact on energy consumption in UK domestic homes based on the case study buildings selected for this study.

7.3 Recommendations for future work

The following areas have been identified as requiring further investigation.

7.3.1 Extended scope of this study

Expand the number of buildings in the study to increase scope and range with varying external conditions, house archetypes and occupant archetypes. This will provide a more comprehensive data set to use in a similar study which would validate the conclusions in this study.

This would be achieved by using the same methodology of temperature data loggers over at least a three month period installed in test case homes with the inclusion of occupant questionnaires to gain more detail into occupancy patterns and build more accurate schedules.

This data would be used within dynamic thermal models to validate the experimental data gathering and with the simulated zoning control to provide results with energy savings for the extended range of case study homes.

7.3.2 Empirical observation of multizone control system retrofit

Retrofit a multizone control system to an existing occupied house. Measure the energy consumption and temperature performance of the home to determine if the system performs as per the numerical modelling predicts.

Questionnaires should be provided to occupants to establish their opinions on the heating control and building performance before and after the retrofit to gauge homeowner reactions to the change along with real time temperature and energy consumption data for the testing period.

7.3.3 Alternative schedules to provide further energy savings

Within this study the same temperature setpoints were used throughout to establish what impact installing a multizone control system would have on building energy consumption without changing the required environmental conditions. Further work should include enhanced schedules to determine the level of impact the occupancy pattern and temperature patterns have on the building energy consumption and performance of the smart control systems.

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Appendix A – Occupant Surveys

Domestic home and occupant comfort survey for manually controlled home

1. Occupancy Type? ~~Owned~~ / Rented
2. Is your home insulated? ~~Yes~~ / ~~No~~ / Partially / ~~Unknown~~

   Further Comments: The home has loft insulation but no wall insulation

3. Is your home double glazed Yes / ~~No~~ / ~~Partially~~ / ~~Unknown~~

   Further Comments:

4. Is your home centrally heated ~~Yes~~ / No / ~~Unknown~~

   Further Comments:

5. How would you rate your knowledge of the operation of your heating control system (1 – None, 2- Basic, 3 – Adequate, 4 – Good, 5 – Excellent)

   3

   Further Comments: We were advised when we moved into the house to leave the heating settings as they are on each storage heater.

6. During winter please rate your thermal comfort in your living room (1 – Very cold, 2- Cool, 3 – Comfortable, 4 – Warm, 5 – Hot)

   2

   If not thermally comfortable, why?

   There is no heater in the living room and so it is sometimes cold until we light the coal fire, we have blankets to sit under.

   If not thermally comfortable, what action did you take?

   We light a coal fire

7. During winter please rate your thermal comfort in your bedroom (1 – Very cold, 2- Cool, 3 – Comfortable, 4 – Warm, 5 – Hot)

   3

   If not thermally comfortable, why?

   N/A

If not thermally comfortable, what action did you take?

It is sometimes cool but we are going to bed anyway, we also have an electric heater to use.

8. During winter please rate your thermal comfort in your kitchen (1 – Very cold, 2- Cool, 3 – Comfortable, 4 – Warm, 5 – Hot)

   2

   If not thermally comfortable, why?

   We cook at different times depending on shifts so heating is not always on enough depending on the shift.

   If not thermally comfortable, what action did you take?

   We open the door to the living room

Domestic home and occupant comfort survey for time controlled home

1. Occupancy Type? ~~Owned~~ / Rented

2. Is your home insulated? ~~Yes~~ / ~~No~~ ~~/ Partially~~ / Unknown

   Further Comments: Interviewer Note – building has loft insulation but no wall insulation

3. Is your home double glazed Yes / ~~No~~ / ~~Partially~~ / ~~Unknown~~

   Further Comments:

4. Is your home centrally heated Yes /~~ No~~ / ~~Unknown~~

   Further Comments:

5. How would you rate your knowledge of the operation of your heating control system (1 – None, 2- Basic, 3 – Adequate, 4 – Good, 5 – Excellent)

   4

   Further Comments: We leave the heating on all the time as we have a young son

6. During winter please rate your thermal comfort in your living room (1 – Very cold, 2- Cool, 3 – Comfortable, 4 – Warm, 5 – Hot)

   3

   If not thermally comfortable, why?

   We keep the living room warm for our son

   If not thermally comfortable, what action did you take?

   We get under a blanket or light the fire

7. During winter please rate your thermal comfort in your bedroom (1 – Very cold, 2- Cool, 3 – Comfortable, 4 – Warm, 5 – Hot)

   3

   If not thermally comfortable, why?

   If not thermally comfortable, what action did you take?

We get into bed

8. During winter please rate your thermal comfort in your kitchen (1 – Very cold, 2- Cool, 3 – Comfortable, 4 – Warm, 5 – Hot)

   2

   If not thermally comfortable, why?

   It can be drafty in the kitchen but it warms up once we start cooking. There is a door to the cellar which lets drafts in.

   If not thermally comfortable, what action did you take?

   It warms up once we start cooking

Domestic home and occupant comfort survey for temperature controlled home

1. Occupancy Type? Owned / ~~Rented~~

2. Is your home insulated? Yes / ~~No~~ / ~~Partially~~ / ~~Unknown~~

   Further Comments:

3. Is your home double glazed Yes / ~~No~~ / ~~Partially~~ / ~~Unknown~~

   Further Comments:

4. Is your home centrally heated Yes / ~~No~~ / ~~Unknown~~

   Further Comments:

5. How would you rate your knowledge of the operation of your heating control system (1 – None, 2- Basic, 3 – Adequate, 4 – Good, 5 – Excellent)

   5

   Further Comments: I set a timing schedule and temperature for the week to save energy at night and when I am out of the house

6. During winter please rate your thermal comfort in your living room (1 – Very cold, 2- Cool, 3 – Comfortable, 4 – Warm, 5 – Hot)

   3

   If not thermally comfortable, why?

   It can get cold late at night if I stay up later than normal

   If not thermally comfortable, what action did you take?

   I use the heating boost on the thermostat to boost the heating for an hour.

7. During winter please rate your thermal comfort in your bedroom (1 – Very cold, 2- Cool, 3 – Comfortable, 4 – Warm, 5 – Hot)

   3

   If not thermally comfortable, why?

If not thermally comfortable, what action did you take?

8. During winter please rate your thermal comfort in your kitchen (1 – Very cold, 2- Cool, 3 – Comfortable, 4 – Warm, 5 – Hot)

   3

   If not thermally comfortable, why?

   If not thermally comfortable, what action did you take?