Measuring and Modelling the Energy Demand Reduction Potential of Using Zonal Space Heating Control in a UK Home

by

Arash Beizaee

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15 February 2016

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgments or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a degree.

Arash Beizaee
15 February 2016

"One important idea is that science is a means whereby learning is achieved, not by mere theoretical speculation on the one hand, nor by the undirected accumulation of practical facts on the other, but rather by a motivated iteration between theory and practice…"

George E.P. Box (1976)

Abstract

Most existing houses in the UK have a single thermostat, a timer and conventional thermostatic radiator valves to control the low pressure, hot water space heating system. A number of companies are now offering a solution for room-by-room temperature and time control in such older houses. These systems comprise of motorised radiator valves with inbuilt thermostats and time control. There is currently no evidence of any rigorous scientific study to support the energy saving claims of these ‘zonal control’ systems.

This thesis quantifies the potential savings of zonal control for a typical UK home. There were three components to the research. Firstly, full-scale experiments were undertaken in a matched pair of instrumented, three bedroom, un-furbished, 1930s, test houses that included equipment to replicate the impacts of an occupant family. Secondly, a dynamic thermal model of the same houses, with the same occupancy pattern, that was calibrated against the measured results. Thirdly, the experimental and model results were assessed to explore how the energy savings might vary in different UK climates or in houses with different levels of insulation.

The results of the experiments indicated that over an 8-week winter period, the house with zonal control used 12% less gas for space heating compared with a conventionally controlled system. This was despite the zonal control system resulting in a 2 percentage point lower boiler efficiency. A calibrated dynamic thermal model was able to predict the energy use, indoor air temperatures and energy savings to a reasonable level of accuracy. Wider scale evaluation showed that the annual gas savings for similar houses in different regions of the UK would be between 10 and 14% but the energy savings in better insulated homes would be lower.

Acknowledgements

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Abbreviations

ACH	Air Changes per Hour
AFN	Air Flow Network
ASHRAE	American Society of Heating Refrigeration and Air-Conditioning
ATTMA	Air Tightness Testing & Measurement Association
BADC	British Atmospheric Data Centre
BI	Boiler Interlock
BRE	Building Research Establishment
BRECSU	Building Research Energy Conservation Support Unit
BREDEM	Building Research Establishment Domestic Energy Model
BSI	British Standards Institution
CC	Conventional Control
CFD	Computational Fluid Dynamics
CHeSS	Central Heating System Specifications
CIBSE	Chartered Institution of Building Services Engineers
CREST	Centre for Renewable Energy Systems Technology
CSV	Comma Separated Value
CT	Cylinder Thermostat
CVRMSE	Coefficient of Variation of Root Mean Square Error
DECC	Department of Energy and Climate Change
DEFACTO	Digital Energy Feedback and Control Technology Optimisation

DHR	Diffuse Horizontal Radiation
DHW	Domestic Hot Water
DNR	Direct Normal Radiation
DTM	Dynamic Thermal Model
EEBPp	Energy Efficiency Best Practice programme
EFUS	Energy Follow Up Survey
EM	Empirical Model
EMS	Energy Management System (EnergyPlus)
EPSRC	Engineering and Physical Sciences Research Council
EPW	EnergyPlus Weather
ERL	EnergyPlus Runtime Language
GHR	Global Horizontal Radiation
GPS	Global Positioning System
HDD	Heating Degree Days
HT	Heating Trial
HVAC	Heating, Ventilation and Air-Conditioning
IDF	Input Data File (EnergyPlus)
IEA	International Energy Agency
IP	Internet Protocol
IRR	Internal Rate of Return
IWEC	International Weather for Energy Calculations

LMP1930	Loughborough University’s Matched Pair of 1930s houses
LPHW	Low Pressure Hot Water
LST	Low Surface Temperature
MBE	Mean Bias Error
MRT	Mean Radiant Temperature
MV	Motorised Valve
NHBC	National House Building Council
NPV	Net Present Value
ONS	Office for National Statistics
PFT	Perfluorocarbon Tracer
PID	Proportional Integral Derivative
PP	Percentage Points
PRT	Programmable Room Thermostat
PTRV	Programmable Thermostatic Radiator Valve
RdSAP	Reduced Standard Assessment Procedure
RECS	Residential Energy Consumption Survey
RT	Room Thermostat
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model
SEDBUK	Seasonal Efficiency of Domestic Boilers in the UK
SNV	Scheduled Natural Ventilation

TACMA	The Association of Controls Manufacturers
TRV	Thermostatic Radiator Valve
VAT	Value Added Tax
WD	Weekday
WE	Weekend
WGC	Weekly Gas Consumption
ZC	Zonal Control

Energy use conversion factors

1 MJ = 0.27777777778 kWh

1 Mtoe = 11630000000 kWh

1 Introduction

1.1 Background

As a part of 2008 Climate Change Act, the UK government made a commitment to reduce the greenhouse gas emissions by at least 80% compared to 1990 levels by 2050 (Office of Public Sector Information, 2008). The Climate Change Act which was initially targeted to reduce emissions by 26% by 2020 was later tightened to 34% (Office of Public Sector Information, 2009). Carbon dioxide is the main greenhouse gas and, in 2013 accounted for 82% of total UK's man-made greenhouse gas emissions (DECC, 2014a). Figure 1-1 indicates the contribution of each sector to the total UK carbon dioxide emissions (DECC, 2012a). Residential fossil fuel use has been the third largest contributor to the UK's total carbon dioxide emissions after the energy supply and transport sectors and accounts for 15% of the total carbon dioxide emissions (DECC, 2012a). However, the share reported for this sector does not even include the emissions from the energy supply sector due to generating electricity for domestic use. Considering the energy supply as well, housing is responsible for 25% of the UK's greenhouse gas emissions and therefore it would be difficult to meet the 2050 target without reducing emissions from residential buildings (Palmer & Cooper, 2011). Moreover, reduction in residential fossil fuel use is crucial for the UK's energy security so that the UK could become less dependent on imports.

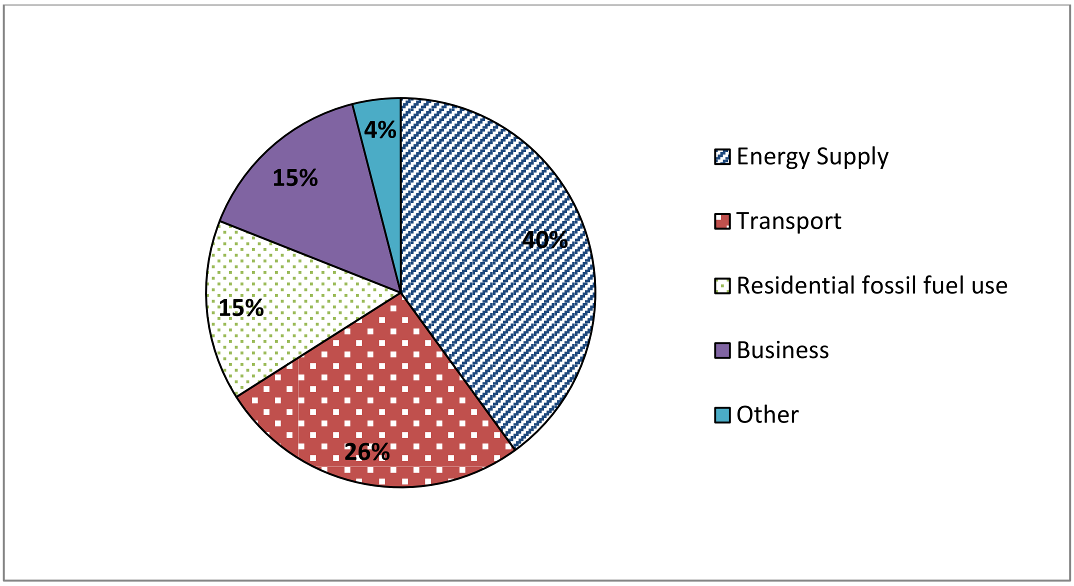

Figure 1-1: Contribution of different sectors to the UK's total carbon dioxide emissions of 2011(DECC, 2012a)

Achieving the Climate Change Act targets will require substantial reductions in energy consumption in different sectors; though reductions in the domestic sector are considered to be "relatively low cost" and "realistically achievable" (Committee on Climate Change, 2008). Since 1990, emissions from fossil fuel use in the residential sector have fluctuated but in 2010 they were 8% above the 1990 level (DECC, 2011c). In 2010, the UK residential sector emissions of carbon dioxide increased by 13.4% compared to the previous year (the highest rise for any single sector) due to a considerable rise in residential gas use for space heating as 2010 was on average the coldest year since 1986 (DECC, 2011c). In 2013, the emissions from this sector were estimated to be 3% below the 1990 level (DECC, 2014a).

The UK's housing stock is one of the oldest and least efficient in Europe (Boardman, Killip, Darby, *et al.*, 2005). The majority of energy consumption in UK dwellings is due to space heating which in 2009 accounted for 61% of the total energy consumption in the domestic sector (DECC, 2011a). Figure 1-2 presents the domestic final energy consumption in UK by end use since 1970 in which space heating has been continuously dominant. Therefore as Shipworth et al. (2010) argues "*Any policies and initiatives aimed at significantly reducing residential* CO_2 *emissions must address the largest residential* CO_2 *emitter – central heating*".

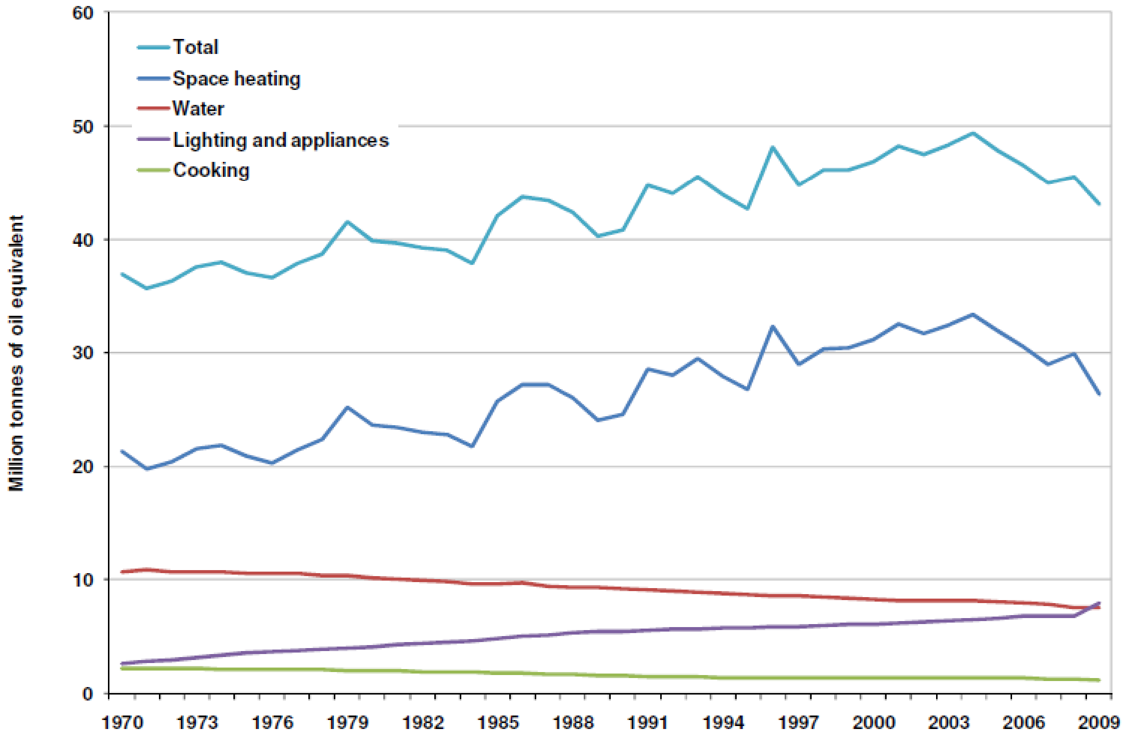

Figure 1-2: Domestic final energy consumption by end use since 1970 (DECC, 2011a)[1]

Improvements in insulation and heating efficiency have saved a considerable amount of heat energy. Figure 1-3 shows that from 1970 to 2006 improvement in the efficiency of domestic heating systems and implementing different types of insulation such as loft (attic), cavity and hot water tank insulation and double glazing kept the current level of space heating energy consumption to almost half of the amount that it could have been without these improvements.

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[1] For conversion of Mtoe to kWh see energy conversion factors, p XXI.

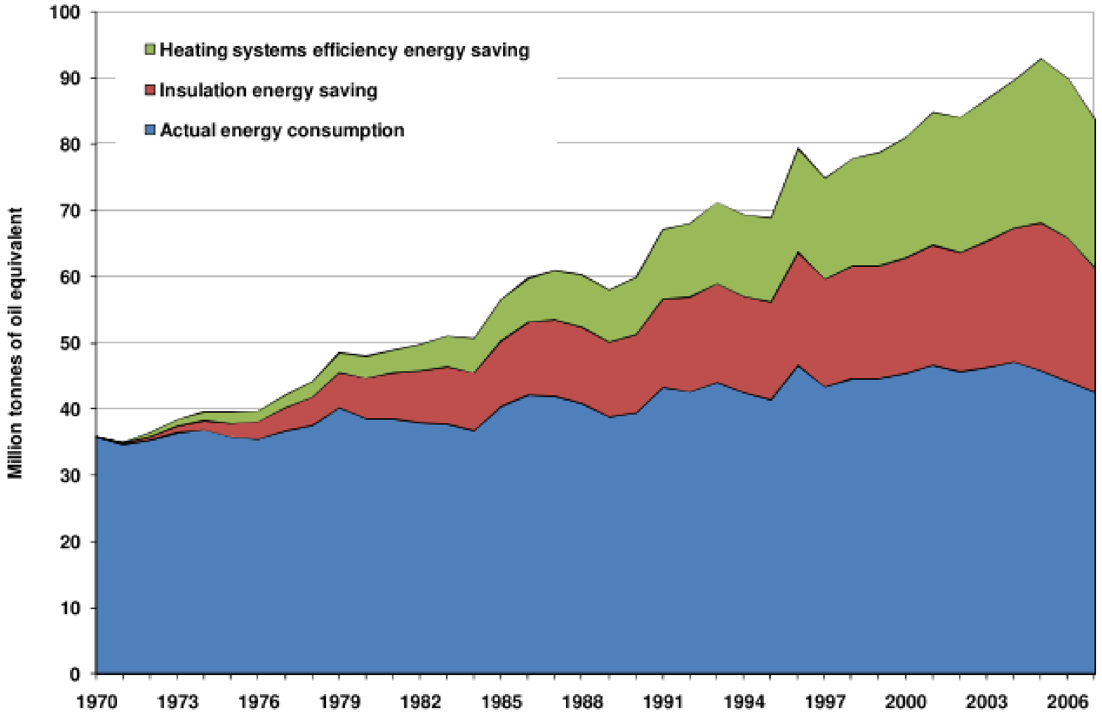

Figure 1-3: Space heating energy savings due to better insulation and heating systems efficiency in UK homes from 1970 to 2006 (DECC, 2011a)

Figure 1-4 shows the energy used for space heating and it's share in total household energy use since 1970 for the UK (Palmer & Cooper, 2011). It indicates that despite the energy efficiency improvements in houses, heating's share of household energy use has increased from 58% in 1970 to 66% in 2007. During this period, the proportion of dwellings with central heating has increased from less than a third to 96%. This increase in heating's share of domestic energy use is despite the fact that the amount of electric equipment in homes has significantly increased and also that gas central heating systems are generally more efficient than individual room appliances such as open coal fires and are therefore expected to use less energy (Utley & Shorrock, 2008).

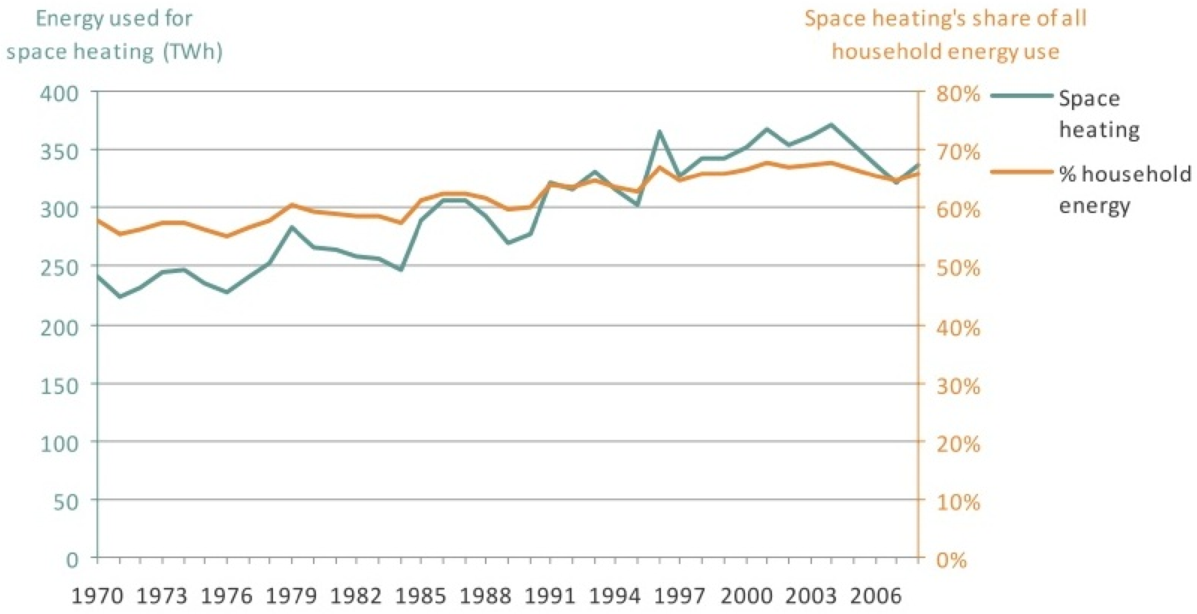

Figure 1-4: Household energy use for space heating and its share of all household energy use for the UK (Palmer & Cooper, 2011)

The rise of central heating has considerably increased the domestic energy use. According to Andrews et al. (2012), central heating contributed to 30% increase in energy consumption between 1970 to 2010. This is because it allows people to heat the whole of their homes rather than just individual rooms and provides expectations of higher indoor temperatures throughout the house. Hunt & Gidman (1982), recorded spot measurements of room temperatures in 1000 homes in the UK during the February and March of 1978 and found that the average temperature in centrally heated homes was 3°C higher than the homes without central heating.

It is likely that a considerable amount of energy is still being wasted in centrally heated homes and there is huge potential for further savings via better control strategies. An example of this waste would be heating all the rooms to maintain the same temperature even when they are unoccupied. Research has shown that an average centrally heated home consumes about twice as much energy for space heating as a similar home with heating only in the living room (Palmer & Cooper, 2011). Utley & Shorrock, (2008) argue that this would be even higher for a house with poor levels of insulation while in a very well insulated house, it may be only necessary to have a simple system of one or two room heaters instead of a full central heating system.

Zonal Control of space heating (ZC) is one option when considering more efficient heating control strategies. ZC could be described simply as restricting the heating of unoccupied areas of the home in order to reduce wasted energy. For example, during the day time, when the bedrooms are unoccupied, only the living room could be heated while the first floor bedrooms would be a separate zone and only heated during the evening when they are occupied and often to a lower temperature compared to main living areas. Therefore, ZC could be potentially more energy efficient as it enables the householders to match their space heating to their lifestyles.

1.2 Justification of the research

Wireless technology and the availability of more powerful batteries have led control manufacturers to develop retrofit systems for zonal space heating. Although market deployment is in its infancy, this is a rapidly developing area with many new systems emerging. The main components of ZC systems are the battery-operated Programmable Thermostatic Radiator Valves (PTRV) which replace normal TRVs and have motorised valves to regulate the hot water flow through the radiators according to a set-point temperature and time schedule. These can be set on the PTRVs themselves, via a central controller which communicates wirelessly with the PTRVs, or even remotely via a mobile phone or computer.

There has been little (if any) research to quantify how much energy can be saved using these devices. These savings are likely to be dependent on house type, size, location and occupancy pattern. Therefore, this research was conducted to answer the following questions:

- How much energy could ZC save in a UK house?
- Does the effectiveness of ZC depend on the local climate or its level of insulation?

1.3 Aim and objectives

The aim of this thesis was to quantify the energy demand reduction potential of using zonal space heating control in a UK home and the implication of this at a wider scale. This was achieved through the following objectives:

1. Design and set up an experimental investigation and measure the energy savings of zonal space heating control compared to conventional control in a real house.
2. Predict the energy savings for the same house using a Dynamic Thermal Model (DTM) calibrated using measurements from the experimental investigation.
3. Use the experimental results and the calibrated DTM to explore how savings might vary in UK houses exposed to a different climate or higher levels of insulation.

1.4 Outline of the thesis

- **Chapter 2** presents a thorough literature review which was conducted for this study. This covers space heating methods in the UK with a focus on wet central heating systems and their controls; studies investigated the impacts of space heating controls on energy use; zonal space heating control systems; and existing literature on modelling energy use in the domestic sector.
- **Chapter 3** provides an overview of the methodology and describes the test houses used in this study and their characterisation tests including co-heating and airtightness tests.
- **Chapter 4** describes the space heating trials conducted in the test houses in order to measure the energy saving potential of ZC and presents the results of the trials.
- **Chapter 5** describes the construction of dynamic thermal models (DTMs) of the test houses for the purpose of modelling the space heating trials and the co-heating test.
- **Chapter 6** compares the results from the DTMs with the measured results from the tests. The chapter also describes the processes of calibration and validation of the DTMs based on these comparisons.
- **Chapter 7** firstly describes the development of an empirical model based on results from the space heating trials to predict the annual energy and cost

savings of ZC in UK homes located in different regions. The differences between the predictions of the empirical model and the calibrated DTM are investigated and potential reasons for the differences identified. The calibrated DTM is then used to predict the likely heating energy and cost savings in better insulated homes.

- **Chapter 8** discusses the findings from chapters 3 to 7, identifies the key messages from the research and makes suggestions for future work.
- **Chapter 9** presents the conclusions from the research.

2 Literature review

2.1 Introduction

This chapter presents the context for the study of zonal space heating control (ZC) in UK homes and reviews the relevant academic, governmental and industry based literature. Firstly, it describes different space heating methods in UK homes (section 2.2) and the configuration and components of the most common system which is currently being used: wet central heating (section 2.3). The literature review then discusses the space heating controls in existing UK homes as well as the regulations for new homes (section 2.4). In section 2.5, studies which had examined the impacts of conventional and occupancy based space heating controls are critically reviewed. Section 2.6 describes ZC and explores different ZC systems currently available in the UK market. Section 2.7 introduces different techniques and tools which are being used to model domestic energy use and discusses model calibration and validation techniques. Finally, section 2.8 summarizes the findings from literature review which have direct implications on the methods chosen for this study.

2.2 Space heating methods in the UK homes

Next to food, heating has been among the most important elements in human existence (Wright, 1964). Since the first fire was lit in a cave, heating the living spaces to increase thermal comfort has been associated with the life of most people especially those living in the colder climates. In the UK, homes were commonly being heated using coal open fires from as early as the 17th Century well into the 1960s (Roberts, 2008 and Wright, 1964). The low pressure gravity hot water heating was common by 1900 but only limited to larger buildings and the heating in the middle- and lower-priced homes were “unplanned” and “almost unknown” (Doherty, 1967). Early central heating systems were heated by back boilers situated behind the grate of open fireplaces which were only able to heat a few radiators (Beattie, 1966). Back-boilers were simple and reliable and a large number of them were installed in the 1980s but they had low efficiencies (Munton, Wright, Mallaburn, *et al.*, 2014).

In the 1970s, with the introduction of North Sea Gas to the UK, gas fired central heating evolved (Roberts, 2008). This was a breakthrough into domestic space heating as, before this, particular rooms were heated when needed but now all the rooms could be heated, regardless of their occupancy.

Currently, central heating is the main method for space heating in the UK homes. According to the 2011 Census (Office for National Statistics, 2011), there are more than 23 million households with at least one usual resident in England and Wales from which 97.3% of them have one or more types of central heating (Table 2-1). Domestic central heating systems can be fuelled by mains gas, Liquefied Petroleum Gas (LPG), oil, electricity or solid fuel. However, the majority of homes in England and Wales (78.7%) have central heating which is supplied by gas (Table 2-1).

Table 2-1: Census 2011 data for domestic heating systems in England and Wales (Office for National Statistics, 2011)

Total number of households with at least one resident	23,366,044
Percentage of households with no central heating	2.7%
Percentage of households with Gas central heating	78.7%
Percentage of households with electric central heating (including storage heaters)	8.1%
Percentage of households with oil central heating	4.1%
Solid fuel central heating (including wood and coal)	0.7%
Other central heating (including solar, LPG or other bottled gas)	1.6%
Percentage of households with two or more types of central heating	4.1%

Central heating systems generally fall into 3 main categories: wet (hydronic) systems with heated water circulating through radiators, convectors or under-floor heating; warm air systems in which the air is delivered through ducts to rooms using a heat exchanger with a fan and filter (Doherty, 1967); and electric storage and panel systems using off peak and on peak electricity.

Wet systems are by far the most common type of heating system in the UK homes (The Carbon Trust, 2011).

2.3 Wet central heating system components and configuration

A standard domestic wet central heating system typically consists of the following components (Figure 2-1):

- Boiler
- Time switch/programmer
- Room thermostat / Programmable room thermostat
- Thermostatic Radiator Valves (TRV)
- Motorised valve
- Cylinder thermostat (only in systems with regular boiler)
- Automatic bypass valve
- pump
- Heat emitters

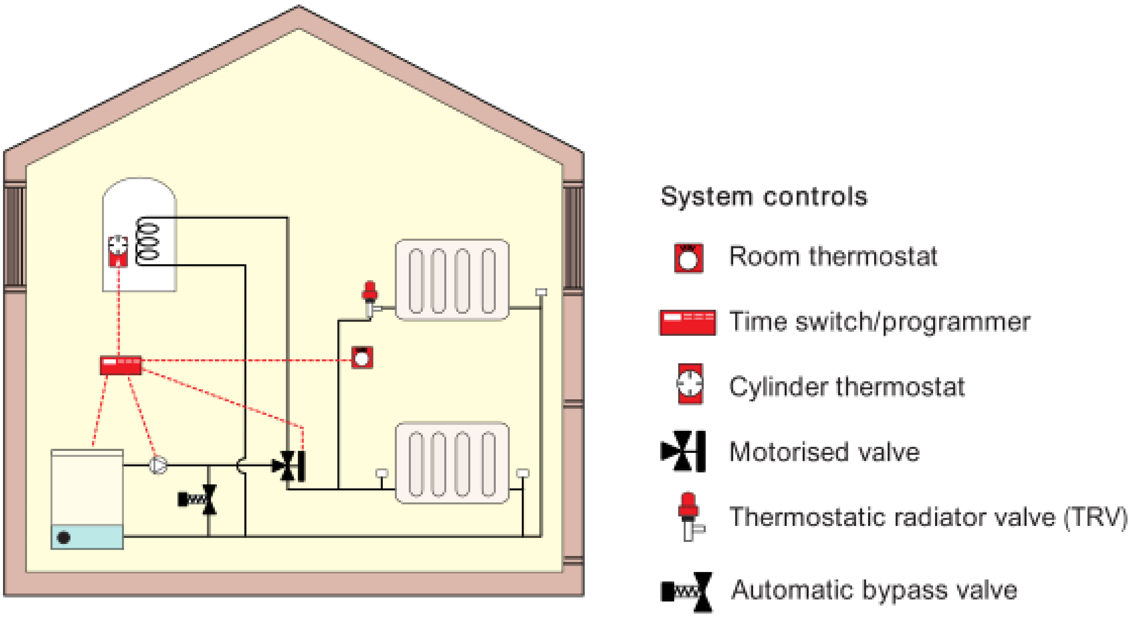

Figure 2-1: A standard domestic wet central heating system configuration (BRECSU, 2001)

2.3.1 Boiler

Boilers can be described as ‘regular’ or ‘combination’ (combi). A regular boiler is not able to provide DHW directly; therefore it does so indirectly via a separate hot water store (Figure 2-1). Historically, these were the most common boiler type and are often referred to as conventional or traditional boilers (BRECSU, 2000). A combination boiler has the capability to provide DHW directly, and some models contain a small internal hot water store. Combination boilers can be often more efficient as the standing losses from the hot water tank will be avoided (Munton, Wright, Mallaburn, *et al.*, 2014). Both regular and combination boilers may either be condensing or non- condensing. Condensing boilers use the heat from the flue gasses as secondary heating to heat the water in addition to direct heat transfer via burning fuel (Hall & Greeno, 2013).They also have a larger heat transfer surface area compared to non-condensing boilers (Hall & Greeno, 2013).

Condensing boilers are generally more efficient with an overall efficiency of above 90% compared to the non-condensing boilers with an expected efficiency of 75% (Hall& Greeno, 2013). The element that defines the efficiency of the condensing boilers in operation is the temperature at which the water returns to the boiler (Oughton and Hodkinson, 2008). High efficiency for the condensing boilers would be achieved with a water returning at a low temperature (Figure 2-2) (Oughton and Hodkinson, 2008).

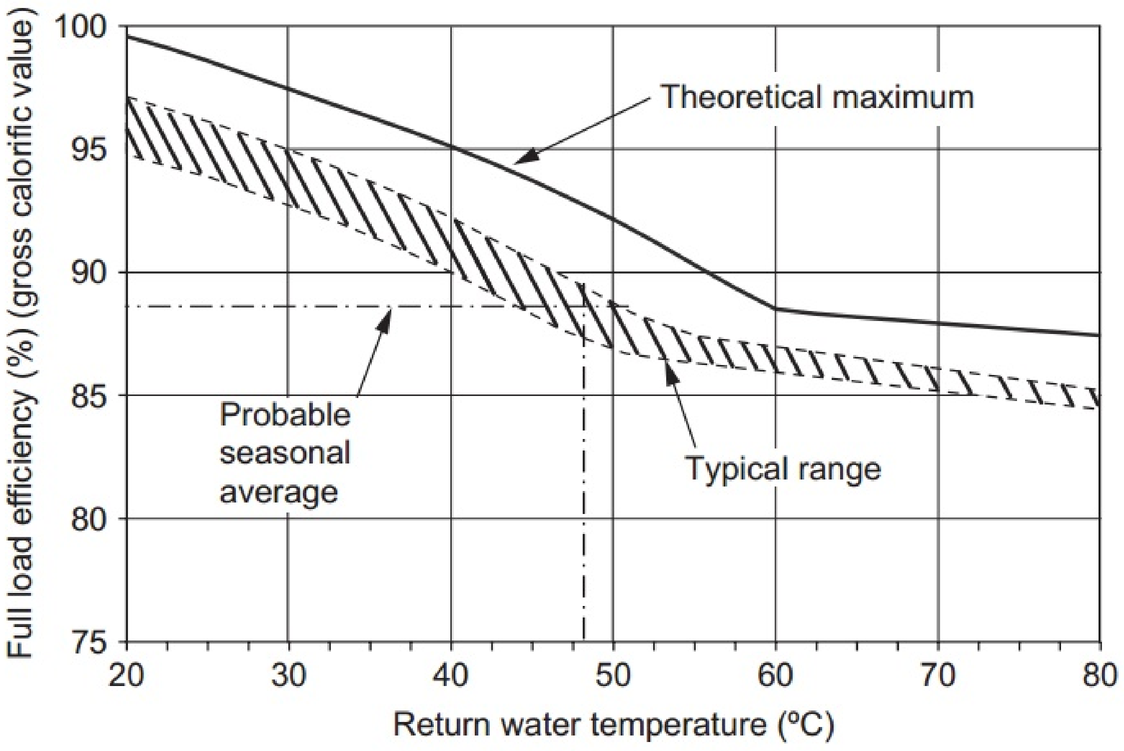

Figure 2-2: Efficiency of condensing boilers (Oughton and Hodkinson, 2008)

Condensing boilers have become mandatory for new and replacement boilers since 2005 according to the UK Building Regulations (The Office of the Deputy Prime Minister, 2005). The percentage of dwellings with condensing boilers and in particular condensing combination boilers has increased to about a third of the UK housing stock in 2010 (Department for Communities and Local Government, 2012). According to the government's Energy Efficiency Best Practice programme (EEBPp), the boiler is one of the main factors influencing energy efficiency of domestic central heating systems (BRECSU, 2000). The Seasonal Efficiency of a Domestic Boiler in the UK (SEDBUK) database records the efficiency of boilers which has been measured in a laboratory.

Internal control of boilers is typically according to the water temperature flowing from the boiler. Based on the set-point and deadband[2] two temperature threshold for Cut-In and Cut-Out can be determined. If the water temperature is higher than Cut-Out, the boiler is switched off. If the water temperature is lower than the Cut-In, the boiler is switched on (Liao, Swainson & Dexter, 2005). The water set-point temperature

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[2] Deadband here means a temperature range that is set around the set-point temperature to avoid excessive hunting by the controller (Race, 2005)

can be fixed, varied based on external air temperature or varied based on heating load. Liao et al. (2005) discussed that the overall performance of a heating system is considerably affected by the scheme for determining the value of water temperature set-point.

2.3.2 Time switch / programmer

A time switch or programmer is the primary way in which the central heating system can be controlled by the occupants. It allows them to set the times at which the system will turn on and turn off. A time switch is an electrical switch operated by a clock to switch only one circuit and therefore control either space heating or hot water, but not both (Energy Saving Trust, 2008a). A programmer can switch two circuits (heating and DHW). Depending on the type of programmer (i.e. mini, standard or full programmer) the heating and DHW time setting can be the same or fully independent (BRECSU, 2001). A mini programmer allows space heating and hot water to be on together or hot water alone but not heating alone. A standard programmer uses the same time setting for space heating and hot water. A full programmer allows the time setting for space heating and hot water to be fully independent (BRECSU, 2001).

2.3.3 Room thermostat / Programmable room thermostat

A room thermostat allows the occupants to control the central heating system by limiting the air temperature when the heating is on. It measures the air temperature, is often located in a central area of the home such as a living room or hallway and switches the space heating off when the temperature is above a single target temperature set by the user (set-point temperature) (Energy Saving Trust, 2008a). Building services handbook (Hall & Greeno, 2013) suggests that the thermostat should be installed somewhere away from draughts, direct sunlight and heat emitters at 1.2 to 1.5 m above the floor level.

A Programmable Room Thermostat (PRT) is a combined time switch and room thermostat that enables the user to set different periods with different set-point temperatures for space heating, usually in a daily or weekly cycle (Energy Saving Trust, 2008a). The use of programmable thermostats was included in the US Environmental Protection Agency’s EnergyStar Programme in 1995, suggesting that using them the households could save around $180 a year (Meier et al, 2012). However, programmable thermostats have not been widely used in the UK as it was believed that they are not necessary considering the milder climate of the UK (Munton, Wright, Mallaburn, *et al.*, 2014).

During 1990s, the ability of the PRTs to set different temperatures throughout a day and heating schedules for weekday/ weekends considerably improved (Peffer, Pritoni, Meier, *et al.*, 2011). Moreover, mobile phones and internet technology have been developed quickly so that a number of remotely controlled thermostats which allow occupants to remotely control their heating system are now available from different manufacturers. Global Positioning System (GPS) in mobile phones allows the proximity of occupants to home to be identified and transferred to the thermostat which then can predict arrival times and ensure that the heating is turned on when the resident is coming home (Consumer focus, 2012). The interface can be remote via web or smart phone, a large full colour LCD, touch screen or even voice controlled (Peffer, Pritoni, Meier, *et al.*, 2011).

Figure 2-3: Two older thermostat designs with slider bars and analogue display on the left compared to two state of the art programmable thermostats with LCD or full touch screen on the right (Peffer, Pritoni, Meier, *et al.*, 2011)

2.3.4 Thermostatic Radiator Valves (TRVs)

Thermostatic radiator valves (TRVs) are used to provide a degree of temperature control in individual rooms by adjusting the water flow through an emitter and controlling its heat output (BRECSU, 2001). TRVs are two-port throttling valves which can be installed in either the flow or return connection of radiators and are self-acting and require no external source of power (Figure 2-4) (CIBSE, 2009).

Head of a TRV contains a liquid or wax-filled capsule which expands or contract with the changes in room air temperature (CIBSE, 2009). The expansion of the liquid or wax filled capsule causes the valve seating to be depressed or elevated and consequently regulates the flow of hot water in the radiator (Watkins, 2011). TRVs are manually set at different levels (commonly 1 to 5 including a frost protection level or 1 to 6) using their temperature selector scale to define a separate target temperature for each room (Figure 2-4). A temperature setting range is often available from the manufacturer’s technical data. For example for one of the products (Drayton RT212) the temperature setting range for levels 1 to 6 was given between 12 °C to 29 °C (Invensys Controls, no date).

Figure 2-4: Left: Manual on/off radiator valve. Right: Thermostatic Radiator Valve (TRV) (Munton, Wright, Mallaburn, *et al.*, 2014)

Figure 2-5 shows the components of a TRV with an integral temperature sensor which means the sensor, transmission unit and temperature selector constitute an assembly which is incorporated with the valve body assembly (BSI, 2006). This type of assembly would allow the TRVs to be fitted as direct replacements for manual on/off radiator valves (CIBSE, 2009).

The accuracy of temperature control achieved by the TRVs is dependent on the ability of its temperature sensor to sense the real temperature of the room (Watkins, 2011). According to BS7478 (1999), there is a relationship between the temperature at the thermostatic head assembly and the temperature at the centre of a room which varies between different installations. TRV head which contains its temperature sensor should be positioned according to manufacturer's recommendation to ensure that the sensor is properly exposed to the room temperature rather than the heat from the radiator (CIBSE, 2009). Since the integral sensor is very close to the radiator, sometimes the sensor is inevitably affected from the convective heat flows (Weker & Mineur, 1980). Therefore, in some TRVs the sensor or both the sensor and temperature selector unit is mounted remotely from the valve body (BSI, 2006).

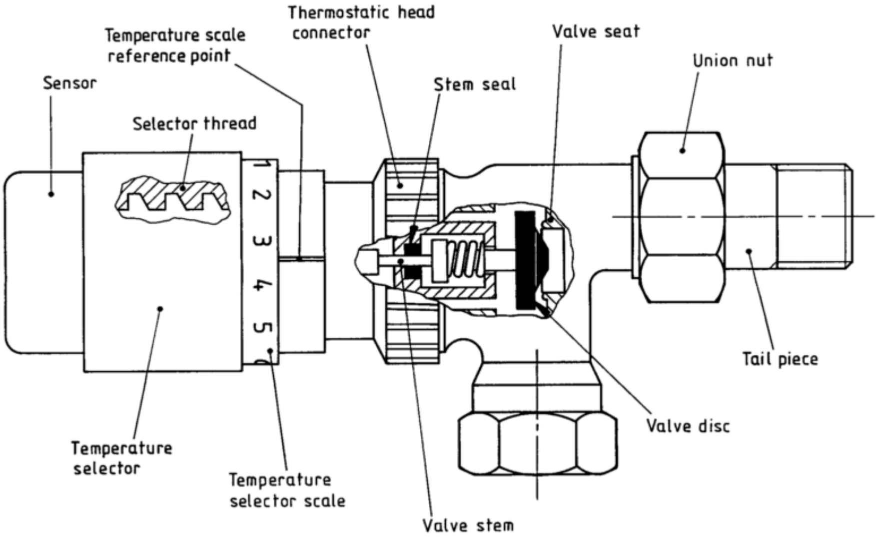

Figure 2-5: Principle components of a Thermostatic Radiator Valve (TRV) (BSI, 1999)

2.3.5 Motorised valve

Motorised valves are used to control the water flow from the boiler to heating and hot water circuits (Energy Saving Trust, 2008b). Motorised valves could be either two-port or three-port (Figure 2-6) and their selection for each system is according to the system's pipework layout and preference (Energy Saving Trust, 2008b).

Figure 2-6: An example of two-port (on the left) and three-port (on the right) motorized valve (Danfoss, no date)

A two-port valve controls water flow to one circuit while a three-port valve controls flow to two circuits (BRECSU, 2001).

When there is only one heating zone, a three-port valve can provide separate heating and hot water circuits. Most three-port valves are mid-position valves which means that they have one central inlet port connected to the flow from the boiler and two outlet ports; one for DHW and one for central heating (BRECSU, 2001). When there is more than one heating zone as well as hot water zone, a two-port valve for each heating circuit is required (Energy Saving Trust, 2008b).

2.3.6 Cylinder thermostat

Cylinder thermostats are only used in the systems with a regular boiler and a hot water tank, as opposed to systems with a combination boiler where hot water is instantly produced (Consumer focus, 2012). A cylinder thermostat which is often strapped to the DHW cylinder, measures the temperature of hot water cylinder and switches the hot water supply on and off using a motorized valve (BRECSU, 2001). A single target temperature can be set by the user or a combined time switch and cylinder thermostat can be used to set different period with different target temperatures for the stored hot water (Energy Saving Trust, 2008b).

2.3.7 Automatic bypass valve

A bypass circuit must be installed if the boiler manufacturer requires one, or specifies that a minimum flow rate has to be maintained while the boiler is firing (Hall and

Greeno, 2013). The bypass circuit must then include an automatic bypass valve installed between the boiler flow and return considering the direction of the flow (Energy Saving Trust, 2008b). Automatic bypass valves are necessary when more than half of the radiators are fitted with TRVs (BRECSU, 2001) as when the TRVs begin to close the bypass valves opens to maintain a steady flow of water through the boiler (Hall and Greeno, 2013). Alternatively fixed bypass can be achieved either by ensuring that one radiator stays open or by adding a short pipe with a fixed position valve between the flow and return pipe (BRE, 2014). A radiator without a TRV or hand valve is a common form of fixed bypass (BRE, 2014).

2.3.8 Boiler interlock

Boiler interlock is not a control device but a wiring arrangement of the system controls (room thermostats, PRTs, cylinder thermostats, programmers and time switches) in order to prevent the boiler from firing when there is no demand for heat (Energy Saving Trust, 2008a). For the systems with a regular boiler, the interlock is usually set so that the room or cylinder thermostat switches the power supply to the boiler through the motorised valve (BRECSU, 2001). For systems with a combination boiler, interlock is usually achieved by using a room thermostat. In most cases, interlock also applies to the pump operation (BRECSU, 2001). TRVs alone are not sufficient for boiler interlock and needed to be installed together with a room thermostat (Energy Saving Trust, 2008a).

2.3.9 Pump

The pumps used in domestic central heating systems are simple centrifugal pumps (Mitchell, 2008). Domestic central heating pumps could be classified into three main categories; fixed speed, three speed and variable speed (Mitchell, 2008). Fixed speed pumps are the simplest type and used to be the standard for many years (Mitchell, 2008). Three speed pumps which are the most common type currently used have three settings which are related to three different pressure/flow diagrams as can be seen in Figure 2-7 (Mitchell, 2008). The speed of the pump is selected manually for the optimal operation of the system and the central heating controls cannot usually change the pump speed (Mitchell, 2008). Having three settings would enable some flexibility for adjustment to individual installations and allows for potential changes to the system in future (Hall and Greeno, 2013).

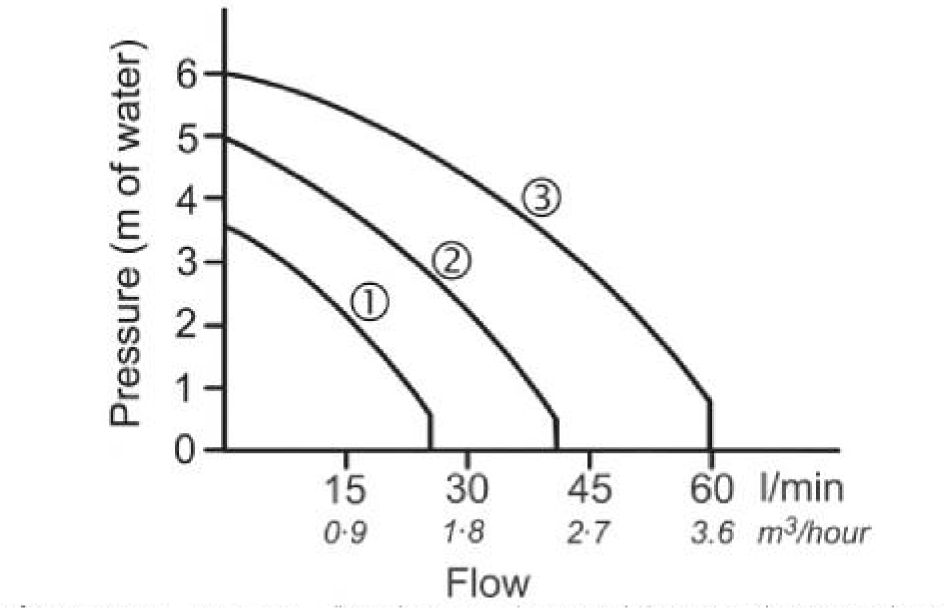

Figure 2-7: Pressure/flow diagram of a typical domestic three-speed central heating pump (Mitchell, 2008)

Variable speed pumps have a self-regulating output facility which responds automatically to varying loads throughout a day in modern standard central heating systems with thermostats, motorized zone valves and TRVs (Hall and Greeno, 2013).

2.3.10 Heat emitters

Heat emitters transfer heat from a heating system into the building spaces by convection and radiation (Brown, 2011). A wide range of heat emitters are available for domestic wet central heating systems including panel radiators, column radiators, Low Surface Temperature (LST) radiators, towel rails, natural and fan convectors and under-floor heating coils (Figure 2-8). The most common type installed in modern housing is panel radiators which are available in a wide range of sizes and outputs to suit different rooms (BRECSU, 2000). Radiators are often installed below windows to counteract any cold downdraughts (Oughton & Hodkinson, 2008). As opposed to its name, the majority of the radiator’s heat is transmitted via convection (about 70%) rather than radiation (about 30%) (Brown, 2011). Fins are often added to the radiators to increase their surface area in order to increase their output

(CIBSE, 2005). LST radiators are used where young children or elderly are at risk in order to limit the surface temperature to 43ºC and prevent injury (HSE, 2012).

Figure 2-8: Three common types of heat emitters: panel radiator, fan convector and underfloor heating coils (Young et al. 2013)

The heat output of radiators are dependent on a number of factors including their size, number of panels (single or double), number of fins and their material (Table 2-2).

Table 2-2: The ranges of heat outputs and heights of different types of radiators according to a manufacturer (BSMW products Ltd, 2011)

Radiator type		**Heat output range (W/m)**	**Height range (mm)**
Finned steel panel	Finned single panel	541-1218	300-750
	Double panel, single fin	820-1868	
	Double panel, double fin	1039-2258	
Old steel panel	Single panel	483-1042	300-740
	Double panel	752-1633	
Column radiators[1]		41-249	460-910 (Depth: 66-140)

[1] Heat output reported in W/Section

Natural convectors are often 100% convective and consists of a copper or steel pipe with fins fitted along its length which is installed at the bottom of the casing (Oughton & Hodkinson, 2008). A convection airflow driven by the warm air above the convector is moved by the cooler air entering below (Oughton & Hodkinson, 2008). The fan convectors are similar to natural convectors but includes a fan and thus have higher outputs compared to natural convectors (Oughton & Hodkinson, 2008).

In under-floor heating (Figure 2-8), circuits of plastic pipes laid in a floor screed or below a timber floor are fed with low temperature hot water. In under-floor heating, heat is typically emitted 40% convective and 60% radiative (Oughton & Hodkinson, 2008).

2.4 Central heating controls in the UK homes

2.4.1 Regulations for central heating controls

Since the first mandatory UK Building Regulations were introduced in 1966, this has been revised several times over the last 40 years in order to improve the energy efficiency of both new and existing dwellings (Boardman, Killip, Darby, *et al.*, 2005). Many factors such as thermal performance of building envelope, energy efficiency of boilers and the distribution systems and control systems influence the energy efficiency of a heating system (BRE, 2014). Central Heating System Specifications (CHeSS) document (Energy Saving Trust, 2008a) has provided the current “Basic” and “Best Practice” specifications for the components of domestic wet central heating systems that are critical to energy efficiency. For example, “Basic” system must have a regular or combination condensing boiler with minimum SEDBUK efficiency of 86% (bands A and B) or “Best practice” system must have a regular or combination condensing boiler with minimum SEDBUK efficiency of 90% (band A only).

CHeSS (2008) defines “Basic” as “sufficient to comply with Building Regulations Part L1 that came into effect in April 2002”. The building regulations apply when:

- A home is built
- A home has an extension or change of use
- More than one individual component, such as a boiler is replaced in a heating system.

CHeSS (2008) also defines “Best Practice” as “the adoption of products and techniques that are already established in the market, cost effective and able to save energy without incurring undue risks”. This section focuses on the “basic” and “best practice” specifications of domestic space heating control systems.

According to CHeSS 2008, a “Basic” central heating system must have following control specifications:

- Full programmer and cylinder thermostat (for regular boiler with separate hot water store)

- Time switch (for combination boilers)
- Room thermostat
- Boiler interlock
- TRVs on all radiators, except in rooms with a room thermostat.
- Automatic bypass valve

According to CHeSS 2008, a “Best Practice” central heating system must have following control specifications:

- Programmable room thermostat (with additional DHW timing capability for regular boiler)
- Boiler interlock
- TRVs on all radiators except in rooms with a room thermostat
- Automatic by pass valve
- Cylinder thermostat (only for regular boilers)

The main difference between the control specifications of “Basic” and “Best Practice” central heating systems is that in “Best Practice”, programmable room thermostat enables the households to program their heating in order to set different target temperatures (i.e. set-point temperature) throughout a day. In “Basic” systems, different set-point temperatures could only be set manually using a room thermostat.

In recent years, more attention has been paid into controlling different zones in dwellings separately as reflected in Building Regulations Part L1A for new dwellings which came into force from 1 October 2010 (HM Government, 2013). According to Domestic Services compliance guide (Department for Communities and Local Government, 2011), which provides more detailed information on the guidance contained in approved documents of Part L1A (for new dwellings) and L1B (for existing dwellings), since 1 October 2010 every new home which is not open plan must be divided to at least two heating zones such that living and sleeping areas can be controlled at different temperatures by means of two thermostats. If the house is smaller (less than 150 m^2), then these two zones can be controlled by the same timer. This means that the flow of heat in each zone is controlled via separate room thermostats and motorised valves; although the same heating schedule can be applied for both zones using the same timer. If the house is larger (more than 150

m^2) then each zone must be controlled by its own timer. This only applies to the new homes but the minimum requirements for heating controls have not changed for existing dwellings since 2002 when the Building regulations part L came into force.

Figure 2-9 and Figure 2-10 were adopted from a guide by The Association of Controls Manufacturers (TACMA) on how to comply with the 2010 Building Regulations Part L. They show examples of heating system layouts for new dwellings (layouts 1-6) and existing systems (layouts 7-12) that comply with “Basic” and “Best Practice” heating controls for different boiler types, dwelling size and valve types. In Figure 2-9, layouts 1, 2, 5 and 6 comply with “Basic”, and 3, 4 with “Best Practice”, heating controls for new dwellings. In Figure 2-10, layouts 7, 8 and 11 comply with “Basic” and 9, 10 and 12 with “Best Practice” heating controls for existing dwellings.

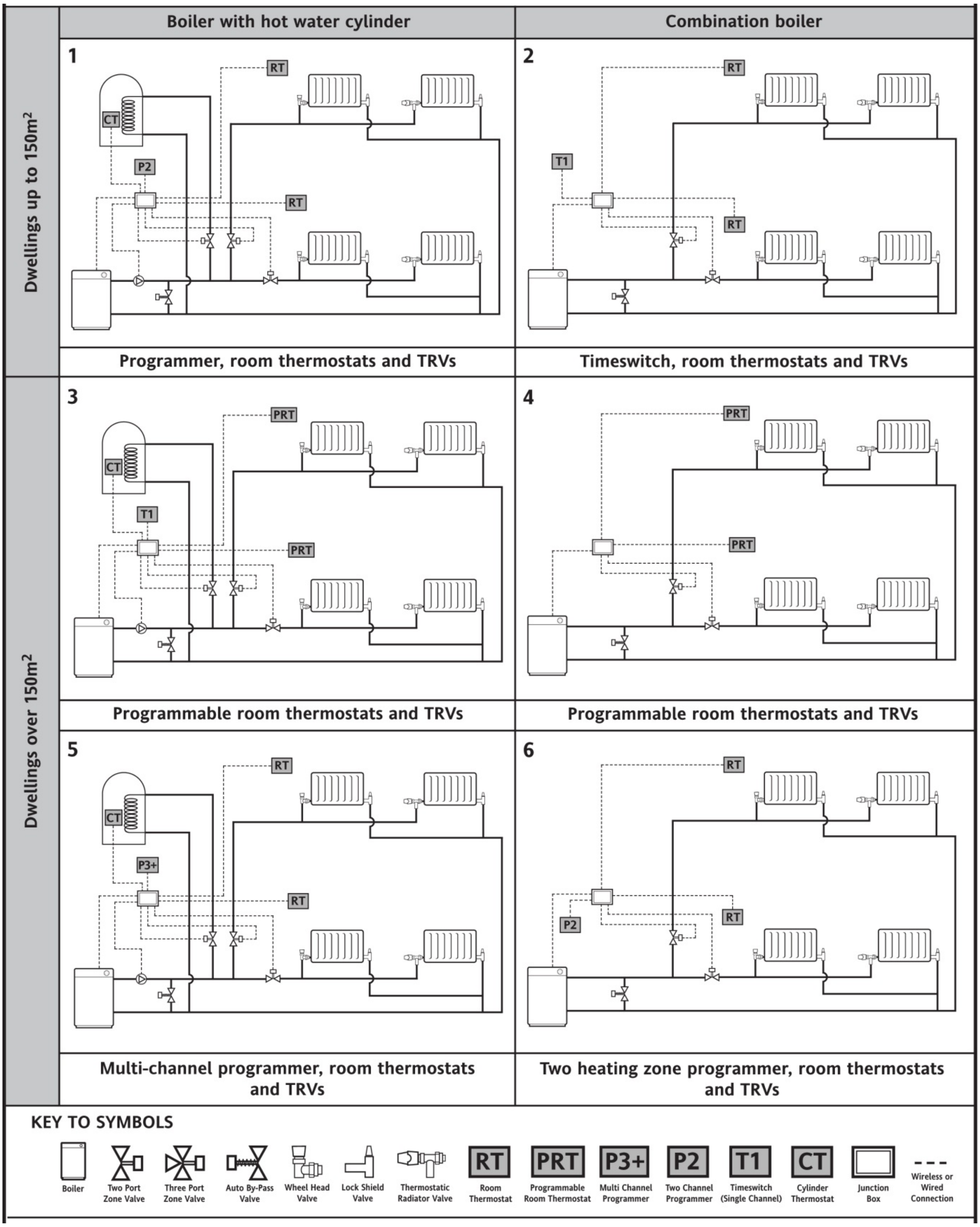

Figure 2-9: Example layout for new systems to ensure compliance with the 2010 Building Regulations Part L1A (TACMA, 2010)

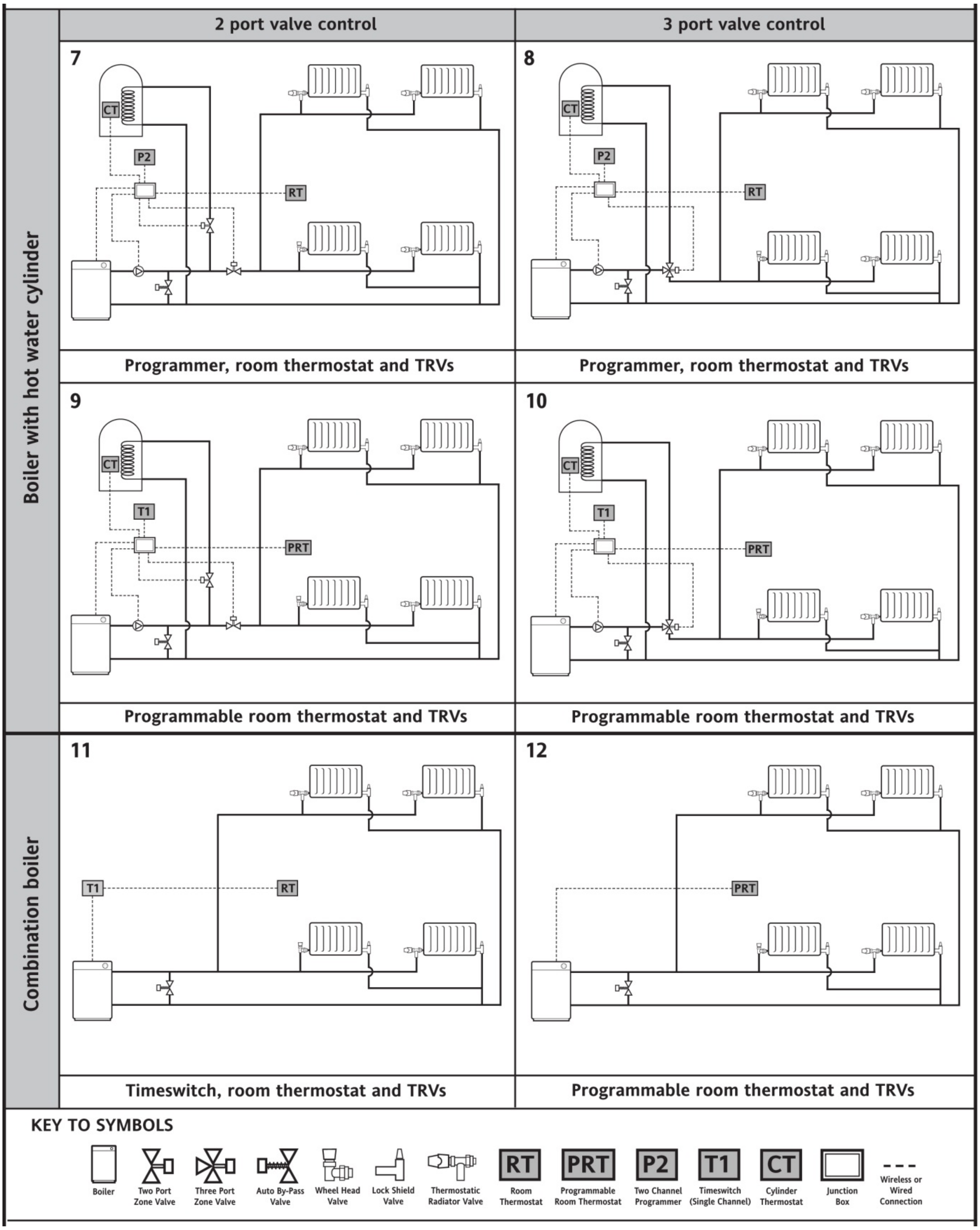

Figure 2-10: Example layout for replacement boilers to ensure compliance with the 2010 Building Regulations Part L1B (TACMA, 2010)

2.4.2 Space heating controls in existing homes

Prior to December 2013, when Energy follow up survey (EFUS) 2011 (BRE, 2013) was published, there were very few reports or literature on the status of central heating controls in UK homes (Munton, Wright, Mallaburn, *et al.*, 2014). Most of the information available was according to control manufacturers which indicated poor levels of space heating control in UK homes.

One of the largest control manufacturers in the UK, Honeywell, noted that from 26 million homes in the UK, about a third, do not have room thermostats which cause excessive room temperatures (Enviros Consulting Ltd, 2008). Similarly, work carried out by TACMA (The Association of Controls Manufacturers) with the Energy Saving Trust reported that 30% of homes in the UK do not have a room thermostat (Heating and Hot Water Task Force, 2010). Enviros Consulting Ltd (2008) estimated that almost a quarter of homes do not have either a programmable thermostat or a room thermostat. In addition, they estimated that nearly 40% do not have any TRVs installed (Enviros Consulting Ltd, 2008). Enviros Consulting Ltd (2008) stated that 70% of the dwellings do not have modern standard heating controls set by building regulations. More dramatically, according to Heating and Hot Water Taskforce (2010) there were 4% of homes with a boiler and no controls at all.

These information were mainly in agreement with findings from a literature review by the statutory consumer champion for England, Wales, Scotland and Northern Ireland published in July 2012 (Consumer focus, 2012) which shed more light on the percentages of UK households with each of the main heating control types (Figure 2-11).

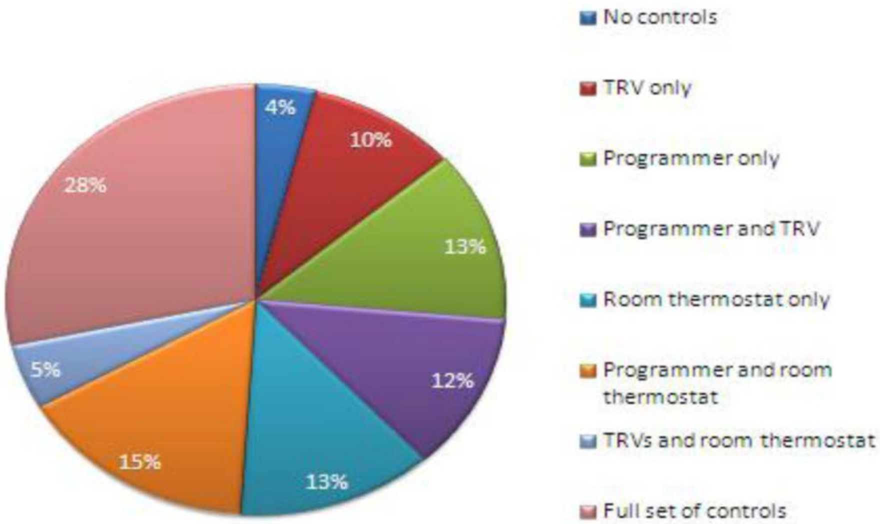

Figure 2-11: Percentage of UK households with a boiler with each of the main heating control types as reported in Munton *et al.* (2014)

EFUS 2011 which was funded by DECC and carried out by the Building Research Establishment (BRE) collected new data on the patterns of household and dwelling energy use including information regarding what heating controls are currently installed in UK homes. Data was collected from an interview survey of a self-selecting rather than randomly selected sample of 2616 households (BRE, 2013). The results of EFUS contradict the earlier findings showing that 49% of the households in their sample have full set of controls compared to only about 30% found in the previous reports. A report by Munton et al. (2014) who compared the data from EFUS 2011 with Consumer Focus report from 2008 argued that the proportion of households with central heating that have a range of controls may have increased over the recent years. Munton et al. (2014) summarized the most recent information available regarding the status of space heating controls in UK homes and its relationship with built type from EFUS 2011 data which are reproduced and presented in Table 2-3.

Table 2-3 shows that most UK homes in their sample (97%) have a central timer regardless of the dwelling type. More than two third of the dwellings in each category have room thermostat with an average of 77% for the whole sample. However, room thermostats are least common in high rise flats (67%) and most common in bungalows (83%). It also indicates that above 60% of the central heating systems in each dwelling type have TRVs installed. The lowest percentage of dwellings which have thermostats was found in high rise purpose built flats which had the highest percentages of dwellings with TRVs installed.

Table 2-3: Proportion of dwelling types reporting primary heating controls (reproduced from Munton et al., (2014))

Dwelling/Household type	**Room Thermostat (%)**	**Central Timer (%)**	**TRV (%)**	**Full set of controls[1] (%)**
Whole sample	**77**	**97**	**66**	**49**
Purpose built flat, high rise	67	99	78	52
Purpose built flat, low rise	77	98	65	49
End terrace	76	96	69	51
Mid terrace	77	97	69	52
Converted flat	77	97	67	51
Bungalow: all ages	83	97	66	53
Detached house: Pre 1919	76	98	70	52
Detached house: Post 1919	74	96	59	43
Semi-detached & terraced: pre 1919	75	98	66	49
Semi-detached & terraced: 1919-1944	71	98	63	43
Semi-detached & terraced: 1945-1964	82	98	61	49
Semi-detached & terraced: 1965 onwards	80	97	66	53

[1] Including TRVs, central timer and a room thermostat

2.5 Impacts of space heating controls on energy demand

Improving the efficiency of domestic heating systems can be studied by considering the individual components such as boilers, thermostats, heat emitter controls (TRVs), pumps etc. or by considering the heating system as a whole (Liao, Swainson & Dexter, 2005). Liao et al. (2005) argues that although each individual item is becoming more efficient, the improvement in efficiency of the heating system as a whole is still unknown to a large extent. They suggested considering all components when looking for ways to improve energy efficiency rather than concentrating only on one individual item. Liao et al. (2005, p344) argue that "*It is vital therefore that the interaction of the whole heating system within a building is considered when looking at controls and that a reliable and repeatable method of testing is developed to allow claims of performance to be assessed in terms of both energy and thermal comfort achieved*".

Heating controls have the potential to reduce the heating energy demand in two main ways; by reducing the length of space heating in a house or altering the heating demand temperature at different spaces of a house according to its occupancy and usage patterns (Firth, Lomas & Wright, 2010). Research shows that the length of heating period and heating demand temperatures are the most influential factors affecting the amount of heating energy which is consumed in homes and their relevant CO2 emissions. Firth et al (2010) estimated the length of the heating period and the heating demand temperature to have normalized sensitivity coefficients of 0.62 and 1.55 on CO2 emissions respectively. This indicates that for every 1% increase in the heating demand temperature, a 1.55% increase in average dwelling CO2 emissions will result. Also, a 1% rise in the number of heating hours is estimated to result in a 0.62% rise in CO2 emissions (Firth et al. 2010).

The studies which investigated the impacts of space heating controls on energy demand can be divided into two main categories depending on the type of heating controls tested. A number of studies examined the effects of adding one or more conventional heating control components such as room thermostat, Programmable Room Thermostat (PRT) or TRVs to an existing heating system. They will be discussed in section 2.5.1. Other studies evaluated the energy saving potential of a number of methods to control the delivery of heat in buildings more efficiently according to the building occupancy. They will be discussed in section 2.5.2.

2.5.1 Conventional space heating controls

Several studies were conducted to investigate the potential space heating energy savings which can be achieved by employing a number of conventional control components in homes including room thermostats, programmable room thermostats and TRVs. Based on their approach, these studies can be divided into three groups. In the first group, there are studies which used models (either steady state or dynamic). The second group used test house facilities to conduct a side-by-side comparison of the effects of different heating controls on energy demand and thermal comfort of a matched pair of test houses with synthetic occupancy. These studies were conducted by Building Research Establishment (BRE) in the late 1970s and 1980s (Rayment et al. 1983 and Rayment & Morgan 1984). In the third group, there are studies which compared energy demand or factors which influences the energy demand between real homes with different types of heating controls. The major difference between groups 1 and 2 and group 3 is that in group 1 and 2, studies often assume standard occupancy behaviour while the third group takes into account effects of occupants’ interaction with the heating system controls.

An example of group 1 studies is the Good Practice Guide 302 (BRECSU, 2001) which used the Standard Assessment Procedure (SAP) for energy rating of dwellings (BRE, 2014) to estimate the energy savings which could be achieved in UK homes by applying better controls. According to them, installation of the minimum standard of controls in a wet system which previously had no controls reduces fuel consumption and CO2 emissions by 17%. They also argues that turning down a room thermostat by 1ºC will reduce space heating demand by 6-10% and reducing the heating on time by two hours a day can reduce demand by 6% (BRECSU, 2001). Good Practice Guide 302 also provided a Table in which the average potential savings which could be achieved by adding different features to improve an existing heating control system is predicted for different house types depending on their boiler type (Table 2-4). The guide explains that these predictions were based on assuming normal controls, systems and user behaviours and therefore actual savings in individual systems may be significantly different. However, the details and assumptions involved in these predictions were not mentioned in the guide.

Table 2-4 shows that the most energy savings across all the dwelling types can be achieved when the existing system does not have any type of controls. When the existing system already has control components such as room thermostat or TRV the percentage energy savings of adding additional control components reduces. For example, adding normal TRVs on all of the radiators to an existing heating system which has a room thermostat and boiler interlock, could on average only save 4% of fuel consumption regardless of the boiler type.

Table 2-4: Typical average annual fuel and cost savings (£) which could be achieved from better heating controls (Table reproduced from Good Practice Guide 302 (BRECSU, 2001))

Existing system has the following controls	Improved system add the following for the minimum set	Approximate average saving (% of the existing fuel consumption)	Typical average Annual fuel cost savings (£)		
			Terraced	Semi-detached	Deatched
Typical boiler with gravity DHW					
-	RT,CT,MV,BI,TRV	17%	51	58	82
RT	CT,MV,BI,TRV	12%	36	41	58
RT,CT,MV,BI	TRV	4%	11	13	18
TRV	RT,CT,MV,BI	9%	27	31	44
Typical boiler-fully pumped					
-	RT,CT,MV,BI,TRV	17%	51	58	82
RT, CT, MV	BI,TRV	10%	30	34	48
RT,CT,MV,BI	TRV	4%	11	13	18
TRV	RT,CT,MV,BI	9%	27	31	44
Typical combination boiler					
-	RT, BI, TRV	15%	45	52	73
TRV	RT, BI	7%	21	24	34
RT, BI	TRV	4%	11	13	18

RT=Room Thermostat, BI=Boiler Interlock

TRV=Thermostatic Radiator Valve, CT=Cylinder Thermostat, MV=Motorised Valve

The estimated typical energy savings of installing TRVs using SAP was considerably lower than the claimed energy savings by their manufacturers. Tahersima et al. (2013) noted that TRVs can reduce the heating demand by up to 20%. However, their reference was only based on a claim on the website of a large manufacturer of heating controls (Danfoss). Hartmann (no date) in another document written for Danfoss noted that “according to experience” TRVs save 10-15% of energy and this could be up to 20% in “individual cases”. It should be noted that although TRVs are in use for decades, there are only a few published literature which investigates the energy savings of TRVs (Dentz & Ansanelli, 2015).

Studies which used dynamic thermal modelling estimated higher potential savings by using TRVs compared to what estimated by Good Practice Guide 302 (BRECSU, 2001). Xu et al. (2008) conducted a modelling analysis based on an existing multi-family building and heating system in China and found that 12.4% of heating energy can be saved if the TRVs were kept on level 2-3 instead of being fully open (level 5). This saving was achieved due to the TRVs help in reducing the overheating. The mean room temperature for the whole building was reduced from 22.8°C when TRVs were fully open (or in other words when the heating system was operated without valve control) to 20.5°C with TRVs on level 2-3 (Xu, Fu & Di, 2008). Xu et al. (2008) also reported a monitoring study by Wang and DI (2002) from the Chinese government demonstration projects that indicated an average heating demand reduction of 10% when using TRVs.

A recent study (Monetti, Fabrizio & Filippi, 2015) used EnergyPlus simulation software to construct and calibrate a dynamic thermal model based on the monitoring data in order to investigate the effect of TRVs on energy demand of an old existing multi-family home in Italy. Their case study results showed that the total heating demand of a heating season can be reduced by up to 10% by using TRVs and suggested that TRVs can be considered as low cost energy efficiency measure that can be easily applied to old buildings (Monetti, Fabrizio & Filippi, 2015). Again, their study was based on theoretical assumptions about occupants’ behaviour. For example no monitored data regarding the occupant’s interaction with TRVs and heating temperature set-points was available. They argued that higher quantity and quality data was needed for better calibration (Monetti, Fabrizio & Filippi, 2015).

In contrast with manufacturer claims and model predictions which suggest considerable potential for energy savings by better heating controls, a number of studies suggest conflicting results in real world configurations.

Shipworth et al. (2010) in a study of 427 UK households argues that in contrast to what is currently assumed in policies and regulations, the use of “simple controls” (thermostats and time clocks) in homes does not reduce energy consumption. They found that the sample of homes without thermostatic control of the central heating system had mean estimated thermostat settings of 0.6ºC below those with thermostatic control. In addition, they found that central heating systems operated by timer are active 0.4 hours/day longer than those operated manually. They suggested that alternative forms of heating controls which appeal to householders should be developed and tested.

In a side-by-side comparison study of BRE (Rayment, Cunliffe & Morgan, 1983), they found that there is no significant difference between the room air temperatures and space heating gas demand of a house controlled by a room thermostat and TRVs compared to a similar house controlled only by TRVs. Rayment et al. (1983) argues that for the type of occupancy and house tested, room thermostat could be as effective as TRV control.

Conventional TRVs were found not to perform and operate as designed in real world set ups after many years in service (Liao et al., 2005) & (Dentz & Ansanelli, 2015). A survey of 35 buildings by Liao et al. (2005) although focusing on non-residential dwellings found that more than 65% of the TRVs were performing poorly as they failed to reduce the heating output of radiators when the room temperature was greater than its desired value and therefore the rooms were overheated.

Figure 2-12 which is adopted from Liao et al. (2005) shows indoor temperatures in three rooms in a building with TRVs in their study and the corresponding external temperature. As it can be seen temperatures of up to even 29ºC was observed showing that the TRVs were not performing well.

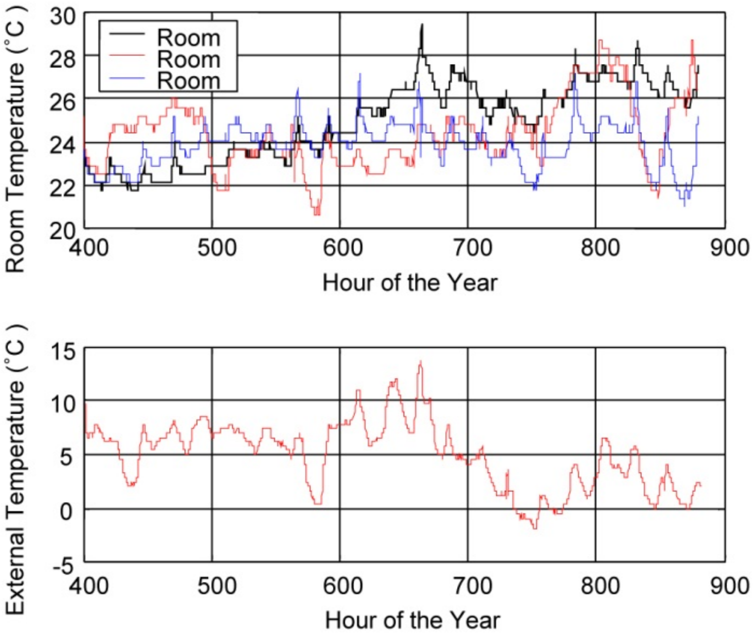

Figure 2-12: Average air temperature in a building with TRV controlled radiators (Liao et al., 2005)

In addition, 32% of the TRVs in this study were found to be set at maximum and more than 65% were found to be set at higher than required. One reason for the settings higher than required could be due to the fact that occupants do not often interact with the TRVs. Osz (2014) described a number of factors that could influence householder’s interaction with the TRVs. These included difficulty in reading and interpreting the settings (poor design), existence of different styles of TRV in homes which caused confusion, and householder’s lack of understanding regarding how TRVs work. Dentz & Ansanelli (2015) argues that even among experienced professionals there is a range of understandings about TRVs and some have little knowledge of TRVs.

Another real world example is the PRTs which have been considered as one of the main components for energy saving in space heating. The basic idea of the PRTs has been to use two temperature targets and heat the house to a set-point temperature when the occupants are present and active and let the house to float to a lower, more energy efficient set-back temperature when the occupants are typically away or asleep (Lu, Sookoor, Srinivasan, *et al.*, 2010). However, Lu et al (2010) argues that the households with a simple dial-type thermostat could easily adjust the temperature settings before going to sleep or leaving the house and save more energy compared to the households with programmable room thermostats in which the heat is often wasted because it is often not possible to find one or two general schedules which can be applied for highly dynamic occupancy patterns of most homes.

A number of studies which compared energy demand and heating practices in houses with a programmable room thermostats and houses with a simple room thermostat were reviewed by Wei et al. (2014). The main findings from a number of these studies were summarized in Table 2-5.

Table 2-5: Studies which compared energy demand and heating practices in homes with a programmable room thermostat and homes with a room thermostat and their main findings (Wei et al. 2014)

Study	**Number of homes, Method of collecting data, country**	**Main findings**
(Nevius & Pigg, 2000)	299 homes, survey & measurement, US	• Houses with PRT had thermostat set-points which were not significantly different than homes with a RT • Houses with PRT uses on average 2.5% less energy than houses with a RT but this difference was not statistically significant
Jeeninga et al. (2001) in Dutch reported in (Groot et al. 2008)	180 homes, questionnaire, Netherlands	• Preferred set-points are not affected by the type of room thermostat (programmable or manual) • Lower set-point temperatures during long unoccupied period in homes with RT compared to PRT
(Guerra Santin & Itard, 2010)	313 homes, questionnaire, Netherlands	• Higher temperature settings during the night in houses with PRT • No statistically significant difference between the hours of use of thermostat and the thermostat setting between the houses with RT and PRT • The type of thermostat affects the number of rooms heated. In houses with PRT the occupants take less actions and leave the control to the PRT
(Tachibana, 2010)	2356 homes, questionnaire, US	• 86% of the homes with PRT applied evening to night time set-back compared to 66% of the homes with RT
(Lutzenhiser, Cesafsky, Chappells, *et al.*, 2009)	279 homes, survey, US	• Homes with manual thermostat use less energy compared to homes with programmable thermostat

PRT=Programmable room thermostat

RT=Room Thermostat

Munton et al. (2014, p57) discusses that the failure to find consistent evidence that improved domestic heating control technologies deliver energy savings could be due to poor experimental design. They suggest a number of important factors which need careful consideration. These include:

- “*having robust and consistent definition of control technologies”,*
- *“monitoring actual house temperatures and heating durations”,*
- *“an experimental design, at the very least involving a matched comparison that enables the study to control for intervening variables”*
- *“measuring consumer behaviour carefully”.*

2.5.2 Occupancy based space heating control

A number of studies have investigated the potential for saving space heating energy by controlling delivery of the heat more efficiently according to the presence of occupants in a space. These studies were mainly undertaken in the US where the majority of buildings are equipped with forced air heating systems. In a monitoring study of 8 homes in the US it was found that only half of the rooms were occupied for up to 60% of the time when the home was occupied, and that the occupancy of these rooms was predictable based on ongoing activities and times of the day (Lu, Sookoor, Srinivasan, *et al.*, 2010).

Meyers et al. (2010) estimated that 2.7% of all residential primary energy in the US is spent on heating unoccupied homes assuming that on average, homes are unoccupied for 4 hours during a weekday. Assuming the percentage of floor space occupied by bedrooms and living rooms to be 48% and 52% respectively, they also estimated that 6.2% of total primary energy is wasted for heating or cooling the living rooms during the night period when unoccupied. Moreover, 9.7% of total primary energy is wasted for heating or cooling the bedrooms during the 4hours of a day which was assumed that occupants spent in the living rooms. This shows a total of 15.9% of wasted primary energy for heating or cooling unoccupied spaces of a typical US home. This was the largest waste amongst different inefficient energy delivery options and appliances which was investigated in their study including thermostat oversetting, leakage current and appliance choice.

In addition, Meyers et al. (2010) investigated the energy savings from having individual control of each zone compared to when there is a single central thermostat controlling the whole house. Having a central thermostat could result in temperature variations in homes (particularly upstairs cf downstairs) and therefore it may cause the thermostat to be set at higher temperatures to sufficiently heat the spaces that are far from the thermostat. Assuming that on average, thermostats in dwellings are set 1ºC higher in winter and 1ºC lower in summer than the residents desired temperatures, they estimated that 1.25% of total primary energy can be saved in US dwellings. However, they did not conduct any measurements or consider the impact of indoor air temperature reductions on thermal comfort. All the estimations were based on a framework developed by using the energy data for 4383 US households collected by Residential Energy Consumption Survey (RECS) (US Department of energy, 2005) in the US.

Several researchers have investigated the use of occupancy sensors to control HVAC systems based on either real time occupancy data or occupancy models integrated into building HVAC systems (Lu et al, 2010; Agarwal et al. 2011;Erickson et al. 2013).

Scott et al. (2011) developed ‘PreHeat’ system and tested it in five homes, three in the US and two in the UK. The ‘PreHeat’ system was designed to enable home heating to be controlled automatically according to occupancy sensors and future occupancy prediction. All homes tested were family homes with two adults and one or more children. All US homes had forced air heating. One of the UK homes had a combination of underfloor heating and radiators while the other had radiators in all rooms. They compared the ‘PreHeat’ prediction algorithm with a seven day programmable thermostat with preconfigured heating schedules (i.e. scheduled algorithm). Individual room heating control according to occupancy sensors were applied in UK homes while in US homes the whole house air heating system was controlled according to the occupancy sensors. They alternated the heating control strategy each day between the ‘PreHeat’’s prediction algorithm and the scheduled algorithm in order to balance any effects of weather or household schedule changes. The resulting difference between the average outdoor temperature of PreHeat days and scheduled days was less than 0.3ºC. However, they did not mention how the household schedules could have been different from day to day. Over a 61 day monitoring period, ‘PreHeat’ resulted in little difference in gas use for the homes in the US with a whole house heating control system but resulted in 8% and 18% reduction in gas use for the individually controlled rooms in the UK homes.

Moreover, Badiei et al (2014) used dynamic thermal modelling to investigate the effect of changing heating set-points and length of heating using programmable TRVs on energy demand of a three bedroom UK house. They found that decreasing heating set-point of every radiator in the house at the same time from 1°C to 5°C would result in 16% to 64% reduction in annual gas demand for space heating. Decreasing heating set-point in an individual room showed 3.7% to 14.5% reduction in annual gas demand. In addition, reducing heating time in all rooms from one hour to five hour resulted in 5.8% to 28% reduction in annual gas demand. Such reduction for an individual room showed a potential of 1.1% to 6.2% reduction in whole house annual gas demand.

Lu et al. (2010) reported average energy savings of 28% from deploying occupancy sensors in 8 homes. The sensors were designed to automatically turn off the HVAC system, when the occupants were sleeping or away from home, using a "*smart thermostat*" compared to a heating system with "*reactive thermostat*". The homes included both single person and multi person residents as well as houses shared between students and professionals. They developed an algorithm that analysed patterns in sensor data in order to recognize people leaving or sleeping so that the system could be switched off within few minutes of the event. The HVAC system was heating the whole house when occupied and not sleeping. There was no individual control of different rooms in their study.

Agarwal et al (2011) used real time occupancy data from a wireless occupancy sensor network across one floor of a four floor US university building to control and actuate individual HVAC zones to be conditioned. They reported space heating and cooling energy savings of 8% to 13%. The authors discuss several applications of real time occupancy information and combined use of HVAC and IT resources for commercial buildings.

According to Erickson et al (2013- p1&2) for occupancy based HVAC control, occupancy detection needs to be accurate, reliable and able to capture occupancy changes in real time. Moreover, the authors argue that "*Unlike lighting, the thermal* *ramp up or down of a room involves delay. While an optical system of occupancy monitoring can give occupancy in near real-time, reactively conditioning a room will likely leave occupants uncomfortable until target temperatures are met. In order to ensure occupant's comfort, we must be able to predict when occupants are likely to enter a room and begin conditioning before-hand*" (Erickson et al, 2013).

Holland (2010) described a number of factors which needed to be taken into account when considering what was named "dynamic zoned control of the heating system" where a zone is not heated unless it is in use. Three important factors were user definable set-back temperatures which should be used for the unoccupied periods; the length of warm up time which is required for the rooms to achieve the comfort condition from the set-back condition; and the expected time of occupancy for each room.

2.6 Zonal space heating control

There are currently an increasing number of manufacturers of heating controls that are providing ZC systems for the new and existing homes with wet central heating systems (for example: Honeywell, 2015; Heat Genius, 2013; Eurotronic, 2011; Honeywell, 2014; Salus controls, 2013). These systems can be implemented easily and quickly and with minimum disruption for households as installing these systems does not need any pipe change, draining down[3], running wires, plastering to do or lifting floor boards (Honeywell, 2014). The main component of such systems is Programmable Thermostatic Radiator Valves (PTRVs) which could replace the existing conventional TRVs simply by unscrewing the TRV heads and screwing PTRVs according to their manual (Honeywell, 2015; Heat Genius, 2013; Eurotronic, 2011; Honeywell, 2014; Salus controls, 2013).

PTRVs are battery-operated and have motorised valves and temperature sensor to control the flow of hot water to the radiators according to a target temperature schedule assigned for the room where the radiator is located (Figure 2-13) (Honeywell, 2014).

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[3] However, if TRVs are not already installed, draining down is required and often a professional installer is needed.

Each room with a PTRV can have a number of different target temperatures throughout a day and schedules could be different from day to day and weekdays to weekends (Honeywell, 2015; Heat Genius, 2013; Eurotronic, 2011; Honeywell, 2014; Salus controls, 2013). Therefore, the rooms can be scheduled to be heated only when they are occupied and to the level needed.

ZC systems available in the market can be divided into two main categories: modern luxury systems including PTRVs, a user friendly touch screen wireless central controller and a boiler relay (type1) (Honeywell, 2015 and Heat Genius, 2013) and simple “stand alone” PTRVs without any central controller or boiler relay (type2) (Eurotronic, 2011; Honeywell, 2014 and Salus controls, 2013).

The schedules for the target temperatures can be set via the central controller which communicates wirelessly with the PTRVs (in type 1 systems) (Honeywell, 2015 and Heat Genius, 2013) or on the PTRVs themselves (in type 2 systems). The central controller can be also connected to a tablet or mobile phone wirelessly via internet and thus, the schedules can be modified remotely in type 1 systems (Honeywell, 2015 and Heat Genius, 2013). In addition, the temperature settings can be manually overridden by the occupants if needed. In contrast to conventional TRVs which were adjustable to 5-6 different levels which often left the households without a clear understanding of what temperature each level is representing (Osz, 2014), exact temperatures can be adjusted using PTRVs.

The main difference between type 1 and 2 systems is that in type 1 systems the boiler is switched on when the air temperature in any of the zones with PTRVs drops below its set-point temperature (Honeywell, 2015 and Heat Genius, 2013) while in type 2 systems, the boiler operation is conventionally controlled using a room thermostat and programmer or a programmable room thermostat (Eurotronic, 2011; Honeywell, 2014 and Salus controls, 2013).

While type 1 systems might be considered as full zonal space heating control, type 2 systems could be more relevant for UK homes where the households often tend to heat their homes for certain hours during a day and the heating is often switched off at night with no set-back temperature (Huebner, 2013). Moreover, applying type 1 systems to existing dwellings requires replacing the thermostat and boiler relay already existed in the system with the new wireless central controller and boiler relay (Honeywell, 2015 and Heat Genius, 2013). This would result in considerably increasing the capital costs of the system (Table 2-6) as well as installation costs (Honeywell, 2015 and Heat Genius, 2013).

Table 2-6: A number of systems currently available in the UK market and their prices (as in 24 February 2015) for a configuration which can apply zonal space heating control in a typical UK house

System	Type	Central controller + boiler relay price[1] (£)	PTRV price per unit[1] (£)	Total system price[1] for a typical UK house[2] (£)
Honeywell Evohome	1	£178.8	£58.69	£531
Heatgenius	1	£249.99	£59.99	£610
Honeywell HR90	2	-	£39.59	£238
Salus PH60C	2	-	£29.38	£177
Eurotronic Sparmatic Comet	2	-	£15.95	£96

[1] Prices are VAT included but do not include the costs of installation and batteries and were sourced from the main dealers of the products in the UK on 24 February 2015.

[2] The house was assumed to have 3 bedrooms, a living room, a dining room, a bathroom and a hallway as heated spaces which comprises 7 zones, 6 of them controlled using PTRV and one controlled using a central controller or the existing room thermostat. The house was assumed to have a combination boiler.

Type 1 systems might be suitable for those homes with no existing heating controls where upgrading to the cheaper type 2 systems would also need capital costs for a room thermostat and programmer (Eurotronic, 2011; Honeywell, 2014 and Salus controls, 2013). While type 1 systems could often be more user friendly as they are programmed using a touch screen central controller or/and computers, tablets or phones and also provide advance features such as remote access control (Honeywell, 2015 and Heat Genius, 2013), type 2 systems could be used as a cheap energy efficiency measure which can be added to an existing heating system by the householders themselves, with no need for any electrical work or plumbing to be done by an external installer (Honeywell, 2014).

Honeywell's latest ZC product Evohome (Honeywell, 2015) (Figure 2-13) is an example of type 1 system which features:

- Touch screen central controller with ability to control up to 12 zones.
- Smart phone application which enables households to monitor and control their heating whether they are home or not. For example, it allows them to start heating their homes before they arrive home from work to avoid a cold home on their return. The connection between the central controller and smartphone is established using a remote access gateway.
- Auto window function which realise if a window has been left open and stop heating that zone in order to save energy.
- Optimum start and stop: According to Honeywell (2015), Evohome is able to understand how a home heats up and cools down and thus, works out the exact time when a room needs to start heating up or cooling down to be at the desired temperature set for a time in a day.

However, additional features such as auto window function, optimum start or remote access which could add extra energy savings to the zonal control systems were out of the scope of this study and were not investigated in this work.

Figure 2-13: Honeywell’s Evohome system components including PTRV and central controller

Heat Genius (Heat Genius, 2013) is another type 1 system with comparable features to Evohome which is currently available in the UK market. According to Heat Genius (2013), one of the unique features of the system compared to its counterparts is that wireless room sensors could be added to the system which detects when people are using different rooms, thus can automatically schedule the radiators in each room to only come on at times when people normally use these rooms. However, the algorithms which lead to such automatic schedules were not described by the manufacturer.

Apart from a limited number of type 1 ZC systems available in the UK market, there are good number of “stand alone” programmable thermostatic radiator valves (PTRV) products (type 2 system) which all have the same function though they have different designs and prices (Figure 2-14). Honeywell’s HR90 (Honeywell, 2014) have similar to PTRVs existed in the Evohome system but they can be programmed using the keys and displays on the PTRV heads and thus do not need a central controller for assigning the heating schedules and set-point temperatures (Figure 2-14). Similar to PTRVs in Evohome system they use two 1.5 Volts batteries and also have auto-window function.

Figure 2-14: A number of PTRVs from different manufacturers: from left to right: Honeywell HR90 (Honeywell, 2014), Salus PH60C (Salus controls, 2013) and Eurotronic Sparmatic Comet (Eurotronic, 2011)

2.7 Modelling domestic energy use

The modelling techniques for estimating energy use in houses can be divided into two main approaches: top-down and bottom-up. The top-down approach considers the residential sector as an energy sink and is not concerned with the individual dwellings (Swan & Ugursal, 2009). It uses historical statistics of energy use and households on a national level and predicts the influence of changes in top level factors such as energy price, climate and macroeconomic indicators such as gross domestic product, unemployment and inflation on energy consumption of the whole housing stock (Swan & Ugursal, 2009). Therefore it is not suitable for investigating the effects of energy efficiency measures on energy demand.

On the other hand, the bottom-up approach is based on principles of building physics and calculates the energy use of a representative group of individual houses, allowing extrapolating the results to regional or national levels (Swan & Ugursal, 2009). The bottom-up models require a large number of input parameters such as building geometry, fabric, characteristics of the heating systems, internal temperatures and heating patterns, ventilation rates, individual appliances, external temperatures etc.

The bottom-up models can be divided into steady state and dynamic models.

2.7.1 Steady state models

Current approaches in bottom-up domestic stock modelling in the UK typically employ steady state or quasi steady state calculations to estimate the monthly or annual energy demand (Taylor, Allinson, Firth, *et al.*, 2013). The majority of bottom-up residential stock models developed to date in the UK such as BREHOMES (Shorrock & Dunster, 1997), The Johnston model (Johnston, 2003), UKDCM (Environmental Change Institute, 2009), The DECarb model (Natarajan & Levermore, 2007) and CDEM (Firth, Lomas & Wright, 2010) have used the same calculation engine known as Building Research Establishment Domestic Energy Model (BREDEM) (Kavgic, Mavrogianni, Mumovic, *et al.*, 2010). BREDEM has different versions such as: BREDEM-8, which is developed for monthly analysis; BREDEM-12, for annual analysis; and BREDEM-9 which is a monthly version and the basis of the UK government’s Standard Assessment Procedure (SAP) (Kavgic et al. 2010). The Standard Assessment Procedure (SAP) 2012 is the latest version of the UK government’s approved methodology for rating the energy performance of new dwellings (BRE, 2014). Reduced Standard Assessment Procedure (RdSAP) is used for the energy performance assessment of existing dwellings (BRE, 2014). RdSAP is based primarily on SAP procedures and has additional standard data tables which are added to the SAP model to replace the information which is not available for the existing dwellings.

Much research has been conducted across the world using the bottom-up approach to evaluate the potential for energy savings and economic benefits of using different energy efficiency measures (Swan & Ugursal (2009)). Bottom-up models could provide good estimates of the effectiveness of different energy efficiency measures for policy makers (Kane, 2013). In the UK, SAP, RdSAP and BREDEM have been used in a number of key energy and environmental policy initiatives such as Warm Front (2014c), Green Deal and Energy Company Obligation (DECC, 2011b), and code for sustainable homes (Department for Communities and Local Government, 2006).

However, SAP's procedure to model the energy use in houses with ZC is simplified and may not be suitable for detailed analysis of specific houses. SAP 2012 (BRE, 2014) defines "time and temperature zone control" as "*a system of control that allows the heating times of at least two zones to be programmed independently as well as having independent temperature control*". SAP 2012 (BRE, 2014) discusses that this could be achieved by "*separate plumbing circuits, either with their own programmer or separate channels in the same programmer*" or "*programmable TRVs or communicating TRVs*".

SAP 2012 (BRE, 2014) considers fewer hours of heating for the "rest of the house"[4] with a system with "time and temperature zone control" (7 hours per day; from 07:00 to 09:00 and 18:00-23:00) for all days compared to other conventional control options with 9 hours during the weekdays (from 07:00-09:00 and 16:00 – 23:00) and 16 hours during the weekends (from 07:00-23:00). In addition, it uses a lower mean temperature for the "rest of the house".

SAP's procedure does not take into account a number of factors. For instance, it does not take into account the number of rooms which are controlled separately using programmable TRVs. As long as the house has two zones or more, the

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[4] In SAP 2012 (BRE, 2014), monthly heating requirements of a house are calculated using mean internal and external temperatures and the heat transfer coefficient allowing for internal and solar gains. The mean internal temperature is calculated separately for the living area (often the living room) and the rest of the house. The mean living room and rest of the house temperatures will then be combined to find the mean internal temperature for the whole house.

procedure will remain the same without differentiating between numbers of zones which are separately controlled. In addition, since SAP estimations are independent of occupant behaviour, different set-back temperatures used in the zones controlled by PTRVs which could influence the energy saving potential of a “time and temperature control” system are not reflected in the SAP’s procedure. The length of the period when each room is heated to set-back temperature could also be different from house to house.

As discussed here, weaknesses exist in SAP 2012 regarding the assumptions made about the occupant behaviour, hours of occupancy and the use of heating system suggests that steady state building physics models such as SAP should not be used for detailed analysis of energy savings before and after installing ZC.

2.7.2 Dynamic models

Dynamic thermal modelling could be used for more detailed analysis of the energy demand reduction potential of applying ZC as they offer the highest flexibility to model any system and occupancy. A number of dynamic thermal modelling tools such as DOE-2, EnergyPlus, TRNSYS, ESP-r and IES<VE> have been widely used in the past decade in early building design as well as analysis of retrofit opportunities (Crawley, Hand, Kummert, *et al.*, 2008). The main focus has been on modelling larger commercial buildings rather than modelling domestic energy use (Porritt, 2012). Taylor et al. (2013) were one of the first to try using dynamic thermal modelling for modelling a whole English region housing stock. They found the level of details available for the model inputs as one of the factors which affected the energy predictions with higher level of details resulted in higher energy predictions.

It is important to consider the capabilities of each dynamic thermal modelling tool and choose the one which suits the most for the specific problem under investigation. The main feature of ZC is that different rooms are kept at different temperatures throughout a day. Any model should be dividable into various zones (i.e. each room with a radiator will be separate zone) where the set-points temperature of each zone could be altered throughout a day. Most of the current dynamic thermal modelling tools such as DOE-2, EnergyPlus, eQuest, TRNSYS and Trace700 are based on multi-zone thermal models and have such capability.

The tools mentioned are often focused on representing building characteristics accurately but to a lesser extent on the heating systems and controls. As a result, detailed hydraulic behaviours of the heating systems (e.g. The TRVs or PTRVs dynamic control process) are often represented in a simplified way.

The other important factor to consider when modelling houses with ZC is the inter-zone heat transfer. Thermal energy is transferred by convection from one zone of a building to another via air flow through doorways and windows (Allard & Utsumi, 1992). This inter-zone convection could be either natural convection due to temperature differences between spaces, or forced convection by the pressure differences which are caused by mechanical ventilation or air distribution systems in buildings or a combination of both (Barakat, 1987). Keeping the rooms of a naturally ventilated house at different air temperatures throughout a day such as in ZC will result in natural convective heat flows through different rooms. Previous research has shown the significance of natural convection through door openings. For example flow rates of more than 1200 W have been observed to occur through a 0.9*2.05 m doorway as a result of a 4 K temperature difference between the spaces on either side of the door (Barakat, 1987). Thus, the selected program should have been able to model the inter zone heat transfer and its influence on energy use of the building.

EnergyPlus (US Department of Energy, 2012) is a well-known and powerful multi-zone building simulation tool that was first released in 2001 by the US department of energy as a replacement for the two existing simulation tools; BLAST and DOE-2 (Crawley, Hand, Kummert, *et al.*, 2008). One of the main advantages of EnergyPlus to its predecessors is that in EnergyPlus, heat balance simulation is coupled with building systems simulation which means that at each time step (down to one minute) the building loads which is calculated by a heat and mass balance module is passed to building systems simulation module which has a variable time step (down to seconds) where the system responses are calculated (Crawley, Lawrie, Winkelmann, *et al.*, 2001). The information from the building systems simulation module on the loads not met by the system is fed back to heat and mass balance module and will be reflected in the next time step of load calculations by adjusting the space temperature if required and thus result in more accurate space temperature predictions (Crawley, Lawrie, Winkelmann, *et al.*, 2001). This integrated feature discussed, allows realistic system controls to be modelled (Crawley, Lawrie, Winkelmann, *et al.*, 2001). In addition, EnergyPlus uses Air Flow Network (AFN) model which allows simulation of inter- zone air flows and its influence on building energy use.

2.7.3 Model calibration and validation

Although building simulation has been widely used during the past three decades to investigate the effect of retrofit measures on energy savings and comfort, without calibration of the base case model, results produced are not reliable (Westphal & Lamberts, 2005). A large number of studies have shown discrepancies (which were often significant) between the model predictions and measured building energy use (Coakley, Raftery & Keane, 2014). Reddy (2006) defines calibrated simulation as "*the process of using an existing building simulation program and "tuning" or calibrating the various inputs to the program so that observed energy use matches closely with that predicted by the simulation program".* The purpose for calibration is to ensure that the model could reasonably represent the thermal and energy behaviour of the real building and thus achieve confidence in model predictions (Westphal & Lamberts, 2005).

Coakley et al. (2014, p. 127) conducted an extensive literature review on current approaches for building simulation calibration and classified them into four classes:

1. *Calibration based on manual, iterative and pragmatic intervention.*
2. *Calibration based on a suite of informative graphical comparative displays*
3. *Calibration based on special tests and analytical procedures.*
4. *Analytical/mathematical methods of calibration*

In addition, a number of techniques and tools were suggested by Coakley et al. (2014) to support the calibration process of building simulation models such as track and record the changes made to the model during the calibration process, in order to improve the reliability and reproducibility of the calibration process, and conducting sensitivity analysis. Sensitivity analysis can be simply described as varying the model inputs and verifying the consequences of that change on the model outputs (Calleja Rodríguez et al. 2013). A number of sensitivity analysis techniques such as differential sensitivity analysis, Monte Carlo analysis and stochastic sensitivity analysis have been used during the past two decades to understand the parameters which should be carefully considered when modelling a building. Lomas & Eppel (1992) were among the earliest to use these sensitivity analysis techniques for dynamic thermal modelling.

ASHRAE (2009) discusses three methods to assess the accuracy of building simulation models: *empirical validation*, *analytical verification* and *Inter-model comparison*. In *empirical validation* results from building simulation are compared with the data measured in real buildings (ASHRAE, 2009). There are various published literature on validation mainly for residential buildings rather than large commercial buildings; where conducting detailed measurements require considerable efforts and costs (ASHRAE, 2009). A number of empirical validation studies are summarized by Neymark and Judkoff (2002). One of the main challenges researchers have been faced with to calibrate building energy models using empirical validation is the lack of detailed empirical data particularly for residential buildings which is necessary to understand the operational complexities and develop better models (Buswell, Marini, Webb, *et al.*, 2013). In majority of the cases, even when the measured data is available, it has not been measured by end use and for example the gas use measured include the use for space heating, hot water and cooking which makes the calibration difficult. In addition, the measured data has also an uncertainty and the differences observed between the models and measurements will be due to errors in either set of data (ASHRAE, 2009). In *Analytical verification* simulation results are compared with the results of a solved analytical solution (ASHRAE, 2009). In *Inter-model comparison* simulated results are compared with simulated results using other models (ASHRAE, 2009). This method is particularly useful to test new models against the well established ones (Clarke, 2011).

Recent research suggests comparison of hourly data measured and predicted using building simulation models rather than monthly or annual comparisons as it allows better comparison of buildings' dynamic energy characteristics (Yoon et al. 2003). ASHRAE Guideline 14 (ASHRAE, 2002) which was initially developed to calculate the energy saving potential of retrofit measures defines the acceptance criteria for the calibration of building simulation models (Royapoor & Roskilly, 2015). When a model meets these criteria, there is a reasonable agreement between measured and simulated data and the model can be considered ‘calibrated’ (ASHRAE, 2002).

The guideline introduces two standardised statistical indices that should be used to compare measured data and simulation results:

1. Mean Bias Error (MBE) (%): This is the sum of errors between measured and predicted energy use for each hour. MBE captures the mean difference between measured and predicted hourly energy use and thus is a good indicator of the overall bias in the model (Coakley, Raftery & Keane, 2014). MBE is calculated by equation (2-1):

$$MBE\ (\%) = \frac{\sum_{i=1}^{N_p}(m_i - s_i)}{\sum_{i=1}^{N_p}(m_i)} \tag{2-1}$$

Where:

m_i = measured data point for each model instance ‘i’

s_i = simulated data point for each model instance ‘i’

N_p= number of data points at interval ‘p’

A limitation of this method is that positive and negative errors will cancel each other when summed which means the positive bias compensate for negative bias.

2. Coefficient of Variation of Root Mean Square Error (CVRMSE) (%): This index does not suffer from the cancellation effect mentioned above and allows one to determine how well a model fits the energy use data by capturing offsetting errors between measured and simulated data which were existed in MBE method (Coakley, Raftery & Keane, 2014). CVRMSE (%) is calculated by equation (2-2):

$$CVRMSE\ (\%) = \frac{\sqrt{(\sum_{i=1}^{N_p}(m_i - s_i)^2/N_p)}}{\overline{m}} \tag{2-2}$$

Where:

m_i , s_i and $N_p$are as defined in equation (2-2)

$\overline{m}$ = average of the measured data points.

According to ASHRAE Guideline 14 the acceptance criteria for hourly calibration of building energy simulation models are: MBE 10% and CVRMSE 30%. These are 5% and 15% for monthly calibrations.

It should be noted that *“the current calibration criteria relate solely to the predicted energy consumption and do not account for uncertainties or inaccuracies of input parameters or the accuracy of the simulated environment (e.g. temperature profile)*” (Coakley, Raftery & Keane, 2014).

2.8 Summary

The main findings from the literature review conducted here with direct implications on this study can be summarized as follows:

- The majority of UK houses (above 97%) have central heating and a large number of them are wet (hydronic) systems.
- In recent years, the importance of having more than one heating zone in dwellings have been realized in the UK as reflected in the Building Regulations Part L1A for new dwellings which came into force from 1 October 2010. However, this does not apply to the existing dwellings.
- A significant number of existing UK homes have poor levels of space heating controls and there is a great potential for improvement. However, there is evidence that the proportion of homes that have a range of controls may have increased over recent years.
- In theory, energy can be saved in houses by advanced space heating controls as they could reduce the length of the heating period, the volume of house which is heated and the heating demand temperature. A number of studies have used models to prove that. However, there are a number of studies which shows that the predicted savings could be hardly achieved in real world settings.
- There is a lack of a robust and repeatable methodology for measuring the energy savings which could be achieved by enhanced heating controls.

- There are a number of products currently available in the market which could be used to establish ZC in the existing houses with wet central heating systems. However, the energy and thermal comfort implications of using them instead of conventional space heating controls are unknown.
- Dynamic thermal modelling could be used as the most detailed tool for calculating the energy savings of ZC in different houses. However, reconciliation of the model predictions with the measured data is crucial before the results could be trusted.

3 Overview of the methodology and test houses

3.1 Introduction

This chapter consists of two main sections. In the first section (section 3.2), an overview of the methods adopted in this study to achieve its aim and objectives is provided. The methods adopted were based on the use of a pair of full size test houses with synthetic occupancy. The second part of this chapter (section 3.3), describes these houses and discusses the characterisation tests which were carried out in them to evaluate and compare their thermal performances. Section 3.4 summarizes the work presented in this chapter.

3.2 Overview of the methodology

This study combined space heating trials to measure the energy savings of zonal space heating controls, dynamic thermal modelling and a wider scale evaluation in order to achieve the aim and objectives described in section 1.3. This section provides an overview of these three components and discusses how they were interconnected. Further details of the methods for the trials, modelling and wider scale evaluation are given in chapters 4 to 7.

3.2.1 Overview of the space heating trials

The purpose of the space heating trials was to achieve the first objective of this study which was to measure the energy savings (if any) of applying zonal space heating control (ZC) in a UK house.

It was decided to measure the energy savings of a house when its space heating is controlled by ZC compared to when it is controlled with a conventional system in comply with Building Regulations Part L1B (here referred to as Conventional Control (CC)). The reason for this choice was that although space heating is not controlled in the same way in every UK house, all new homes need to comply with the regulations.

In addition, nearly half of UK existing homes already have such sets of controls according to EFUS 2011 (BRE, 2013).

Such comparison was not ideal to be conducted in a single house. Unless the house was built in a fully controlled environment such as in an environmental chamber, the changes in the weather for the periods when the house is controlled by ZC and then by CC could largely influence the energy consumption of the house and any potential energy savings measured. Therefore, this comparison was conducted using a matched pair of side-by-side test houses which will be fully described in section 3.3. In order to ensure that the two houses had a similar thermal performance, a side-by-side co-heating test and air tightness tests were carried out in both prior to the space heating trials (see section 3.3.6).

Two space heating trials (HT1 and HT2) each lasted four weeks were conducted during the winter of 2014. During the HT1 and HT2, the same synthetic, yet realistic, occupancy schedule was applied to both houses (see section 3.3.5). The two test houses were each equipped with the same new wet central heating system. In one house the space heating was controlled conventionally (CC) in compliance with requirements in UK Building Regulation Part L1B for existing dwellings, whereas in the other house ZC was used to heat the rooms only when they were ‘occupied’. In the HT1 ZC was applied to House 1 and CC to House 2 then, for the HT2, the heating control strategies were swapped with CC in House 1and ZC in House 2. This was done to negate any small differences between the thermal performances of the building fabric of the two test houses (see section 3.3.6). The energy use for space heating and indoor air temperatures of the two houses were measured and compared.

The potential energy savings of a house heated by ZC instead of CC were quantified for one particular house in one location and over one winter period during the space heating trials. However, conducting further experimental studies in order to measure the annual energy savings of ZC or energy savings in houses located in different regions of the UK was not possible considering the time, budget and scope of this work. Instead, dynamic thermal modelling was used as an alternative method to assess the potential energy savings of ZC for better insulated houses and those exposed to different climate.

3.2.2 Overview of the dynamic thermal modelling

EnergyPlus was used to create a Dynamic Thermal Model (DTM) of the building envelope of the test houses according to the existing knowledge of the test houses and information obtained via detailed house audits (chapter 5). In order to verify the building envelope model, the co-heating test was simulated and the predicted energy use during the co-heating test period was compared to the measured energy use according to ASHRAE guideline 14 acceptance criteria for hourly calibration of building energy simulation models (chapter 6, Section 6.2). The effects of employing two different air flow modelling strategies (i.e. scheduled natural ventilation (SNV) and Air flow network (AFN)) on model predictions were studied (model 1 and 2, Table 3-1).

The verified building envelope model was then used and the HT1 (the period when data was successfully measured continuously for the period of 4 weeks) was simulated (chapter 6, section 6.3). Similar to the co-heating test, predicted energy use and indoor air temperatures using the two different air flow modelling strategies were compared to the measured data (model 3 and 4, Table 3-1). Any observed discrepancies between the predictions and measurements were then explored and modelling limitations and potential solutions were discussed.

Based on the discrepancies observed between the predictions and measurements, a sensitivity analysis was conducted to investigate the effects of a number of parameters on improving model predictions of energy use and indoor air temperatures (chapter 6, section 6.4). Based on the results from the sensitivity analysis, a refined model was constructed and assessed against the ASHRAE guideline 14 calibration criteria (Refined model, Table 3-1).

The second objective of this research was achieved as the refined model which was calibrated using the measurements was able to closely predict the energy savings of applying zonal control in the same house under the same conditions.

Table 3-1: Summary of the DTMs created during the modelling campaign

Model	Experiment	Heating	Occupancy modelled (Yes/No)	Air flow modelling strategy	Heating control in House 1	Heating control in House 2
1	Co-heating	Electrical	No	SNV	Constant air temperature	Constant air temperature
2	Co-heating	Electrical	No	AFN	Constant temperature	Constant temperature
3	HT1	Wet	Yes	SNV	ZC	CC
4	HT1	Wet	Yes	AFN	ZC	CC
Refined model	HT1	Wet	Yes	AFN	ZC	CC

3.2.3 Overview of the wider scale evaluation

Two different approaches were undertaken in order to achieve the final objective of this study which was to explore how the energy savings would vary in better insulated houses and in different UK locations. In the first approach, an empirical model was developed using the Heating Degree Day (HDD) method based on the experimental data collected from the heating trials (chapter 7, section 7.2). The empirical model was used to extend the measured gas consumptions with CC and ZC to annual values, and to make an initial estimate of the effect of the weather in different parts of the UK on the potential savings. The empirical model estimated the annual gas savings of ZC and the corresponding cost savings. The model was also used to estimate the pay back periods of upgrading a same size house with conventional heating controls to zonal heating control in different UK regions.

In the second approach, the calibrated DTM was used to investigate energy savings of applying ZC instead of CC in the same house for different regions of the UK using the same weather data as in the empirical model (chapter 7, section 7.3). The cost benefits were also recalculated based on the DTM results. The predictions of the DTM were then compared against the predictions of the empirical model. The potential reasons for the differences observed in the predictions of the DTM and empirical model were then discussed.

Finally, the calibrated DTM was employed and the effects of better insulated building envelope on the potential energy and cost savings of ZC in different regions were investigated (chapter 7, Section 7.4).

3.3 Test houses

This section introduces the test houses which were used for this study and describes their geometries, construction materials and properties, heating systems and their synthetic occupancy.

3.3.1 Description of the test houses

Loughborough University's Matched Pair of 1930s houses (LMP1930) are a pair of adjoining semi-detached homes which were used for this research. The houses, which are typical family homes of the 1930s period, are located in the East Midland's town of Loughborough, UK (Figure 3-1).

Figure 3-1: Bird's-eye view of the test houses, their surrounding buildings and vegetation (Google Maps, 2015)

Semi-detached houses are the most common house type in England representing 26% of the housing stock with over 30% of them built between 1919 and 1944 (Department for Communities and Local Government, 2001). However, semi-detached house layouts and construction methods remained largely unchanged from the 1930s through to as late as the 1960s (Rock, 2005) and so the house layouts could be representative of a larger proportion of homes.

The test houses had the same geometry, size and construction and had not been significantly modified since they were built (Figure 3-2).

Figure 3-2: Views of the two test houses: front, south-facing (left) and back, north-facing (right)

The fronts of the houses faced south and the windows were unshaded except for those on the West facade of House 1 and the East facade of House 2; these windows were covered by 50 mm of Polyisocyanurate (PIR) insulation boards from the inside of the houses to minimize the effect of different morning and afternoon solar heat transfer to the two houses (Figure 3-3).

Figure 3-3: The West facing windows in the House 1 which were covered by 50 mm PIR insulation boards

Original open fire places were located at the party wall of the two houses in the living room and dining room of each house (Figure 3-4). These were blocked to avoid unnecessary air leakage.

Figure 3-4: Blocked original open fire places located in the living room of House 1

3.3.2 Building geometry

Internal dimensions of the test houses were measured at the beginning of this study and their floor plans were drawn (Figure 3-5). Each house had a total floor area of 91.2 m^2(including both floors) and a total volume of 240 m^3. Each house had three rooms located on the ground floor including living room, dining room and kitchen plus a hallway and four rooms on the first floor including three bedrooms and a bathroom plus a WC and a hallway (Figure 3-5).

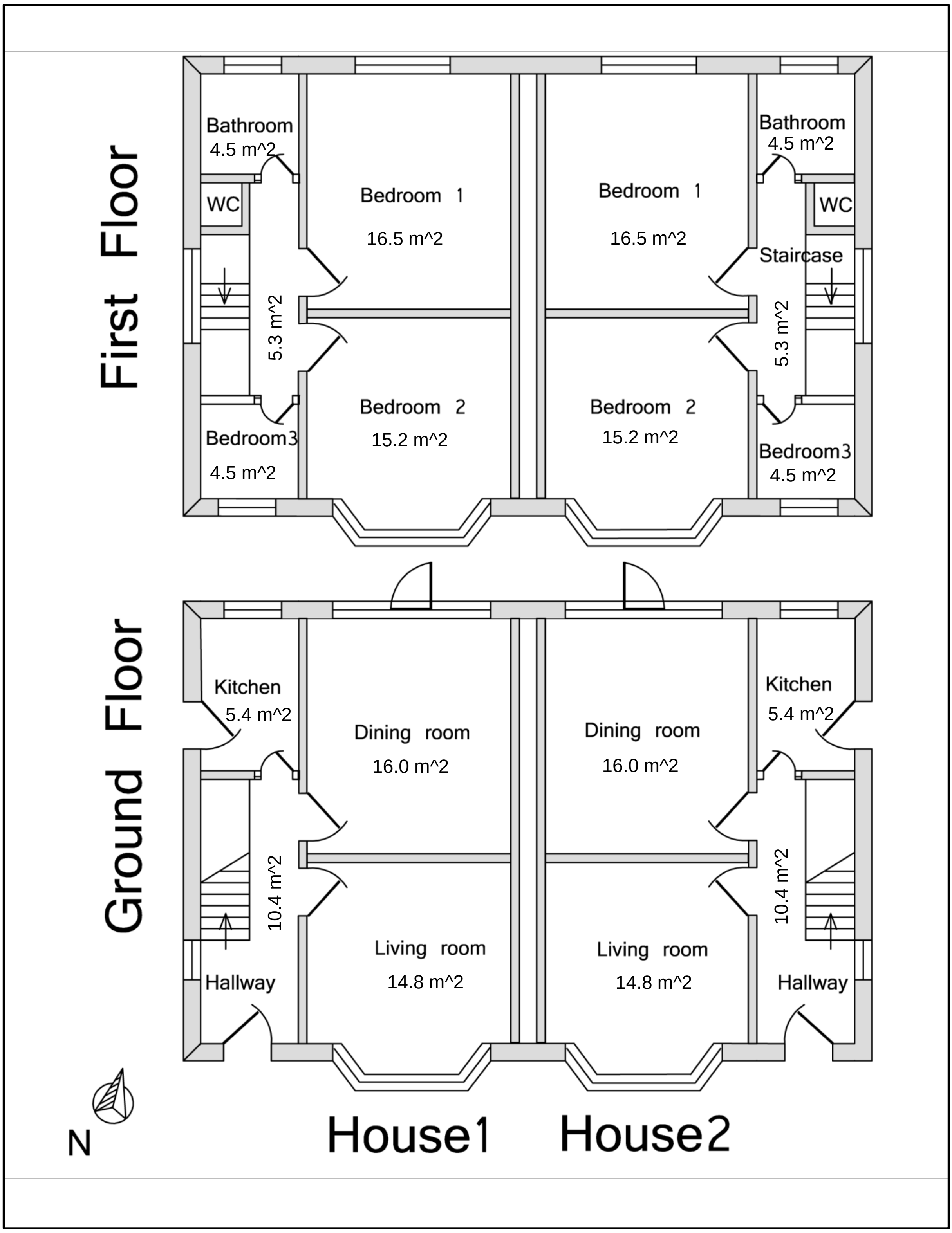

Figure 3-5: The floor plans of the test houses[5] with the floor area of each room

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[5] The floor plans (here and throughout the thesis) are schematics and not to scale. The blocked fire places were not shown

3.3.3 Construction materials and properties

Test house audits were conducted in the test houses to understand details of the construction materials used in the test houses. The areas and thicknesses of the bricks, cavity air gap, plaster, floor boarding, carpets and doors were measured and the materials used for each construction element were noted. A summary of construction elements, their areas and their calculated U-values according to RdSAP (BRE, 2014) are presented in Table 3-2.

Table 3-2: Summary of construction elements of the test houses, their areas and calculated U-values according to RdSAP (BRE, 2014)

Element	Description	Total Area (m^2)	U-value (W/m^2K)[1]
External walls	Brick Cavity	81.6	1.6
Floor (except kitchen)	Suspended Timber	40.2	0.8
Floor (kitchen)	Solid floor	5.4	0.7
Roof	Pitched roof covered with clay tiles	45.6[2]	2.3
Windows	Single glazing with wooden frames	20.7	4.8
Entrance doors	Wooden	3.4	3.0
Party walls	Brick Cavity with closed air vents	42.2	0.5
Internal partitions	Solid Brick covered with gypsum plaster	56.1	2.1

[1] Approximate U-values from UK Government's Standard Assessment Procedure for energy rating of the existing dwellings (RdSAP) (BRE, 2014).

[2] The horizontal, not pitched, area.

As found by the test house audits, both houses had 100% single glazed windows, un-insulated cavity external walls, and no floor or loft (attic) insulation (Table 3-2). In contrast, many UK homes have been refurbished, such that in 2011, of the 3.6 million UK homes built between 1919 and 1944, only 4% had no loft insulation, only 6% were still fully single glazed, and only 28% had uninsulated cavity walls (Department for Communities and Local Government, 2012). Therefore, the test houses would represent the un-furbished interwar houses in the UK which account for about 180 thousand homes.

The ground floor of LMP1930 test houses was mainly suspended timber ventilated with outdoor air using six cast iron air bricks located around the perimeter of each house (Figure 3-6). The underfloor void was 0.2 m deep (from the bottom of the floor boarding to the ground). In the UK, naturally ventilated floors are used to control the moisture from the ground. The Kitchen floors were constructed from solid concrete.

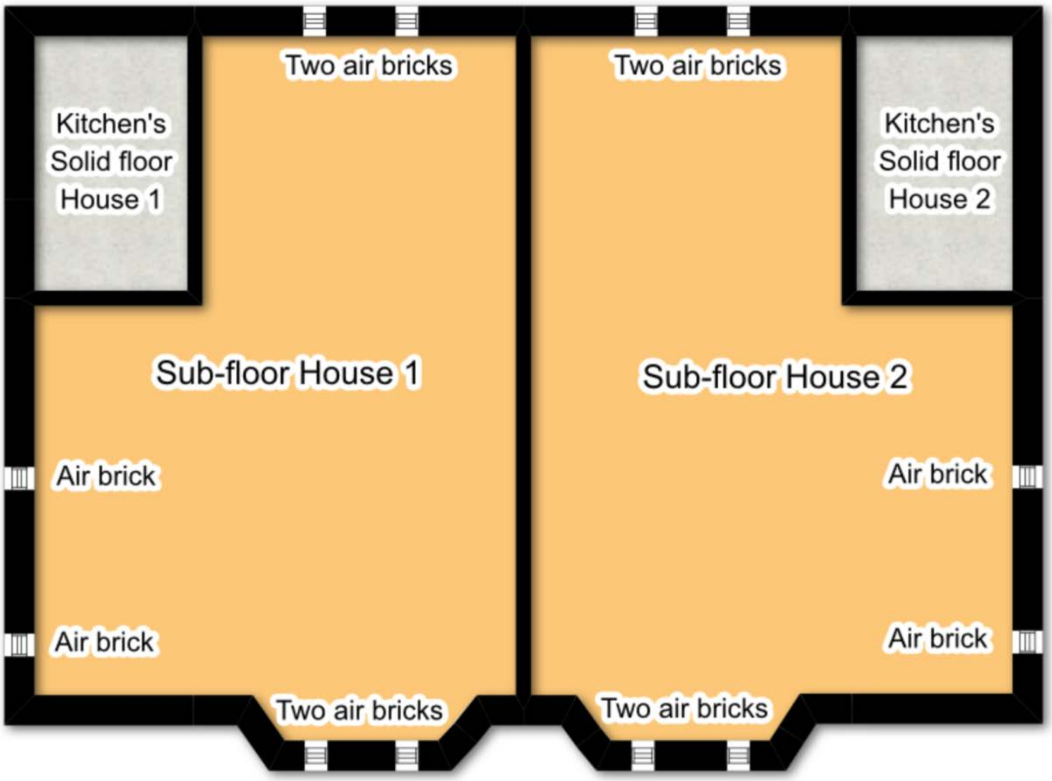

Figure 3-6: Floor plan of the ventilated subfloors existed below the ground floor of each house and the location of air bricks

Figure 3-7 shows examples of test house inspections when a part of carpet and floor boards were temporarily removed in a bedroom to measure the thicknesses of the floor materials[6] (Figure 3-7 (a)) or the inspection in the loft (attic) space where no insulation was found (Figure 3-7 (b)).

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[6] The photo was taken in an adjacent house which was built in the same year by the same builder

Figure 3-7: Examples of test house inspections for understanding details of construction materials: (a) construction of internal floors; (b) loft (attic) space construction (before removing debris)

Figure 3-8 shows the inspection of cavity walls and underfloor void using a borescope. No insulation was found in the cavity (Figure 3-8 (a)). Acquiring better knowledge of the ground surface material (under the suspended floor), by taking photos and videos using a borescope inside the air bricks (Figure 3-8 (b)), was not successful due to filth existed under the suspended floors.

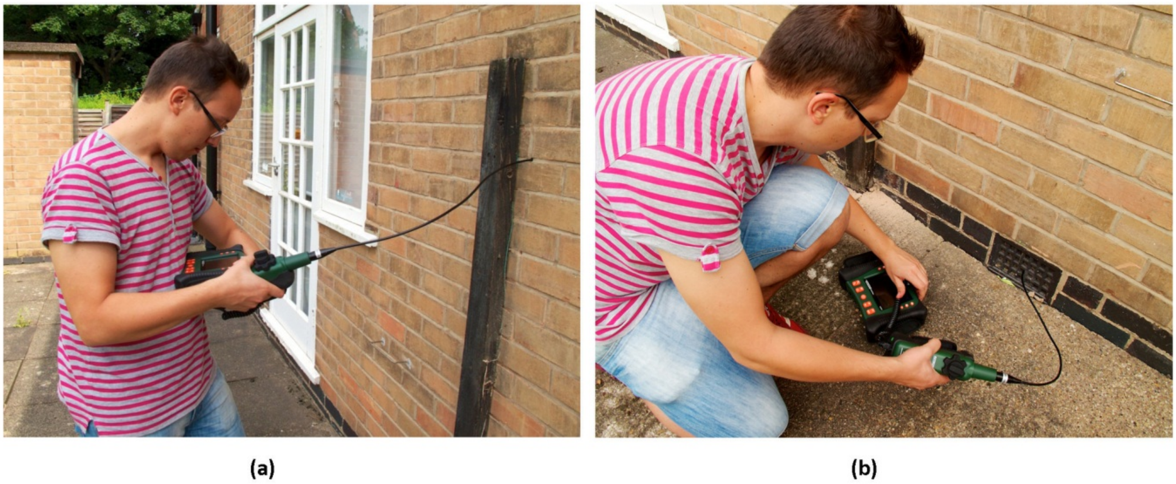

Figure 3-8: Borescope investigation at the test houses: (a) exploring external wall cavity; (b) exploring subfloor construction through air bricks (*Photos by Stephen Porritt*)

3.3.4 Heating system

Each house was equipped with an identical low pressure hot water (LPHW) wet central heating system consisting of a 30 kW condensing combination boiler (Worcester Greenstar 30 CDi combi) located in the kitchen, identical Eco-Compact radiators sized to suit each room, and a Horstmann wireless C-stat 17-B programmable room thermostat located in the hallway. Drayton RT212 TRVs were installed on all radiators apart from the ones located in the hallway of each house. The boilers were less than seven years old.

Rated capacities of radiators which were selected according to each radiator’s height and width from their manufacturer’s data for a 50 K temperature difference between the room’s air and mean water temperature were reported in Table 3-3.

Table 3-3: Rated capacities of the radiators in the LMP1930 test houses according to their manufacturer’s data for 50K temperature difference

Room	Radiator rated capacity (W)
Living room	1372
Dining room	882
Hallway ground floor	1568
Bedroom 1	1568
Bedroom 2	1764
Unoccupied room	980
Bathroom	588

3.3.5 Synthetic occupancy

Both houses were equipped with synthetic occupancy to represent heat gains from people, domestic equipment and lighting, internal door opening/closing and window blind operation in both houses.

Reviewing previous published reports and papers, it was found that a wide range of occupancy profiles have been used but mostly without any detailed information about the sources of their assumptions. Capon & Hacker (2009) assumed partial daytime occupancy and full evening and weekend occupancy for a case study house without presenting any specific schedules. Hacker et al. (2008) provided more detailed occupancy profile for a family in a case study dwelling assuming the house is occupied all the time with one adult at work from 08:00 to 18:00. Adult bedrooms were assumed to be occupied from 23:00 to 07:00 and children bedrooms from 20:00 to 07:00. The sources of these assumptions are not known. A relatively old report by Building Research Establishment (Allen and Pinney, 1990) provides occupancy periods for each room to be used in modelling. However, the profiles were constructed more than 20 years ago when due to absence of personal computers and TVs or game consoles, it cannot reflect realistic occupancy patterns of nowadays (Porritt, 2012).

Porrit (2012) was the only recent study that was found to report a detailed occupancy schedule for each room. Porritt (2012) derived two occupancy profiles using data from the Time Use Survey 2000 which recorded, in ten minutely slots, the daily activity of over 6000 households as a representative sample of the population of households and individuals in the UK (ONS, 2002) (Table 3-4).

Two occupancy profiles were assumed by Porritt: an occupancy profile for a family consisted of 2 working adults and school age children (number of children depending on house size), who are out of dwelling during the day time and an occupancy profile that assumed two elderly residence who occupy the dwelling all the time.

Although Time Use Survey 2000 had detailed information regarding the type of activity and whether it happened inside or outside the house, it did not contain any detail regarding which room the activity had taken place. Therefore, Porritt’s occupancy profiles were based on a number of assumptions:

- When sleeping is recorded the occupant is in their bedroom.
- When children recorded that they are using computer or watching TV, it was assumed that they are in their bedrooms.
- When adults recorded that they are using a computer it was assumed that they are in their bedroom and, when watching TV, are in their living room.
- Cooking activities were happening in the kitchen.
- Eating activities was happening in the dining rooms in the terraced and semi-detached houses and in the living rooms in Flats as the kitchen in these

house types are small and does not allow the occupants to eat in the kitchen. In detached homes, eating was assumed to happen in the Kitchen where larger space would let the occupants to use it for dining.

Moreover, Porritt (2012) assumed slightly different occupancy patterns for the weekends compared to the weekdays for a typical family. In weekends, the bedroom occupied periods were extended to consider morning lie-ins for some occupants.

The chosen occupancy profile for the two houses in this study represented a family of two working adults, and two school-aged children. The ‘occupied hours’ for each room was set according to Porritt (2012) (Table 3-4).

Table 3-4: Weekday and weekend ‘occupied’ hours of each room

Room	**Weekday ‘occupied’ hours**	**Weekend ‘occupied’ hours**
Living Room	18:00-22:30	18:00-22:30
Dining Room	08:00-08:30 17:00-18:00	09:30-10:00 17:00-18:00
Kitchen	07:30-08:00 16:00-17:00	09:00-09:30 16:00-17:00
Bedroom 1	19:00-22:30 22:30-08:00 08:30-09:00 16:00-17:00	19:00-22:30 22:30-09:30 10:00-10:30 16:00-17:00
Bedroom 2	22:30-07:30	22:30-09:00
Bathroom	07:30-08:00 08:30-09:00 19:00-20:00	09:00-09:30 10:00-10:30 19:00-20:00
Bedroom 3	-	-

Bedroom 1 was assumed to be used only by the two children and Bedroom 2 by the two adults. It was assumed that bedroom 3 was unoccupied all the time. Although the occupancy patterns of the rooms were the same for all the weekdays, for the weekends, bedroom occupied periods were extended by 1.5 hours thus shifting morning gains in other rooms 1.5 hours forward compared to the weekdays. During the day time (09:00 to 16:00 hrs on weekdays and 10:30 to 16:00 hrs on weekends) all the occupants were assumed to be out of the house. Evening occupancy patterns were the same for all days of the week including weekdays and weekends (Table 3-4).

The occupancy profile was mimicked in each house using a z-wave smart home controller: Vera 3 (Vera control Ltd, 2014) (Figure 3-9). Each house was equipped with its own Vera 3. A z-wave network was established in each house by linking Vera 3 to a number of z-wave enabled smart plugs and motor controllers which allowed Vera 3 to send on/off commands to each plug or motor controller.

Figure 3-9: Z-wave smart home controller used in each house for synthetic occupancy during the HT1 and HT2

Tables published by the American Society of heating Refrigeration and Air conditioning Engineers (ASHRAE) (ASHRAE, 2009) were used to estimate the heat output rates from occupants, equipment and lighting. Similar to Porritt (2012), each house was assumed to have a refrigerator in the kitchen which was rated at 60 W, a 150 W modern LCD TV in the living room and a computer or game console in the children’s bedroom with 100 W heat output. Cooking gains were 1.6 kW for period of one hour during the evening, 160 W for the 30 minutes breakfast period and no cooker use at lunch time (Table 3-5).

Table 3-5: The timing and magnitude of internal heat gains presented in different rooms of both houses during each trial

Room	Time of day weekday	Time of day weekend	Gain source: estimated rate (W)	Total estimated gains (W)	Total actual gains (W)
Kitchen	07:30-08:00	09:00-09:30	Morning cooking: 160 Adult cooking: 189 Fridge: 60	409	400
	16:00-17:00	16:00-17:00	Evening cooking: 1600 Adult cooking: 189 Lighting: 54 Fridge: 60	1903	1900
			Fridge: 60	60	60
Living Room	18:00-19:00	18:00-19:00	TV: 150 Lighting: 30 Adult seated: 108*2[1] Children seated: 80*2[1]	556	580
	19:00-22:30	19:00-22:30	TV: 150 Lighting: 30 Adult seated: 108*2[1]	396	400
Dining Room	08:00-08:30	09:30-10:00	Hot food: 18 *4[1] Adult seated: 108 *2[1] Children seated: 80 *2[1]	448	460
	17:00-18:00	17:00-18:00	Hot food: 18 *4[1] Lighting: 30 Adult seated: 108 *2[1] Children seated: 80 *2[1]	478	480
Bedroom 1	08:30-09:00	10:00-10:30	Children seated: 80 *2[1]	160	160
	16:00-17:00	16:00-17:00	Lighting: 30 Children seated: 80 *2[1]	190	200
	19:00-20:00	19:00-20:00	Lighting: 30 Child seated: 80	110	120
	20:00-22:30	20:00-22:30	Lighting: 30 Children seated: 80 *2[1] Computer: 100	290	300
	22:30-08:00	22:30-09:30	Children sleeping: 54*2[1]	108	120
Bedroom 2	22:30-07:30	22:30-09:00	Adult sleeping: 72 *2[1]	144	140

[1] Multiplied by the number of people

The total amount of heat required at any time and in each room was delivered using a series of incandescent, halogen and low energy light bulbs, oil-filled radiators or fan heaters (Table 3-6). The light bulbs were used instead of other potential heat emitters with small outputs due to the university's health and safety policies which did not allow the researcher to use any other type of heaters in the unoccupied test houses. However, similar to any other heat emitter, all the electricity used by the light bulbs would end up as heat in the space.

Table 3-6: Number of heat emitters and their nominal outputs used to deliver internal heat gains in each room

Heat emitters and their nominal heat output (W)	Number of heat emitters in each room				
	Living room	**Dining room**	**Kitchen**	**Bedroom 1**	**Bedroom 2**
Light bulbs					
400W	1	1	-	-	-
60W	3	1	1	5	2
20W	-	1	-	2	1
Heaters					
Oil-filled radiator (400W)	-	-	1	-	-
Fan heater (1500W)	-	-	1	-	-

All the light bulbs used were placed on tripods for safety reasons (Figure 3-10). The location where the heat emitters were located and the height of the light bulbs on the tripods were matched between each room of the two houses. All the wire runs on the floors were covered by adhesive tape to avoid trips or falls.

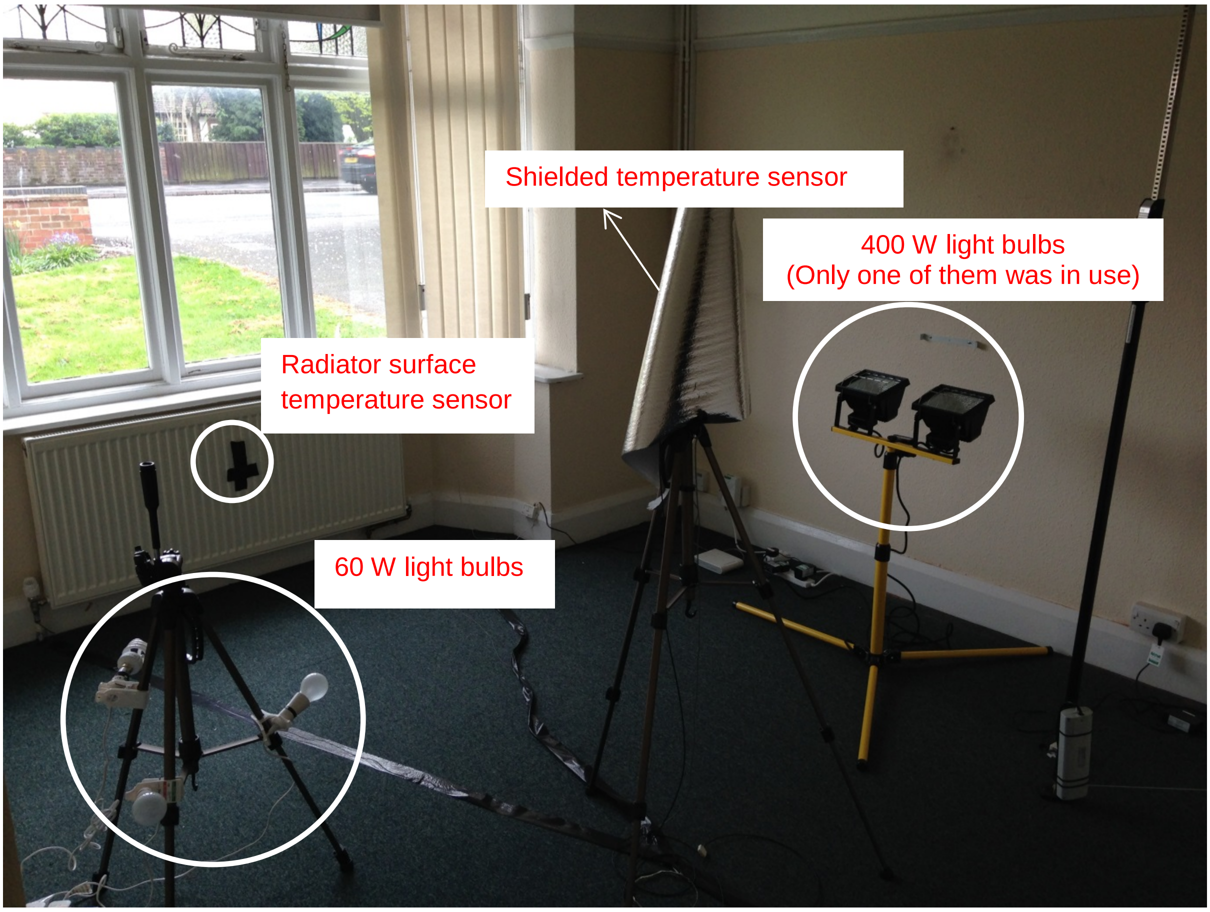

Figure 3-10: light bulbs with different outputs used to produce the internal heat gains in the living room of House 2

The heat emitters were controlled from the home automation controller to produce the repeating weekday and weekend total heat gain profiles (Figure 3-11). The z-wave enabled smart plugs were AN148 by Everspring and used to switch on and off heat emitters in order to produce internal heat gains in different rooms. The actual total heat gains produced in each room were identical in each house and were within ±10% difference of the total estimated values calculated from the ASHRAE tables (Table 3-5) (ASHRAE, 2009). This was due to the sizes of heat emitters that were available (Table 3-6). Variations in the mains electricity supply voltage also resulted in small differences in the heat gains achieved; however, this discrepancy was also the same for both test houses.

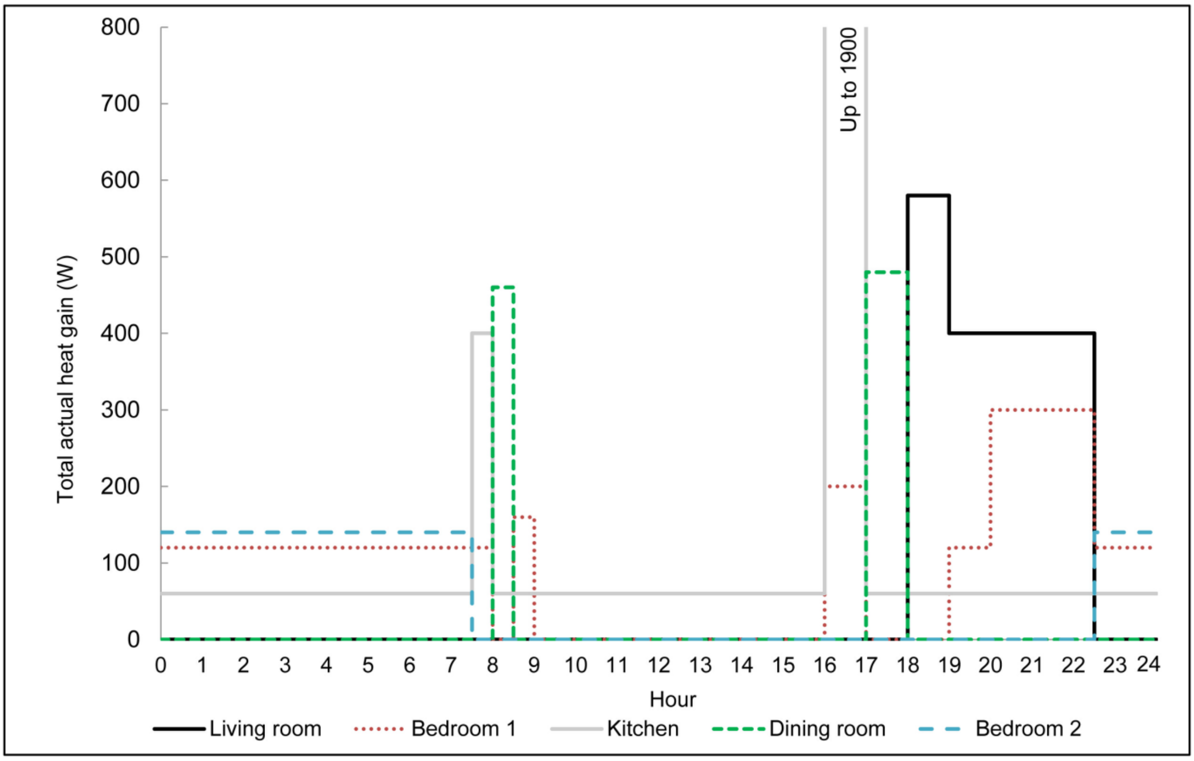

Figure 3-11: Total actual heat gains in different rooms of a house during a weekday

All windows were fitted with internal roller blinds. The roller blind fabric was cut to the appropriate sizes to fit each window. The fabric used was thin (1 mm thick), with closed weave and had a grey colour. Blind rotary motors which were controlled by Z-wave motor controllers (DBMZ Hunter Douglas) were used to move the blinds up and down. The roller blinds in the living room and bedrooms 1 and 2 were opened every weekday at 08:00 hrs and at 09:30 hrs on Saturday and Sunday. All blinds were closed at 16:00 hrs every day. The blinds in the dining room, bathroom and kitchen which all were facing north and the unoccupied spare bedroom were always remained closed.

The internal doors were operated using electrical actuators controlled by the motor controllers which were receiving commands from the home automation controller. The internal doors of the living room, dining room and bedrooms 1 and 2 (Figure 3-5) were closed when the room was 'occupied'[7] and open otherwise (Table 3-4). The internal door of the kitchen was open at all times whilst the doors of the unoccupied

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[7] Throughout, 'occupied' means that the room had synthetic occupants present.

spare bedroom (bedroom 3), the bathroom and the two doors to the outside, were closed at all times.

In order to avoid any possibility of entrapment, the internal doors were needed to be manually operable as well as automatically. Therefore, a mechanism was designed by attaching the actuators to support rods using cable ties to firmly hold the actuators in an appropriate position (Figure 3-12). In order to open a door, the actuator chain pulled the door using a rope which was attached to the actuator chain from one side and to the door from the other side (Figure 3-12). When a door needed to be closed, the actuator chain was released and the door closer installed on the top of each door pushed the door back to its fully closed position.

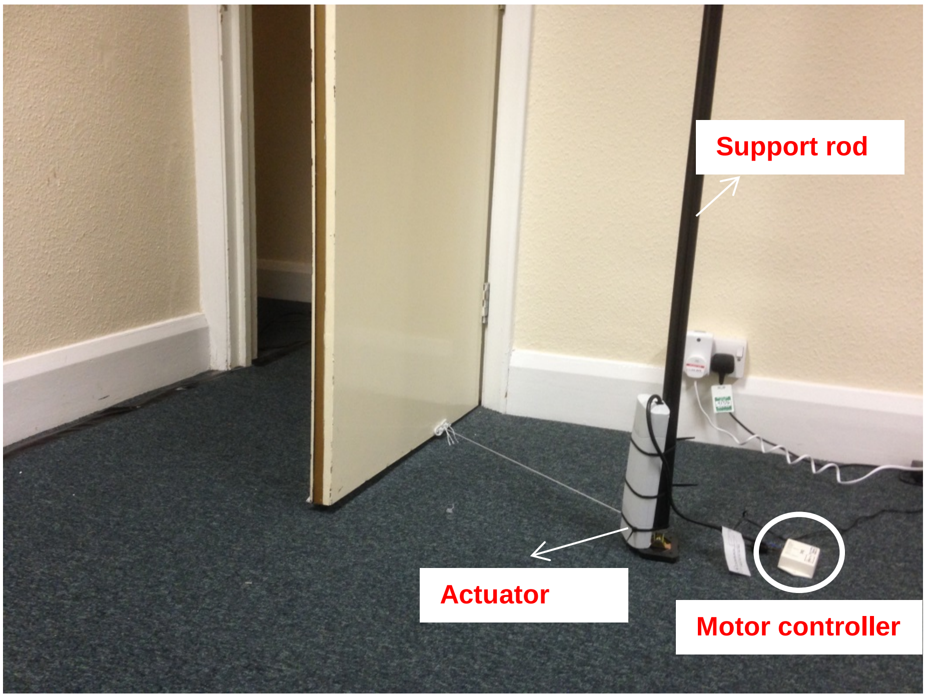

Figure 3-12: Internal door operation mechanism used in the test houses

Aspects of occupancy that were not mimicked include outside door openings, window opening, domestic hot water use, bathroom heat gains and occasional electrical usage such as dish washers, clothes washing and kettles. Windows and doors could not be simulated due to security concerns. The potential heat gains from hot water use and occupants in the bathroom were considered to be negligible as any heat produced was assumed to be transferred directly to the outside by extract fans or window openings or drainage. Most importantly however, as both houses were operated in the same manner, their heating energy demands were not differently affected by the occupancy.

The assumption of blinds in the dining room, kitchen and bathroom being always closed might not reflect the behaviour of real occupants. The blinds will reduce radiative and convective heat losses but, as these rooms were all facing north, the closed blinds have negligible effect on solar gains. The net effect is the same in both houses.

All the synthetic occupancy equipment had been tested both in the laboratory and in situ prior to the start of the heating trials. In addition, Internet Protocol (IP) cameras, which were located in the living room of each house, were used to check the operation of some synthetic occupancy equipment such as internal door or window blinds opening/closing and the lighting status (Figure 3-13).

Figure 3-13: IP camera which was used in the living room of a test house to check the operation of synthetic occupancy devices

3.3.6 Experimental characterisation of the test houses

Characterisation tests were conducted to assess and compare the thermal performance of the test houses. These tests consisted of a standard blower door test in accordance with ATTMA Technical Standard L1 (2010) and a standard co-heating test as described by Wingfield et al (2010). No occupancy was simulated during the characterisation tests.

The blower door tests were carried out on the same day (3 July 2013) for both houses (Figure 3-14). During the tests, the openings of the passive ventilation, extractor fan in the kitchen and original open fire places were sealed and all drainage traps were filled by water, as required by the standard test protocol. Thus the measured air leakage rate does not measure the in-use ventilation rate of the dwelling.

Figure 3-14: The blower door tests set up during the test in House 1

The front door of the test houses were arc shaped which did not allow the rectangular shaped blower door to be fitted to the front doors. Therefore, as it can be seen in Figure 3-14, a piece of wood were carefully cut and fitted above the rectangular blower door to cover all the open area of the front door.

The co-heating tests were conducted simultaneously in the two test houses during the period of 23 November to 1 December 2013. Seven electrical fan heaters which were set on a level to emit a nominal heat output of 1500 W were used in each house during the co-heating test (Figure 3-15). Four of them were placed in the ground floor rooms (i.e. living room, dining room, kitchen and hallway) and three of them were placed in the first floor; one in each bedroom (Figure 3-15).

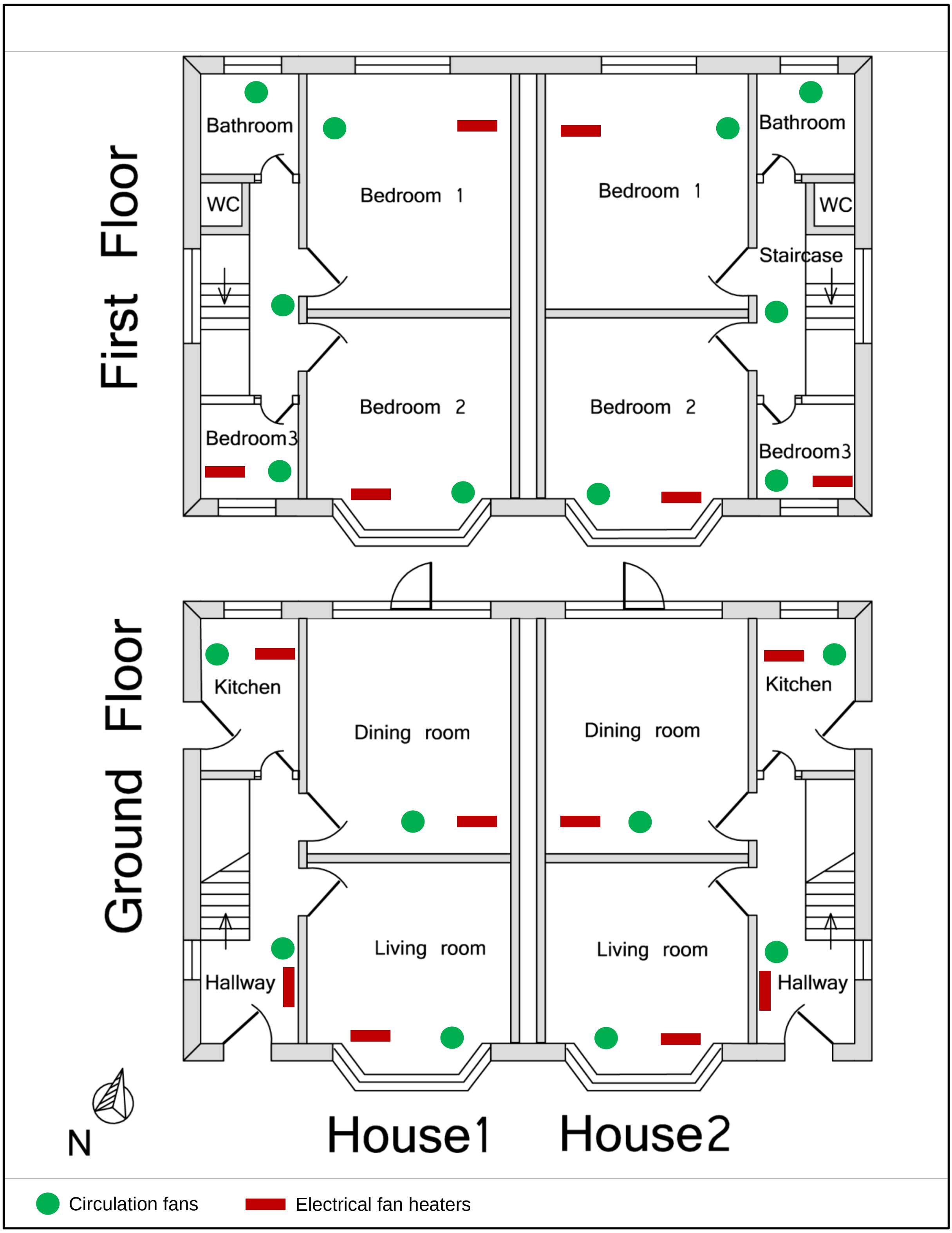

Figure 3-15: The location of fan heaters and circulation fans during the co-heating test

These electrical fan heaters were used to maintain a nominal internal air temperature of 25ºC in each room for a period of 9 days, plus 2 days of pre-conditioning. The two days pre-conditioning period was considered in order to allow the houses to achieve the steady state conditions required for the test. Circulation fans were used in each room to mix the air in the whole house and reduce stratification (Figure 3-16); the doors to all rooms were left open.

The heat output of each fan heater was controlled using a thermostat located in the centre of each room, 1.5 m above the floor level. The thermostats were 4-wire PT100 resistance thermometers. They were shaded from direct sunlight and the hot air from the fan heaters (Figure 3-16).

The thermostat was connected to a PID temperature control unit (InstCube 3216 L SSR Temperature Control Unit by TMS Europe Ltd) to switch the fan heater on and off using their PID control algorithm to maintain the constant air temperature of 25ºC. The electrical energy supplied to each house was measured at the meter (see section 4.2).

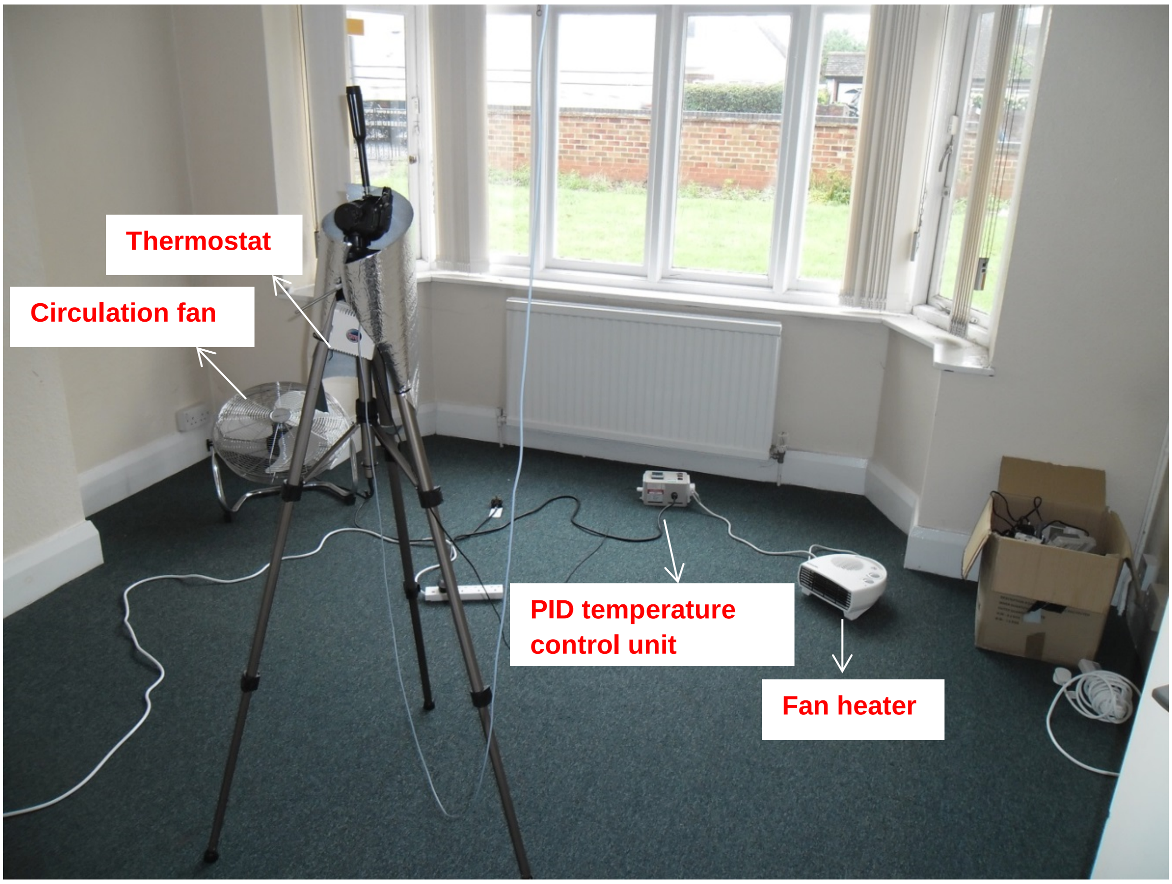

Figure 3-16: The co-heating test set up in the living room of House 1

The internal air temperature of every room was measured at 1 minute intervals using calibrated thermistors (see section 4.2). Minutely values for outdoor air temperature and hourly values for global horizontal solar irradiance during the test period were sourced locally (see section 4.2).

The "Siviour" linear regression method described in Butler & Dengel (2013) was used to calculate the solar-corrected heat loss coefficient of each house by plotting $^{\mathrm{Q}}/_{\Delta \mathrm{T}}$ against $^{\mathrm{S}}/_{\Delta \mathrm{T}}$ for each day (i.e. 23 November to 1 December 2013) of the co-heating test (Figure 3-17) where:

Q: Average daily measured power consumption (W)

$\Delta\mathrm{T}$: Average daily air temperature difference between indoor and outdoor (ºK)

S: Average daily global horizontal solar irradiance (W/m^2)

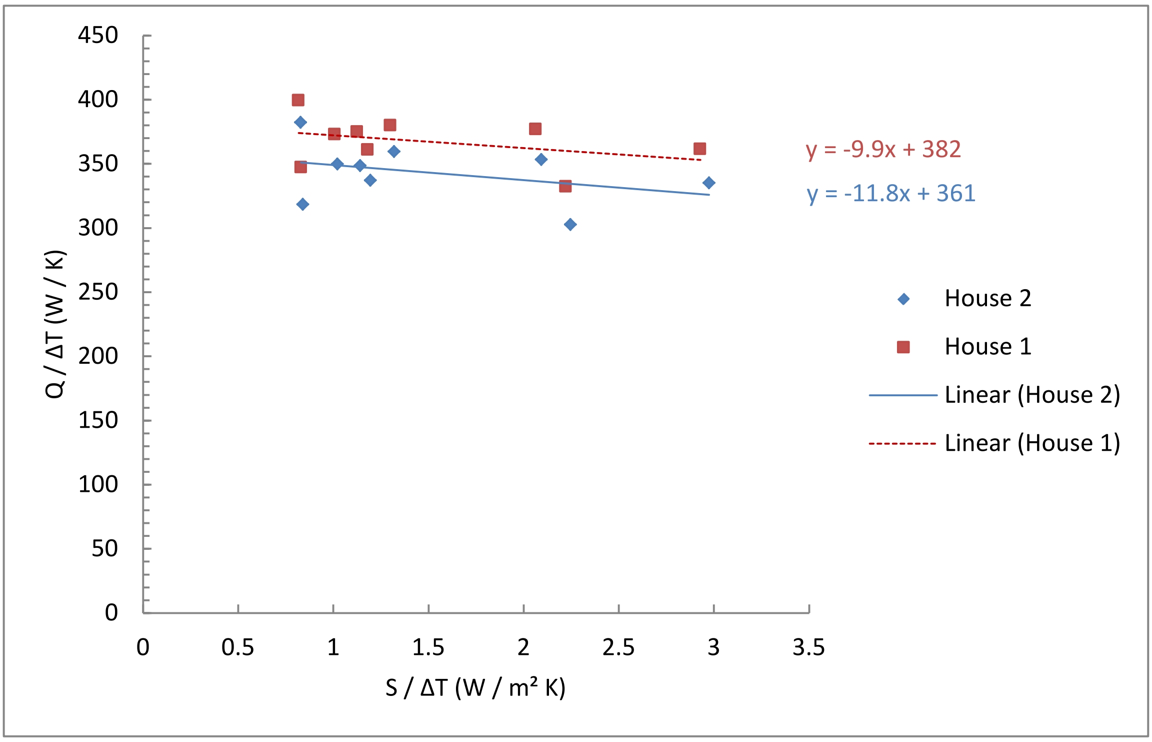

Figure 3-17: Siviour regression analysis for the two test houses

The resulting slope of the plot is the solar aperture R in m^2 and the Y intercept is the solar corrected total heat loss coefficient in W/K.

The results of the characterisation tests are presented in Table 3-7 and show that the two houses had very similar overall heat loss coefficients that were within 6%. This is a remarkably similar performance, especially given the uncertainty of co-heating tests, which may be greater than 10% (Butler & Dengel, 2013). In National House Building Council's (NHBC's) review of co-heating test methodologies (Butler & Dengel, 2013) solar corrected whole house heat loss coefficients found by 6 independent co-heating tests conducted by different project partners ranged from -17% to +11% of the calculated steady state heat loss based on as-built dimensions and specific fabric element U-values and infiltration rates (BRE, 2014). It should be noted that although Wingfield et al. (2010) recommends the use of at least one week's worth of co-heating test data and 9 days' worth of data was used in this study, a longer period could have led to slightly different heat loss coefficients.

The blower door test results also showed air leakages for the two houses were within 3% (Table 3-7). Full reports of the blower door tests were presented in Appendix A.1. An estimate of the background air infiltration rate, for the houses in the blower door test state (with the large purpose made openings blocked), can be achieved by dividing the air change rate at 50 Pa (N50) by 20 (CIBSE, 2000); which gives 1.07 ACH and 1.1 ACH for Houses 1 and 2 respectively. The test houses were less airtight than the average for UK houses of a similar age as reported by Building Research Establishment (Stephen, 2000): the mean air leakage rate of 58 dwellings built between 1930 and 1939 was 15.9 ACH at 50 Pa.

Table 3-7: Summary of the house characterisation test results

Performance measure	House 1	House 2	% difference
Total heat loss coefficient (W/K)	382	361	+5.6%
Air leakage (m^3/ $h*m^2$ Surface area at 50Pa)	20.76[1]	21.39[2]	-2.9%
Infiltration rate (^{ACH})	1.07	1.1	-2.9%
Solar aperture (m^2)	9.9	11.8	-16%

[1] Equals to 21.5 ACH at 50 Pa

[2] Equals to 22.1 ACH at 50 Pa

3.4 Summary

This chapter provided an overview of the space heating trials, modelling and wider scale evaluation campaigns which formed the methodology of this research. It also described the LMP1930 test houses used in this study, their geometries, construction materials, heating systems and the synthetic occupancy regime. In addition, the characterisation tests which were carried out in the houses were described and their results were discussed. The building envelope of the two houses showed a close thermal performance which was considered suitable for a side-by-side comparison of the energy performance of different heating control strategies.

4 Space heating trials

4.1 Introduction

This chapter describes the two space heating trials (HT1 and HT2) and present their results. It starts with describing the test houses' instrumentation set up (Section 4.2) and space heating control strategies (Section 4.3) during the HT1 and HT2 trials. The chapter then discusses the results by comparing the indoor air temperatures (Section 4.4), heating demand, boiler efficiencies and fuel use (Section 4.5) of the two houses. The chapter finishes by providing a summary of the findings from the space heating trials in section 4.6.

4.2 Instrumentation

Identical instrumentation was used in each house. Indoor air temperature was measured throughout the testing period, in each room, at 1 minute intervals, using U type thermistors. These were located in the volumetric centre of each room using tripods and were shielded from any direct sunlight using aluminium sheets (Figure 3-10).

The surface temperature of each radiator was measured at 10 minute intervals using I-button temperature loggers (Hindman, 2006). They were attached to the centre of each radiators surface using adhesive tape (Figure 3-10).

Boiler heat output was measured at 1 minute intervals using a heat flow meter consisting of Supercal 531 energy integrator (Sontex SA, 2014a) programmed for 10Wh per pulse, Superstatic 440 flow meter (Sontex SA, 2014b) installed at the return water going to the boiler and Pt500 temperature sensors inserted into ½" BSP pockets both at supply and return water pipes to the boiler (Figure 4-1). The active measuring temperature sensor tips were placed in the centre of the pipe cross section and the water pipes were insulated around the area where the temperature sensors were inserted according to the manufacturer's guidance to increase the accuracy of measurements. Supercal 531 calculated the heat captured into the water (i.e. boiler heat output) from the mean flow rate, the water temperature difference and the heat coefficient.

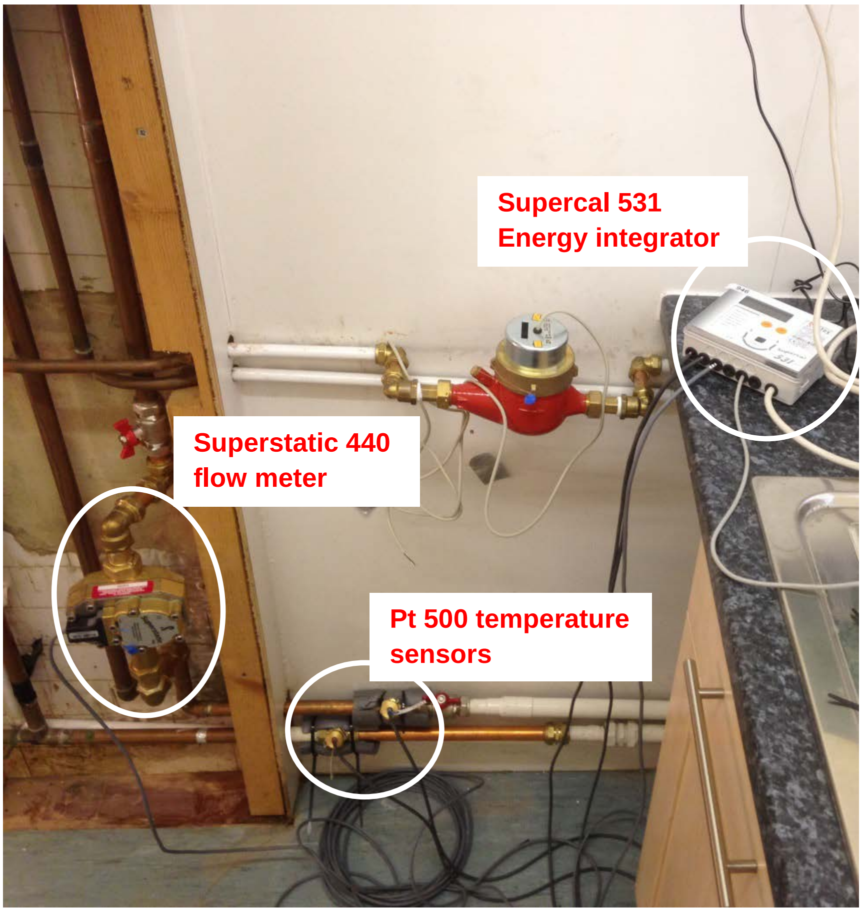

Figure 4-1: Equipment used to measure boiler heat output in the test houses; consisted of flow meter, temperature sensors and energy integrator

The volume of gas consumption for the boiler was measured every 10 minutes at the supply company gas meter of each house using an intrinsically safe pulse counter. This consisted of a Technolog Zmart Link gas flow transmitter which transmitted the pulse outputs from the gas meter to a gateway used for data recording and monitoring[8]. The gas pulse data could be then downloaded via web. The gas consumption (in kWh) was then calculated using the natural gas calorific value of 39.6 MJm^{-3} (DECC, 2014b).

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[8] The gas flow transmitter and the gateway were sourced from Loughborough University's DEFACTO (Digital Energy Feedback and Control Technology Optimisation) project partners and were not commercially available in the market

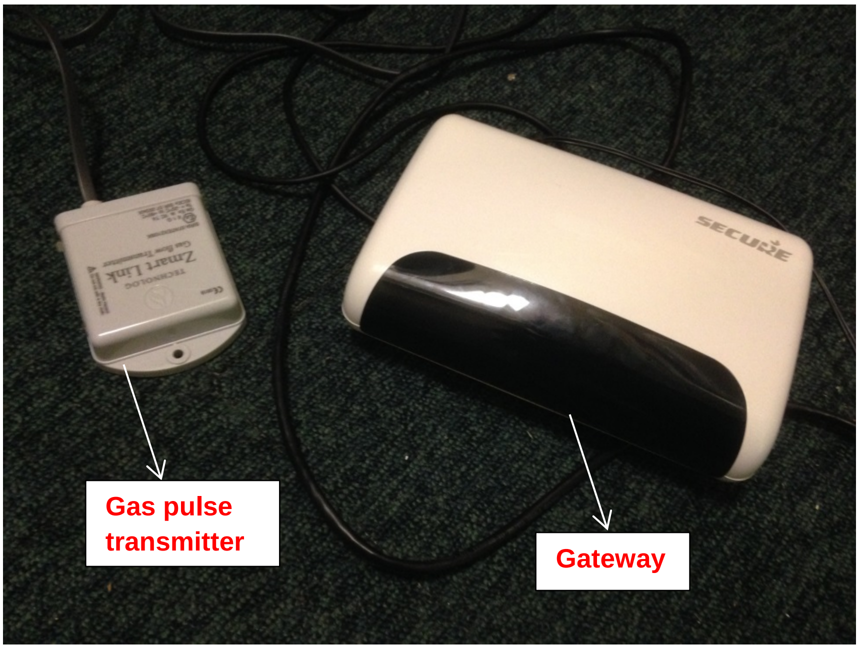

Figure 4-2: Equipment used to measure and record volume of gas use in the test houses

Electricity consumption was recorded every 5 minutes using LED pulse loggers (Enica Ltd, 2014) installed on the supply company electricity meter of each house, and at the individual appliance level using Plogg energy meters (Constable & Shaw 2011). This provided a measure of the heat delivered to the houses as electricity. All supplied electricity emerges as heat in the house.

Outdoor air temperature was measured every minute using a thermistor located adjacent to the houses but far enough away to avoid any thermal effects from the external walls. The thermistor was shaded from direct solar radiation and the sky and was shielded to protect it from rain and moisture (Figure 4-3).

Data logging at each house was carried out using a DT 85 Datataker data logger with in-built web server. The recorded data could be accessed online and downloaded at any time. Data collected was checked on a daily basis during the space heating trials. Checking the data on a daily basis was particularly useful on an occasion during the HT2 when it was found that there is no heat output from the boiler in one of the test houses, and immediate inspection of the test house revealed a leak in the pipes; which was quickly fixed with minimum loss of testing time and data.

Figure 4-3: The location of temperature sensor used to measure outdoor air temperature and its shielding

Hourly global horizontal solar irradiance was sourced from the MIDAS Land Surface Observation database at the British Atmospheric Data Centre (BADC) operated by the UK Meteorological Office (UK Meteorological Office, 2012). The nearest weather station was Sutton Bonington located 8 km away from the test houses.

All the temperature sensors used had been calibrated by the researcher before and after the experiments using a controlled water bath calibrator (Figure 4-4).

Figure 4-4: The calibration of U type thermistors using water bath calibrator

The accuracy of the equipment and uncertainty in values used in this study is indicated in Table 4-1.

Table 4-1: Accuracy of the equipment and uncertainty in values used

Equipment / values used	**Parameter measured / calculated**	**Accuracy / uncertainty**	**Source**
U type thermistors	Air temperature	±0.2ºC	Manufacturer stated accuracy
Data logger	Air temperature	0.1%	Manufacturer stated accuracy
I-buttons	Radiator surface temperature	±0.5ºC	Manufacturer stated accuracy
Gas meter	Volume of gas	±2%	National Measurement Office (2014)
Gas calorific value	Energy of gas	±1.5 MJm^{-3}	Buswell (2013)
Heat meter	Boiler heat output	±2%	Manufacturer stated accuracy

4.3 The control strategies

Two space heating trials (HT1 and HT2) were conducted in the test houses. HT1 was conducted continuously from 16 February to 15 March 2014. HT2 started on 18 March 2014, was stopped for 1 week due to equipment failure (9 to 15 April) and then continued afterwards until 21 April 2014. Thus each heating trial consisted of 4 weeks of reliable data including 20 weekdays and 8 weekend days.

The CC system consisted of the programmable room thermostat (PRT) in the hallway and TRVs on all radiators apart from the one located in the hallway (Figure 4-5). This enabled the heating system to be operated on a daily schedule using the PRT. The PRT controlled the boiler, which delivered hot water to all the radiators, while the individual TRVs provide some room-by-room temperature control.

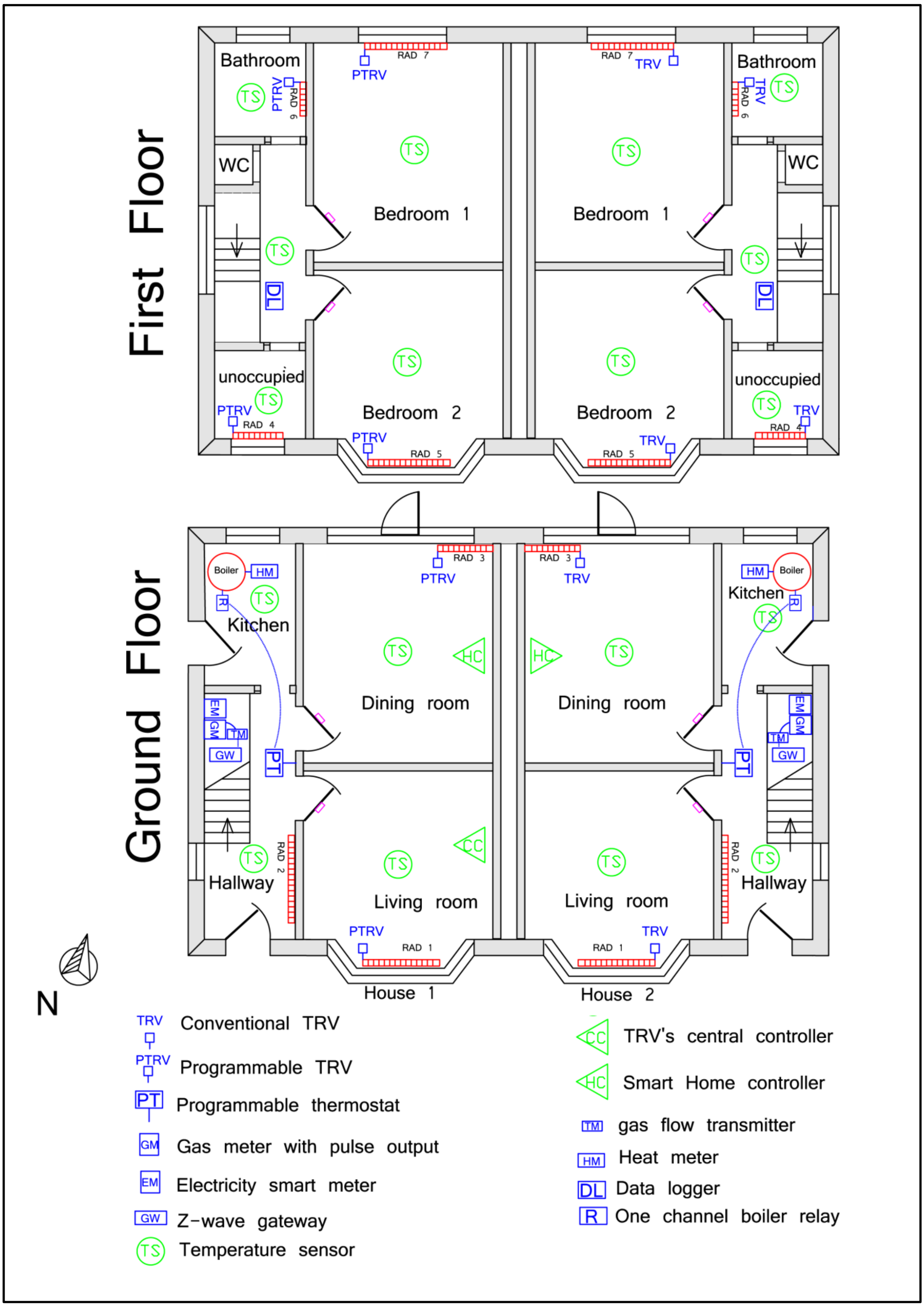

Figure 4-5: Test house schematic plans with heating systems and environmental monitoring equipment as configured during heating trial 1, for heating trial 2 the PTRVs with their central controller were swapped with TRVs in the opposite house

The PRT was set to switch the heating on for 10.5 hours per day on weekdays (06:00- 09:00 and 15:00 – 22:30) and 17 hours per day during the weekends (06:00 – 23:00) (i.e. the 'Heating on' periods) and the boiler was switched off during the rest of the day (i.e. the 'Heating off' periods)[9]. There was no set-back temperature during the heating off period (Table 4-2). This is similar to the heating durations specified in the UK standard calculation method (SAP) (BRE, 2014) but with each heating period starting one hour earlier. This was because the poorly-insulated house needed longer time to achieve suitable temperatures for the assumed periods of occupant activity.

Suitable TRV positions were found for each radiator by trial and error in order to achieve the comfort temperature specified by CIBSE Guide A (CIBSE, 2006a) for winter comfort: i.e. 21^{o}C in the living room and bathroom and 19^{o}C in the bedrooms. In the unoccupied spare room a setting that yielded approximately 12°C was used to as this was assumed to be the lowest temperature that would avoid frost and condensation (BRECSU, 2001) (Table 4-2). The TRV settings were determined for the radiators in house 2 before starting the HT1 and were not changed when they were transferred to the radiators in house 1 for the HT2.

For ZC, the whole system 'heating on' and 'heating off' periods were set by the PRT, and were the same as for the CC. The difference between ZC and CC was that programmable thermostatic radiator valves (PTRV) replaced the normal TRVs in 6 of the rooms (Figure 4-5). Room temperature set-points were the same as for CC but were set only for the 'occupied' hours (Table 4-2). However, the PTRVs' central controller adjusted the set-point temperature of the PTRVs 30 minutes before each 'occupied' period in order to allow the room to reach the set-point temperature (Figure 4-6). The set-point temperatures were held whilst the room was 'occupied', but allowed to fall to the set-back temperatures when the heating system was on but the room scheduled to be unoccupied. The set-back temperature was 16°C in all rooms except the unoccupied spare room for which 12°C was used (as for CC). When the heating system was off according to the PRT there was no set-back

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[9] Throughout, 'Heating on' and 'Heating off' periods means the times given here.[10] This is thus the average of 4 weeks with ZC in House 1 and 4 weeks in House 2, and likewise for CC.

temperature. In other words, PTRVs could not cause the heating system to turn on as it was controlled by the central thermostat.

FROM	7:00	9:00	18:30	20:00
UNTIL	9:00	18:30	20:00	7:00
Setting	21.0°	16.0°	21.0°	16.0°

Figure 4-6: A PTRV installed on a radiator (on the left) and the interface of the central controller used to programme the PTRVs (on the right)

Compared to CC, in which all the rooms were heated to their set-point temperatures for 10.5 hours during weekdays and 17 hours during weekends (i.e. ‘Heating on’ hours), ZC established shorter periods of time when each room was heated to its set-point temperature (see Table 4-2).

Table 4-2: Weekday and weekend ‘occupied’ hours with the number of hours each room was heated to the set-point or set-back temperatures and, for ZC, the PTRV set-point and set-back temperatures, and for CC, the TRV position

			ZC				CC	
Room	Weekday ‘occupied’ hours	Weekend ‘occupied’ hours	Set-point (ºC)	Set-back (ºC)	Number of hours heated to the set-point (WD[1] WE[2])	Number of hours heated to the set-back (WD[1], WE[2])	Number of hours heated to the set-point (WD[1], WE[2])	TRV level (1-6)[3]
Living Room	18:00-22:30	18:00-22:30	21	16	5, 5	5.5, 12	10.5, 17	4
Dining Room	08:00-08:30 17:00-18:00	09:30-10:00 17:00-18:00	19	16	2.5, 2.5	8, 14.5	10.5, 17	3
Kitchen	07:30-08:00 16:00-17:00	09:00-09:30 16:00-17:00	-	-	-	-	-	-
Bedroom 1	19:00-22:30 22:30-08:00 08:30-09:00 16:00-17:00	19:00-22:30 22:30-09:30 10:00-10:30 16:00-17:00	19	16	8.5, 10	2, 7	10.5, 17	3
Bedroom 2	22:30-07:30	22:30-09:00	19	16	2, 3.5	8.5, 13.5	10.5, 17	4
Bathroom	07:30-08:00 08:30-09:00 19:00-20:00	09:00-09:30 10:00-10:30 19:00-20:00	21	16	3.5, 3.5	7, 13.5	10.5, 17	4
Un-occupied Bedroom	-	-	12	-	10.5, 17	-	10.5, 17	1

1WD – weekdays
2 WE - weekends
3 The TRV settings provided the same set-point temperatures in each room as the set-points with ZC

4.4 Comparison of indoor air temperatures

The air temperature and radiator surface temperatures varied throughout a typical weekday and weekend according to the heating strategy set on the PRT, but there were distinct room-by-room temperature differences depending on whether CC or ZC was used (e.g. Figure 4-7). In the morning, the radiators started to warm up when the heating came on and with CC continued to emit heat until the set-point temperature was reached. With ZC however, if the room was not scheduled to be ‘occupied’, the PTRV stopped the flow of water to the radiator when the set-back temperature was reached (see Figure 4-7, dining room and living room, morning heating period). If the room remained unoccupied, ZC only provided heat when the air temperature fell below the set-back temperature whereas, with CC, heat was provided to maintain the higher, set-point temperature (Figure 4-7, living room, morning on period, bedroom 2 evening heating period). If a room with ZC became occupied during a ‘heating on’ period, the PTRV would enable flow to the radiator to bring the room temperature up to the set-point (Figure 4-7, dining room, living room and bedroom evening heating on periods). It is the difference in the energy needed to achieve the set-point temperature compared to the set-back temperature when the heating is on but rooms are unoccupied, that leads to potentially lower heating energy consumption. The lower the set-back temperature and the shorter the occupied time relative to the heating on time, the more energy ZC might, in principle, save. However, in ZC the heated rooms would lose more heat to neighbouring spaces that are at a lower temperature compared to CC when the neighbouring spaces are at a higher temperature.

The houses exhibited other characteristics common to UK centrally heated homes, especially poorly insulated homes. For example, even though bedroom 2 was ‘occupied’ from 06:00 hrs to 07:30 hrs and the heating was on, the room failed to reach the set-point temperature with either ZC or CC. In fact, the set-point wasn’t reached even after 3 hours of heating using CC. Bedroom 2 has a particularly large single-glazed bay window and therefore high rates of heat loss. In the middle of the day, when the house was unheated, the temperatures in the north-facing rooms fell to below the set-back temperature in the case of bedroom 1. In contrast, the solar gain through the large, south-facing window of bedroom 2, and the similarly sized window in the living room, caused the temperatures in the middle of the day to exceed the heating set-point; especially in the house with CC (Figure 4-7). In the evening heating period, with both CC and ZC, the living room, and to a lesser extent the dining room temperatures exceeded the set-point during the occupied hours. This was most likely due to the internal heat gains.

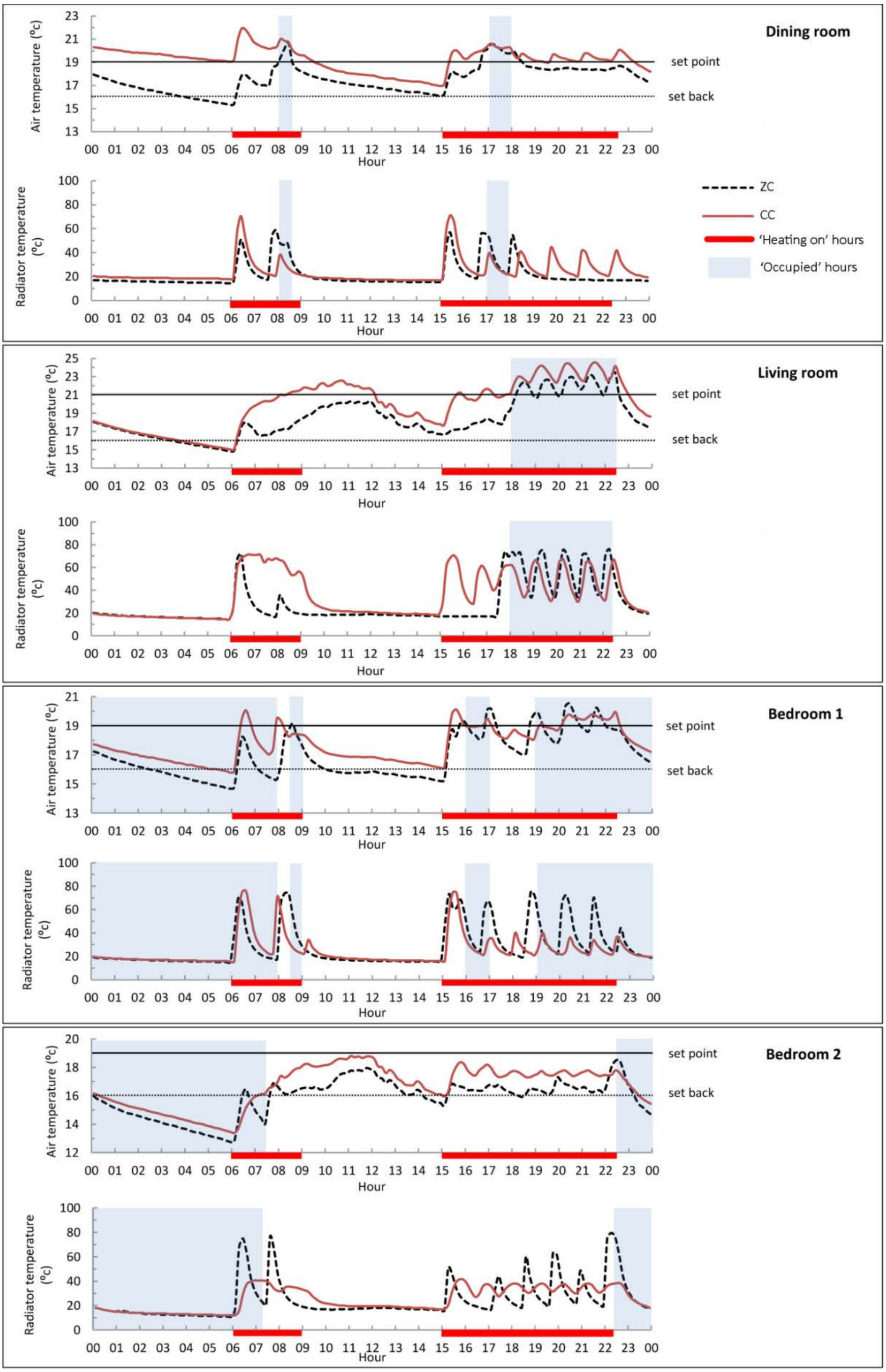

Figure 4-7: Air and radiator surface temperature variations in different rooms: heating trial 1, 21st Feb 2014, ZC in House 1, CC in House 2.

Table 4-3 shows the average air temperature in each room for the 8 weeks trial periods[10]. These are broken down into five different averaging periods: the whole of each day; when the PRT had switched the ‘Heating on’; when the heating was on and the space occupied, ‘Heating on and occupied’; when the heating was on but the space was unoccupied, ‘Heating on and unoccupied’; and, finally, the average during the ‘Heating off’ hours. The table also gives the floor area-weighted[11] average temperature for the whole house during each of these five periods.

Table 4-3: Average indoor air temperatures in each room during five different periods, and the spatially averaged whole house temperature

					‘Heating on’				‘Heating off’	
	Whole day		‘Heating on’		‘occupied’		‘unoccupied’			
Room	ZC (ºC)	CC (ºC)	ZC (ºC)	CC (ºC)	ZC (ºC)	CC (ºC)	ZC (ºC)	CC (ºC)	ZC (ºC)	CC (ºC)
Living Room	19.2	20.0	20.3	21.5	22.3	22.5	18.7	20.5	18.0	18.4
Dining Room	18.2	18.7	19.0	19.5	20.4	20.1	18.8	19.4	17.4	17.7
Bedroom 1	18.0	18.3	18.9	19.2	18.9	19.2	18.7	19.4	17.1	17.3
Bedroom 2	17.2	18.2	17.6	19.1	16.3	18.1	17.9	19.3	16.5	17.1
Bathroom	16.5	17.7	17.3	18.9	19.7	19.1	17.2	18.9	15.5	16.4
Unoccupied room	14.8	15.3	14.9	15.5	-	-	14.9	15.5	14.6	15.0
Circulation areas[1]	19.1	19.5	20.3	20.8	-	-	20.3	20.8	17.8	18.1
Kitchen	19.6	20.0	20.7	21.2	23.0	23.6	20.4	20.8	18.4	18.6
Whole house[2]	18.1	18.7	18.9	19.7	19.7	20.1	18.6	19.6	17.1	17.5

[1] Average air temperature in hallways on the ground and first floors.

[2] Floor area weighted average air temperature.

The averages are across four weeks with the control system in one house and four weeks in the other house.

Considering the whole day, the average air temperature of all the rooms and the whole house was lower with ZC than with CC. The temperatures were also lower

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[10] This is thus the average of 4 weeks with ZC in House 1 and 4 weeks in House 2, and likewise for CC.

[11] Calculated as: $(T_1 * A_1 + T_2 * A_2 + \cdots + T_n * A_n)/(A_1 + A_2 + \cdots + A_n)$ where: T_1 to T_n are the average air temperature of different rooms during each of the 5 periods and $A_1$to A_n are the floor area of those rooms

with ZC during periods when the heating system was on and when the heating system was off. This was because ZC kept space temperatures low when rooms were scheduled to be unoccupied, but provided similar air temperatures to CC (not less than the set-point temperature) when the rooms were scheduled to be occupied. During the ‘occupied’ hours when the heating was on, for both control strategies, the average indoor air temperatures measured in the living room and dining room were higher than their set-point temperature, which is thought to be due to the effect of internal heat gains and closing the doors when the rooms were occupied.

The average air temperature in bedroom 2 was lower than its set-point temperature during the ‘occupied’ hours especially in the house with ZC. This was because this bedroom was ‘occupied’ mostly during the night when the occupants were assumed to be sleeping and the heating was switched off (it is usual to sleep in an unheated bedroom in the UK (Huebner et al. 2013). Therefore, the daily period when the heating was on and the room was ‘occupied’ and thus heated was too short for the room to achieve its set-point temperature (Table 4-2).

On a similar basis, the average air temperature in bedroom 1 during the occupied hours was higher than bedroom 2 and close to the set-point temperature because it was ‘occupied’ for longer each day, when the heating was on, for purposes other than sleeping.

The average air temperatures during the sleeping periods are worth noting. In the house with ZC they were 15.5ºC and 14.3ºC, in bedrooms 1 and 2, respectively, which was lower than the averages of 16.2ºC and 14.6ºC found for CC. Bedroom air temperatures in both homes are thus lower than the CIBSE recommendation for bedrooms of 17ºC. However, Humphreys (1979) reports good sleep quality even for bedroom temperatures as low as 12ºC while Collins (1986) and Hartley (2006) indicate the world health organization’s bedroom temperature limit of 16ºC to reduce the risk of decreasing resistance to respiratory infections which can occur at lower temperatures (Peeters et al. 2009).

Bathroom average air temperatures were lower than the designed set-point temperature with both ZC and CC during ‘occupied’ hours. This could be due to an undersized radiator. Also, there were no internal heat gains as it was assumed that in real houses any heat gain produced in this room would be quickly transferred to outdoor via extract fans or window opening.

The mean temperatures in the unheated rooms (i.e. unoccupied room and kitchen) were found to be lower for ZC during all the periods of the day. Again this was assumed to be due to higher rates of heat loss and lower rates of heat gain to and from the adjacent rooms in which were cooler in ZC compared to CC. The mean temperature of the kitchen was much higher than all other rooms during the ‘occupied’ hours (23ºC and 23.6ºC for ZC and CC respectively). This was clearly due to the considerable heat gains from cooking.

The daily average air temperatures in the circulation areas on the ground floor and first floor were lower in the house with ZC compared to the house with CC. This could again be explained by the lower temperatures in adjacent rooms acting as a heat sink.

It is important to quote the energy savings of ZC when the same level of comfort as CC is being provided. In this work, it is assumed that indoor air temperature alone is a good proxy for thermal comfort. However, in this experimental work, it was not possible and in fact intended to provide identical temperatures at the same time in the two homes using the different control strategies. The consequence, as can be seen from Table 4-3, is that the whole house average air temperature during ‘occupied’ hours was slightly lower with ZC (19.7°C), than it was with CC (20.1°C). However, the main reason for the whole house average air temperature during the “occupied” hours being slightly lower in ZC compared to CC was that ZC provided lower air temperatures in bedroom 2 which was mainly occupied for the purpose of sleeping as it was discussed earlier.

Considering the hours of ‘active occupancy’ (i.e. when the occupants are assumed to be present and awake) for the entire 8 weeks of the trials the average air temperatures of the whole house was 21.0ºC for ZC and 20.8ºC for CC. Therefore, on average, for this experiment ZC provided a slightly higher air temperature compared to CC during the time period of most interest (i.e. ‘active occupancy’). Therefore, it was assumed that both control strategies provided the same level of thermal comfort to the occupants.

4.5 Heating demand, boiler efficiencies and fuel use

During the heating trials the daily average outdoor air temperature ranged from a minimum of 2.5ºC (Day 14) to a maximum of 13.1ºC (Day 48) with an average of 7.1ºC (Figure 4-8). As expected, whole house heating demand, as measured by the boiler heat output, was greater on colder days than on warmer days. During the weekends, the heat output was generally higher than for weekdays because the heating was switched on for longer (Figure 4-8).

The daily heat output with ZC varied from 22.6 to 80.6 kWh/day with an average of 53.6 kWh/day, while with CC it varied from 25.0 to 90.8 kWh/day with an average of 62.4 kWh/day. On every day of the trials the daily boiler heat output in the house with ZC was lower than the boiler output in the house with CC (Figure 4-8). Overall, daily heat output with ZC was between 2.6% (Day 7) and 22.1% (Day 25) lower than with CC, giving a daily average of 14.1% lower heat output.

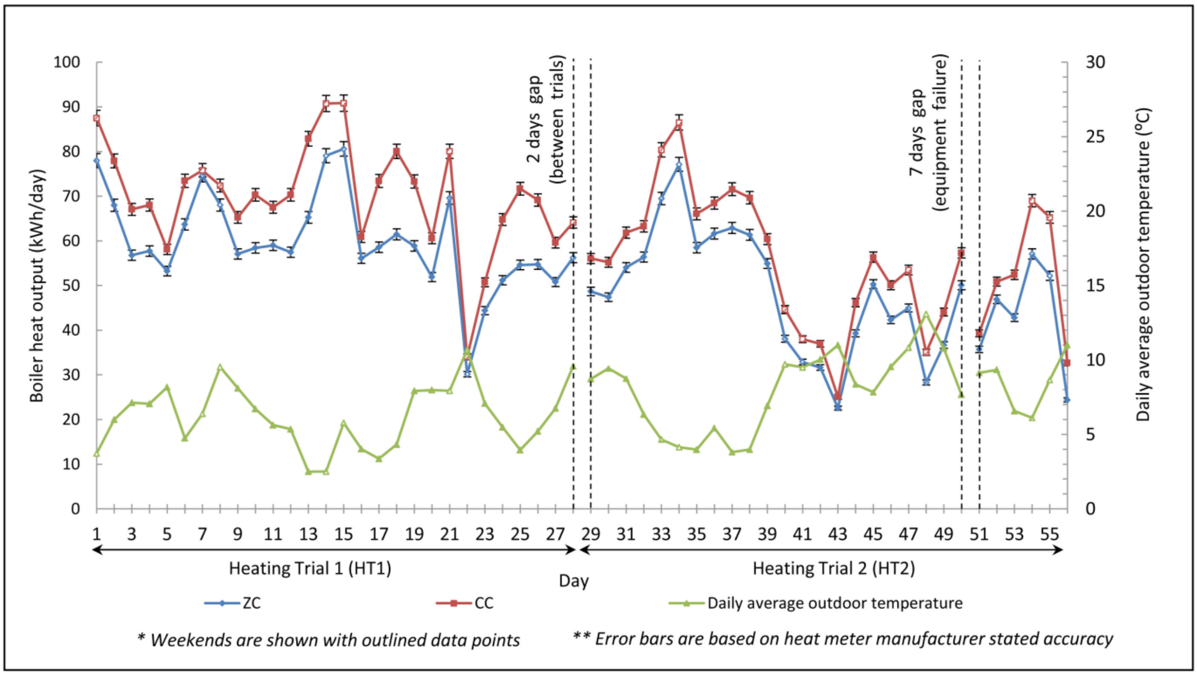

Figure 4-8: Measured daily heat output from the boilers during the heating trials 1 and 2 and their error bars (based on heat meter's manufacturer stated accuracy) together with the average daily outdoor temperature

The efficiency of boilers when operating with ZC was lower than the efficiency of the boilers when operating with CC (Figure 4-9). However, the difference was quite small, being on average 1.5 percentage points (pp) less efficient during the first trial (HT1) and 3.3pp less in the second trial (HT2). The larger difference during the HT2 is perhaps due to the warmer weather which meant the boiler outputs were less and so they were operating further away from the peak efficiencies for longer. At part load, small differences in power output lead to larger differences in efficiency than at, or near, peak load. There may also be some small differences between the boilers installed in the two houses as they were less than seven years old.

Averaged over both trials, the efficiency of the boilers associated with ZC were 2.4pp less efficient than the boilers controlled conventionally (CC) (Table 4-4). A standard chi-square test was conducted to determine if the results were statistically significant. This difference was found to be statistically significant ($p<0.01$) and is likely to be because boilers operated under ZC, experiencing lower heating loads, and so operate further away from the peak load capacity – at which they are most efficient.

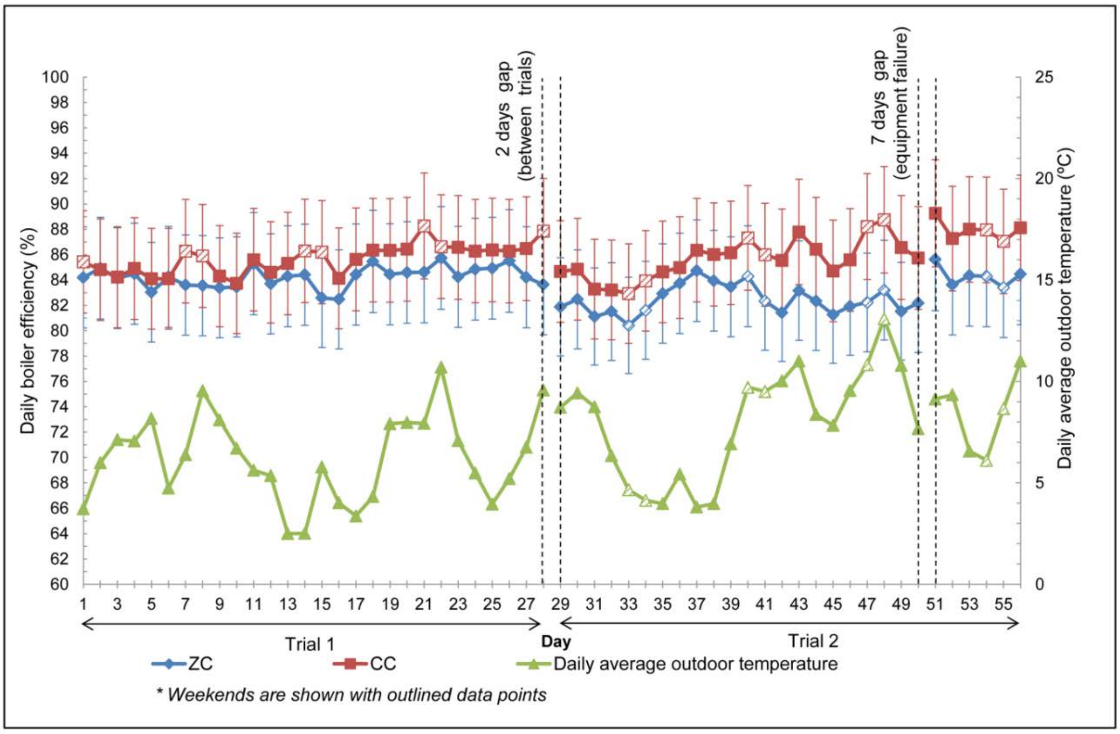

Figure 4-9: Daily efficiency of the boilers with zonal control (ZC) and conventional control (CC) in each heating trial with their error bars[12] together with the daily average outdoor temperature

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[12] Uncertainty in daily boiler efficiencies are calculated as the quadratic sum of the uncertainties in calorific value of gas, gas meter and heat meter (Table 5)

Table 4-4: Summary of daily average boiler efficiencies in each heating trial and overall efficiency

	Heating Trial 1, Boiler Efficiency (%) Daily Average (minimum, maximum)	Heating Trial 2, Boiler Efficiency (%) Daily Average (minimum, maximum)	Overall Average Boiler Efficiency (%) Daily Average (minimum, maximum)
Zonal Control (ZC)	84.2% (82.5%, 85.7%)	82.8% (80.4%, 85.6%)	83.5% (80.4%, 85.7%)
Conventional Control (CC)	85.7% (83.7%, 88.3%)	86.1% (82.9%, 89.3%)	85.9% (83.7%, 89.3%)
Difference	1.5pp[1]	3.3pp[1]	2.4pp[1]

[1] Percentage points

The total gas consumption across both heating trials was 11.8% less with ZC than with CC. This resulted from the combination of a reduced heat demand of 14.1% but a reduction in boiler efficiency of 2.4pp. Average daily gas consumption was significantly less ($p<0.05$) with ZC (64.2 kWh) rather than CC (72.8 kWh). During the 40 weekdays of monitoring, average daily gas consumption was significantly less ($p<0.01$) in the house operating with ZC (61.8 kWh) rather than the house operating with CC (71 kWh); a difference in gas consumption of 13%. During the 16 weekend days the house with ZC used on average 70.3 kWh/day while the house operating with CC used 77.3 kWh/day; a difference of 9.1% . However, this was not found to be statistically significant; due to the relatively small number of weekend days (n=16) for testing any statistical significance. Compared to weekdays, at the weekends rooms are occupied for a greater proportion of the time that the heating is on (Table 4-2) and the programmable thermostat (located in the hallway) tends to reach the set-point more often with CC than with ZC and so the heating system is cycled off for slightly longer with CC. These results suggest that houses that are more intermittently occupied and which have rooms that are used infrequently might benefit more from ZC than homes that are occupied extensively and for longer (see chapter 8).

4.6 Summary

This chapter has described the space heating trials conducted in the LMP1930 test houses during an 8-weeks winter test period and has presented the trials results. The main findings from the space heating trials can be summarised as:

- The average air temperature of all the rooms and the whole house was lower with ZC than with CC considering the whole day, the period when the heating system was on and the period when the heating was off.
- In most rooms and in both houses, the average air temperature measured during the occupied period when the heating was on was different from their set-point temperatures.
- The average air temperatures in bedrooms in both houses during the sleeping period were below air temperatures recommended by CIBSE.
- Whole house average air temperature during ‘occupied’ hours was slightly lower with ZC (19.7°C), than it was with CC (20.1°C). However, these were very close when excluding the air temperatures during the sleeping period.
- Daily boiler heat output of the house with ZC was lower than that of the house with CC on every single day. On average, daily heat output of the boiler in the house with ZC was 14.1% lower than the boiler in the house with CC.
- The average efficiency of the boilers associated with ZC were 2.4pp lower than that of the boilers controlled conventionally (CC)
- The total gas consumption across both heating trials was 11.8% less with ZC than with CC.
- The average gas savings of ZC were found to be higher during the intermittently heated weekdays rather than weekends when the houses were heated for longer periods.

5 Dynamic thermal modelling

5.1 Introduction

This chapter describes the use of of dynamic thermal models (DTMs) to simulate the co-heating test (section 3.3.6) and space heating trials (chapter 4) conducted during the experimental campaign of this study. The modelling approach adopted here was according to recommendations by Lomas et al. (1997) in which the experimental work was firstly simulated in a so called “blind phase” where the modeller is unaware of the actual measured performance of the building. The empirical validation was then conducted in an “open phase” (chapter 6) in which the measurements were made available.

EnergyPlus version 8.1.0.009 which was released in October 2013 was used in this research. EnergyPlus is a freely available dynamic thermal modelling tool which has undergone a number of revisions and the current version 8.3 was released in March 2015. The input data for EnergyPlus simulations is contained in a text file called the Input Data File (IDF). This enables the user to change sections of the input file and control these changes using a text editor or a third party such as IDF editor.

DesignBuilder (2014) is a commercially available software package that offers detailed dynamic thermal simulations, for which it uses the EnergyPlus simulation engine and provides a user friendly graphical user interface. In this study, DesignBuilder version 3.4.0.0.41 which was released in April 2014 was used to input the building geometries, construction materials and input parameters for modelling the air flow and heating systems. The model created in DesignBuilder were then converted to the EnergyPlus IDF files, which were modified further using a text editor and the EnergyPlus IDF Editor in order to construct the final EnergyPlus model and run simulations.

The chapter starts with the description of modelling the building envelope of the test houses (section 5.2). Then in section 5.3, it describes two different air flow modelling methods which were used to model air flows in the houses. In section 5.4, modelling of the heating systems which were used during the co-heating test and HT1 are discussed. In section 5.5, the procedure for modelling the synthetic occupancy of the houses is discussed. In section 5.6, the generation of the weather file for the periods of co-heating test and the HT1 is described. Finally, section 5.7 presents a summary of this chapter.

5.2 Modelling the building envelope of test houses

In this section, construction of a DTM of the building envelope of the LMP1930 test houses is described including details of geometry, zoning, ground modelling and construction materials.

5.2.1 Building geometry

Internal dimensions of the LMP1930 test houses were entered in to the DesignBuilder software. The semi-detached test houses were modelled together (Figure 5-1) as this allows influences of the adjacent house on thermal behaviour of each house to be considered in the model. In addition, the neighbouring houses were modelled as component blocks in order to take into account their potential shading and reflection effects on LMP1930 houses (Figure 5-2).

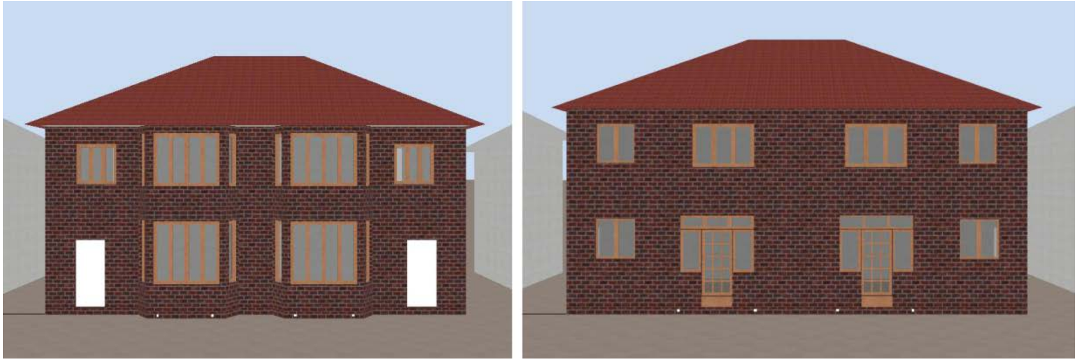

Figure 5-1: Views of the LMP1930 test house model in DesignBuilder: front, south-facing (left) and back, north-facing (right)

Figure 5-2 View of the LMP1930 test house model with the effect of shading from the neighbour blocks (15 March at 16:00)

A number of simplifications were made in the models. The party wall between the two houses was modelled as a partition wall (see section 5.2.4 for details of construction materials). The chimneys and sealed fire places were not considered in the model.

The width and height of each window was entered separately, including the frame according to the window corner definition in DesignBuilder (Figure 5-3). The window frames and dividers were also entered separately for each window (Figure 5-3). The window area which is provided to EnergyPlus IDF input file after conversion have slightly smaller area compared to the area defined in DesignBuilder in order to take into account the frames which is not considered in definition of window area in EnergyPlus (Figure 5-3). Internal doors and external doors were also entered into the model.

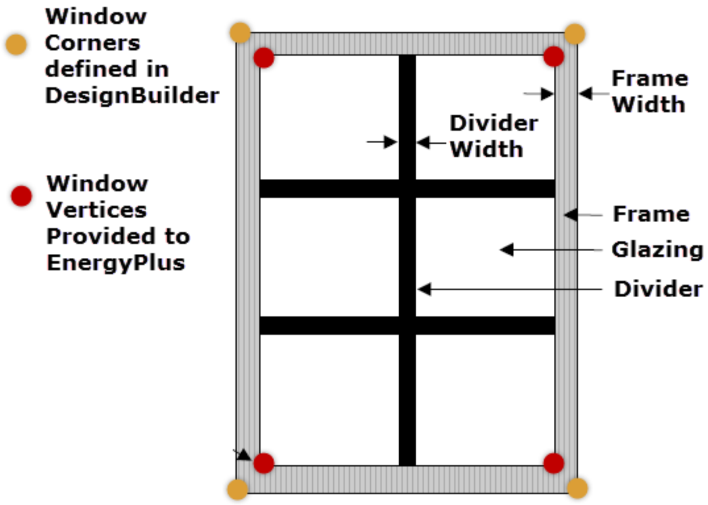

Figure 5-3: Window geometry definition in DesignBuilder and EnergyPlus (DesignBuilder, 2014)

5.2.2 Zoning

In each house, the lower storey was divided into 4 zones including the living room, dining room, kitchen and hallway while the upper storey was divided into 6 zones of hallway, bathroom, bedroom 1, bedroom 2, bedroom 3 (unoccupied room) and a WC (Figure 5-4). The subfloor and the loft (attic) space of each house was considered as additional unheated zones.

Each EnergyPlus zone is defined as a common air mass at a specific temperature (i.e. the air is fully mixed). In space heating with ZC, each room with a radiator and PTRV is controlled to a temperature which is often different from the temperatures at which other rooms are being controlled. Although few zones such as bedroom 1 and 2 which have the same set-point temperature could have been merged into one zone for the house with CC, keeping the same zoning configuration for the houses with CC and ZC would enable room by room comparison of the two control strategies. In addition, having separate zones enabled the internal heat gains of each zone to be modelled more accurately.

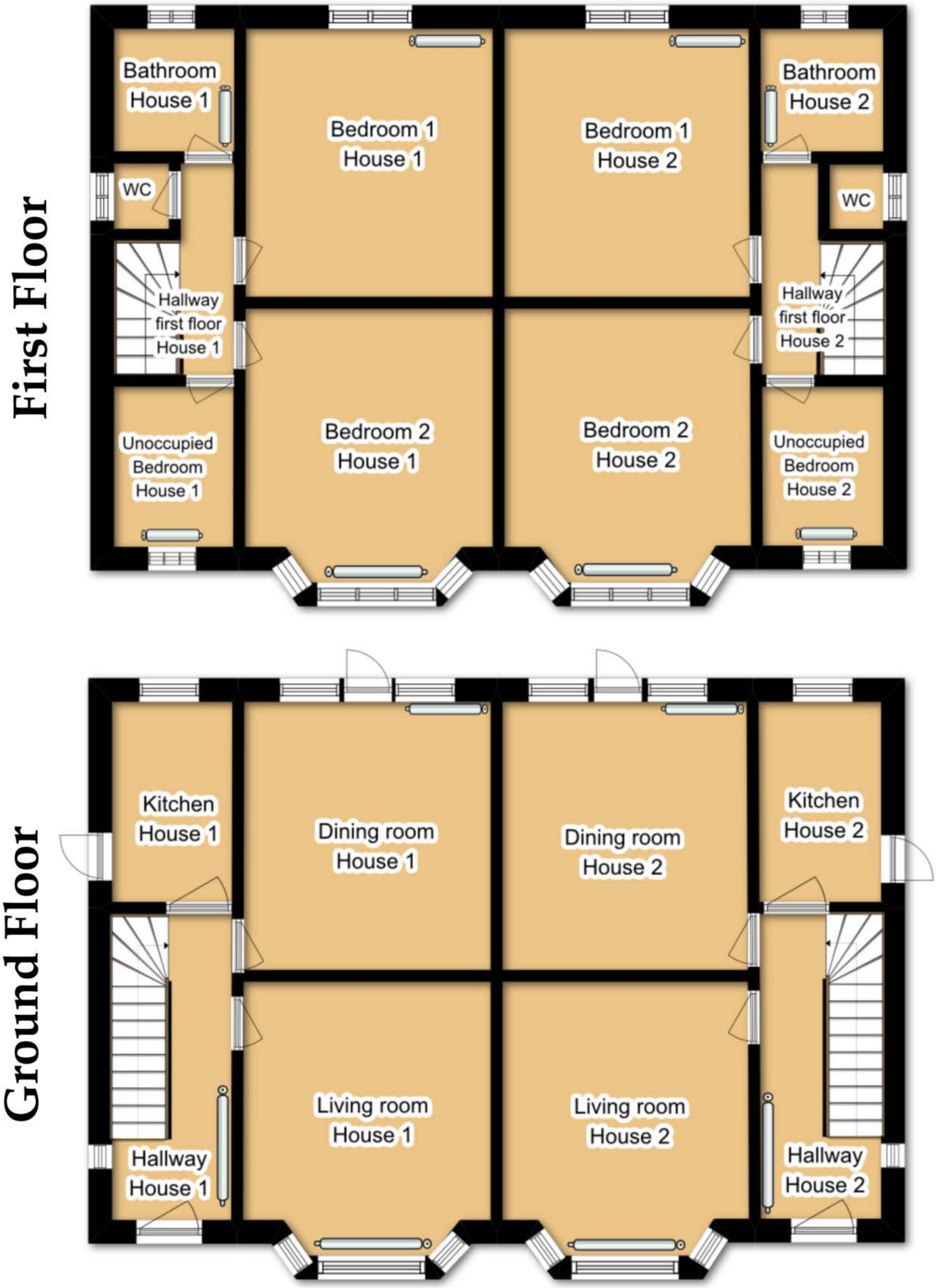

Figure 5-4: LMP1930 test house model zoning strategy for ground floor and first floor

5.2.3 Ground modelling

The suspended timber ground floor of each house was modelled explicitly as a separate zone (subfloor zone) which was added below the ground floor. The subfloor zone had six air bricks each having an open area of 0.01 m^2 as measured at the test houses. The height of the subfloor was 0.2 m according to the measured depth of the underfloor void existed (from the bottom of the floor boarding to the ground). It was assumed that the ground under the suspended timber floor is just bare earth (see section 3.3.3).

The solid floors of the kitchens were represented by a 100 mm concrete slab. The thickness of concrete slab could not be directly measured and was assumed to be 100 mm, according to a document by University of the West of England (2009).

Average monthly ground surface temperatures under the building are used by EnergyPlus as the outside surface temperature for all surfaces adjacent to the ground to calculate the heat transfer between the ground and any adjacent zone. Average monthly ground surface temperatures could be calculated using 3D ground heat transfer program of EnergyPlus for slabs (US Department of Energy, 2013b). The 3D slab program included in EnergyPlus produces outside surface temperature of the core and perimeter of a slab in contact with the ground. The programme uses twelve separate average monthly indoor temperatures as inputs for the calculation of the ground temperature. However, this programme could not be used to calculate the ground temperature under a ventilated suspended timber floor, and this was not measured during the experimental work.

According to EnergyPlus documentation, the undisturbed ground temperatures calculated by EnergyPlus’s weather converter program are often not appropriate for building loss calculations as these values are too extreme for the soil under a conditioned building (US Department of Energy, 2013b). EnergyPlus documentation (US Department of Energy, 2013b) suggests using ground temperatures of 2°C below mean internal temperatures for large commercial buildings in the US. However, it does not suggest any method for calculating or estimating ground surface temperature under a ventilated suspended timber floor or for small residential buildings such as this case. An article by (Lstiburek, 2008) published in ASHRAE

Journal of Building Sciences suggests that a reasonable rule of thumb to estimate the ground surface temperature of ventilated crawlspaces is to use the average annual ambient air temperature of that location. In absence of any other reference, the average annual ambient air temperature measured at Sutton Bonnington weather station for the year 2014 which was 11.8ºC (UK Meteorological Office, 2012) was assumed as the monthly ground surface temperatures.

5.2.4 Construction materials and properties

Construction materials properties were selected from DesignBuilder’s library as shown in Table 5-1.

Table 5-1: Construction materials properties used in LMP1930 model

Material	Conductivity (W/m. K)	Density (kg/m^3)	Specific heat capacity (J/kg. K)
Brick (outer leaf)	0.84	800	1700
Brick (inner leaf)	0.62	800	1700
Plaster (dense)	0.50	1000	1300
Clay tile	1.00	800	2000
Roofing felt	0.19	837	960
Glazing	0.9	-	-
Polyisocyanurate	0.022	1470	45
Timber flooring	0.14	1200	650
Cast concrete	1.13	1000	2000
Carpet	0.06	1300	200
Plasterboard	0.25	896	2800
Painted oak (doors and windows)	0.19	2390	700

DesignBuilder models each building element as one or more layers of construction materials with a specific thickness. The U-value of each element was automatically calculated by DesignBuilder (Table 5-2).

Table 5-2: Construction elements of the test houses and their U-values and thicknesses of the materials used in each construction element

Building element	**Materials (outermost to innermost layer)**	**Thicknesses (outermost to innermost layer) (m)**	**U-value[1] (W/m^2K)**
External cavity walls	Brick, air gap, brick, dense plaster	0.105, 0.07, 0.105, 0.013	1.666
Internal partition walls	Plaster, brick, dense plaster	0.013, 0.105, 0.013	2.077
Party wall	Plaster, brick, air gap, brick, dense plaster	0.013, 0.105, 0.07, 0.105, 0.013	1.281
Ground floor (semi exposed)	Timber flooring, carpet	0.02, 0.005	2.015
Kitchen's solid floor	Cast concrete	0.1	3.35
Internal floor (between ground floor and first floor)	Plasterboard, air gap, timber flooring, carpet	0.013, 0.1, 0.02, 0.005	1.373
First floor ceiling (semi exposed)	Plaster board	0.013	3.1
Pitched roof	Clay tile, air gap, roofing felt	0.025, 0.02, 0.005	2.93
Glazing	Single glazing	0.003	5.894
Window Frame	Wooden (oak)	0.02	3.633
Window covered with insulation board	Glass, air gap, Polyisocyanurate	0.003, 0.01, 0.05	0.377
Doors (internal & external)	Wooden (oak)	0.044	2.034

[1] U-values were calculated by DesignBuilder for simple calculation methods such as SBEM

For the windows, 3 mm single layer clear glass was selected from DesignBuilder glazing type templates for the whole house model. Characteristics of the glazing material selected were presented in Table 5-3.

Table 5-3: Characteristics of the glazing in LMP1930 model

Type	**Conductivity (W/m K)**	**Solar transmittance (SHGC)**	**Outside/ inside solar reflectance**	**Visible transmittance**	**Outside/ inside visible reflectance**	**Outside/ inside emissivity**
3mm clear	0.9	0.837	0.075	0.898	0.081	0.84

Sub-surfaces in DesignBuilder define areas which have a different construction to that of the main. The windows on the East and West facades, which were covered from inside with insulation boards during the experiments, were modelled using a sub-surface with 3 layers: 3 mm glass, 10 mm air gap and 50 mm Polyisocyanurate insulation boards (thermal conductivity of 0.022 W/mK (Celotex, 2015)). The total U-value of the sub-surface was calculated as 0.377 W/m^2K (Table 5-2).

The blinds in the houses were modelled as a closed weave, medium coloured shade from the DesignBuilder database. The transmittance and reflectance characteristics matched those in the ASHRAE handbook of fundamentals (ASHRAE, 2009) (Table 5-4).

Table 5-4: Characteristics of the blinds material chosen for the model

Characteristics	Values
Thickness (m)	0.001
Conductivity (W/m-K)	0.1
Solar / visible transmittance	0.05
Solar / visible reflectance	0.3
Long wave emissivity	0.9
Long wave transmittance	0

5.3 Modelling the air flow

Air flows in buildings happen when there is a pressure difference between two points and a continuous flow path or opening which connects the points (Straube, 2008). In a naturally ventilated building, the pressure difference can be caused by wind and air density differences between the points due to their temperature difference (buoyancy or stack effect) (Straube, 2008).

EnergyPlus has three approaches to modelling the air flow in buildings: scheduled natural ventilation (SNV), Air Flow Networks (AFN) and Computational Fluid Dynamics (CFD). However, only two of them (i.e. SNV and AFN) could be used when the model is used for the purpose of predicting the energy consumption of the building. Each approach has its own advantages and disadvantages and one important decision was to select the most appropriate method of modelling air flows for this research. In order to test the suitability of the two air flow modelling approaches, both approaches were used to simulate the co-heating test and space heating trials and the results were compared with each other and the measured data.

5.3.1 Scheduled Natural Ventilation (SNV)

Scheduled natural ventilation is the simplest approach for modelling air flows. A design air infiltration rate for each zone is input directly in units such as flow per zone (m^3/s) or flow per zone floor area ($m^3/s\ m^2$) or flow per exterior surface area ($m^3/s\ m^2$) or air change rates per hour. EnergyPlus then modifies these design flow rates using equation (5-1).

$$Infiltration = I_{design} * F_{schedule} * (A + B|T_{zone} - T_{outdoor}| + C\ Wind\ speed + D\ Wind\ speed\ ^2) \tag{5-1}$$

Where:

I_{design} = specified infiltration of the zone as a design level

$F_{schedule}$ = schedule fraction which can modify the infiltration volume flow rate for each time step according to a defined schedule for each zone.

A= constant term coefficient with a default value of 1

B= temperature term coefficient with a default value of 0

$T_{zone} - T_{outdoor}$ = temperature difference between the zone and outdoor

C= velocity term coefficient with a default value of 0

D= velocity squared term coefficient with a default value of 0

As default EnergyPlus assumes the values of 1 for coefficient A and 0 for coefficients B, C and D which gives a constant volume of infiltration air flow under all conditions. According to EnergyPlus input output reference (US Department of Energy, 2013c) a detailed analysis is needed to determine a custom set of coefficients. Therefore, the default coefficients were not changed for LMP1930 model.

Measuring infiltration rates of the individual zones of the LMP1930 was not possible. Instead, the whole house infiltration rate, as measured during the airtightness test, was used in the model. DesignBuilder uses equation (5-2), sourced from BS EN 12831 (British Standards, 2013), to convert the whole house infiltration rate measured at 50 Pa to infiltration rate at normal operating conditions for each zone. Equation (5-2) uses a shielding coefficient (e) which takes into account the number of exposed openings in each zone and wind exposure and a height correction factor (ε).

$$\dot{V}_{inf,i} = 2.\ V_i.\ n_{50}.\ e_i.\ \varepsilon_i \qquad [m^3/h] \tag{5-2}$$

Where:

$\dot{V}_{inf,i}$ = infiltration air flow rate of heated space (i) induced by wind and stack effect on the building envelope

V_i= volume of heated space (i) in m^3 calculated on the basis of internal dimensions

n_{50}= air exchange rate per hour (h^{-1}), resulting from a pressure difference of 50 Pa between the inside and outside of the building

e_i= shielding coefficient obtained from Table 5-5. For the case of LMP1930 model, moderate shielding was set in the model.

ε_i= height correction factor which takes into account the increase in wind speed with the height of the space from ground level. ε_i=1 when the centre of zone height to ground level is below 10 m which was the case for all the zones in LMP1930 model.

Table 5-5: Shielding coefficient (e) reproduced from Table D.8 BS EN 12831 (British Standards, 2013)

Shielding class	e		
	Heated space without exposed openings	Heated space with one exposed opening	Heated space with more than one exposed opening
No shielding (buildings in windy areas, high rise buildings in city centres)	0	0.03	0.05
Moderate shielding (buildings in the country with trees or other buildings around them, suburbs)	0	0.02	0.03
Heavy shielding (average height buildings in city centres, buildings in forests)	0	0.01	0.02

As there was no significant difference between the infiltration rates measured in the two test houses (see section 3.3.6), the mean result (i.e. 21.75 ACH at 50 pa) was used in the model for the both houses.

The ventilation rates of the subfloor and the loft (attic) space could not be estimated by this method as they were not measured in the airtightness test. Measurements of the ventilation rates of suspended floors (either concrete or timber) are very limited (Hartless, 2004 & Edwards et al, 1990). In a study by Edwards et al. (1990), subfloor ventilation rates of a 45 m^2 low energy UK house was measured between about 0.1 to near 2 ACH for different wind speeds and wind directions. However, the total effective area of the air bricks was only 0.018 m^2 compared to 0.06 m^2 in the LMP1930 houses with the same floor area. Also the void depth was 1.0 m compared to 0.2 m for the LMP1930 houses. The smaller total effective area of the air bricks (about 1/3 of the total effective area of the LMP1930) and considerably larger volume of the void (about 5 times larger) in the house examined by Edwards et al (1990) suggests that the subfloor ventilation rates of the LMP1930 houses could be considerably higher in air changes per hour.

The only study which was found to report the measured ventilation rates beneath a suspended timber floor of a UK house with a similar void depth (i.e. 0.022 m compared to 0.02 m in LMP1930) and total effective area of air bricks (0.07 vs 0.06 m^2 in LMP 1930) reported that the subfloor ventilation rate was widely fluctuating; ranging from about 3 air changes per hour (ach) to over 13 ACH (Hartless & White, 1994). Hartless & White (1994) argues that the subfloor ventilation rate of the house examined was heavily influenced by the subfloor/external temperature difference rather than the wind speed. Infra-red thermography showed that the air was moving from the subfloor void to the gap behind the plasterboard in the walls due to a leakage path at the wall/floor junction. Hartless & White (1994) discussed that this problem has been also observed in other UK homes and could explain the high subfloor ventilation rates found in their study. However, there was no plasterboard used in the walls of LMP1930 test houses.

Considering the lack of comprehensive data regarding the subfloor ventilation rates, ventilation rate of 8 ACH which was the mean value of 3 and 13 ACH found as lower and upper limits of subfloor ventilation rate in Hartless's (1994) study was chosen in this study as the constant subfloor ventilation rate of both LMP1930 test houses.

Ventilation rates of loft (attic) spaces were measured in a number of studies; mainly in the US. Dietz et al. (1986) conducted detail multi-zone PFT gas measurements in a number of homes in the US and reported 3 ACH as “typical” for ventilation rate of loft spaces. I'anson et al. (1982) measured loft space ventilation rate of 4.3 ACH in a middle terraced three bedroom house using three tracer gases. The loft space of this house was ventilated by a continuous gap with 10 mm width behind the fascia board. Allinson (2007) modelled ventilated pitched roofs during low wind speed conditions in the UK and chose a ventilation rate of 2 ACH according to assumptions by Burch (1980). Sanders et al. (2006) developed a number of broad rules for estimating the loft ventilation based on a series of measurements of the ventilation rates of the houses (including loft) using tracer gas techniques which were conducted in about eighty properties in England and Scotland during 1970s and 1980s. According to this document, where the loft is not sealed, but with no eaves or ridge ventilators, the loft ventilation rate in air changes per hour (ACH) is approximately equivalent to the wind speed in m/s*.* This is similar to the case of the LMP1930 houses where there were no eaves or ridge ventilators. Therefore, the average wind speed during each test was used as the constant ventilation rate of the loft space of the LMP1930 test houses. The average wind speed measured during the co-heating test and heating trial 1 were 2.7 m/s and 4.0 m/s which suggested 2.7 and 4.0 ACH for the loft space ventilation rate of the LMP1930 houses during the co-heating test and heating trial 1 respectively. These were close to the suggested typical loft space ventilation rates measured or assumed in the other studies.

In SNV, the air exchange between zones through openings such as internal doors, windows or holes (i.e. stairs) is modelled using the concept of mixing where equal amounts of air are transferred from one zone to another and vice versa. It is not possible to model unidirectional air flow from one zone to another using this method. The design flow rate is the maximum air exchange between the two zones and is explicitly defined for each opening as flow rate per zone (m^3/s), flow rate per zone floor area ($m^3/s\ m^2$), flow rate per person or air changes per hour (ach). This maximum value is then modified by a schedule fraction which defines the operating schedule of the opening.

DesignBuilder’s default value of 0.1 $m^3/s.m^2$ was selected as the air flow rate per opening area which exchanges between each two adjacent zone through openings. The same value of 0.1 $m^3/s.m^2$ was also considered for the air flow rate per square meter of the opening which connected the lower storey to the upper storey. The opening has a measured area of 2.25 m^2. This value of 0.1 $m^3/s.m^2$ was automatically multiplied by the area of each opening by DesignBuilder to provide the air flow rate of each zone in m^3/s which is used in IDF file.

5.3.2 Air Flow Network (AFN)

A second, more detailed approach to modelling the air flows through a building is to establish an Air Flow Network (AFN). The AFN consists of a number of nodes connected by air flow components through surface linkages (Gu, 2007). Each heat transfer surface in a building, with both faces exposed to air, works as a surface linkage through which air flows (Gu, 2007).The associated air flow component for each surface can be one crack (or surface effective leakage area) at the average height of the surface, one opening in an exterior or interior window or door, or a horizontal opening. In EnergyPlus, each linkage surface specifies two connected nodes: two zone nodes based on inside and outside face environment for an interior surface, or a zone node based on inside face environment and an external node (US Department of Energy, 2013c). Since AFN assumes that air flows from one node to another, it simplifies airflows through its pathways and cannot predict internal air circulation within a thermal zone (Gu, 2007).

DesignBuilder was employed in this study to facilitate the process of defining the nodes and linkage surfaces via its “calculated natural ventilation” simulation option. The air flow through cracks in the walls, floors and the roof is calculated by AFN model as a function of the pressure difference across the crack according to power law in form of equation (5-3) (US Department of Energy, 2013c).

$$Q = (Crack\ Factor) *\ C_T * C_Q\ (\Delta P)^n \tag{5-3}$$

Where:

Q = air mass flow rate (kg/s)

Crack factor = multiplier for a crack

C_T = reference condition temperature correction factor (dimensionless)

C_Q = air mass flow coefficient (kg/sat1 Pa)

ΔP = pressure difference across crack (Pa)

n = Air flow exponent (dimensionless): The valid range is 0.5 for fully turbulent flow to 1.0, for fully laminar flow (US Department of Energy, 2013c).

Air flows through doors, windows and vents when they are open or closed are calculated by a similar method. When these openings are closed, AFN model automatically generates a crack around the perimeter of each opening. The air mass flow coefficient (C_Q) (kg/s at1 Pa) is calculated by multiplying the air mass flow coefficient (kg/s. crack length at1 Pa) by the length of the crack (i.e. the perimeter of the opening).

When these openings are open another form of the power law equation in form of equation (5-4) is used:

$$Q = C_d A \sqrt{\frac{2\Delta P}{\rho}} \tag{5-4}$$

Where:

Q = volume flow rate across the opening (m^3/s)

C_d = discharge coefficient (dimensionless); depends on the geometry of the opening and the Reynolds number of the flow

A = surface area of the opening (m^2); defined using an opening factor which defines the fraction of total surface area of an opening which is opened

ΔP = pressure difference across the opening (Pa)

ρ = air density (kg/m^3)

The air mass flow rate (kg/s) is then calculated by multiplying the volume flow rate by the air density. Bi-directional flows can be modelled for vertical openings when air is simultaneously moving in two directions depending on stack effects and wind conditions (US Department of Energy, 2013c).

EnergyPlus can also use AFN to model air flows through horizontal openings such as staircase. Horizontal openings can produce two-way flow when forced and buoyancy flows co- exists, however, AFN cannot model bi-directional flows at a given time step (US Department of Energy, 2013c)

The input variables required for establishing the AFN were: wind pressure coefficients (C_p), air mass flow coefficient (C_Q) (kg/s at1 Pa) and flow exponent (n) for each crack, air mass flow coefficient (C_Q) (kg/s. m crack length) and flow exponent (n) for the doors and windows when they are closed and discharge coefficient (C_d) for each opening at each opening factor. These are discussed in more detail below.

- **Wind pressure coefficients (C_p)**

AFN uses wind pressure coefficients (C_p) to calculate the wind driven pressure on the external surfaces of a building. Wind pressure coefficient values are required for each wind direction at an interval (for example: every 45 degrees) on each external surface. Sensitivity analysis by Cóstola et al. (2010) has shown C_p as one of the most influential input parameters on air change rate and thus several building performance indicators such as energy consumption and thermal comfort (Cóstola, Blocken & Hensen, 2009). The wind pressure coefficient is dependent on a number of factors including building geometry, facade detailing, position on the facade, the degree of exposure, wind speed and wind direction (Cóstola, Blocken & Hensen, 2009). Therefore, wind pressure coefficients are generally unknown, except in the case of very simple structures or extremely well studied buildings, and must be assumed which could significantly influence the accuracy of the air change rate calculations (ASHRAE, 2009).

Wind pressure coefficients could be obtained from full scale measurements or wind tunnel model tests of the specific site and building or via CFD (ASHRAE, 2009). However, full scale experiments are very complex and expensive. Alternatively, there are databases of C_p values which could be used as secondary sources of data. DesignBuilder is supplied with a database of wind pressure coefficients based on data from Liddament (1986) which is also reported in CIBSE guide A (CIBSE, 2006a) and is often used as a "*good first level of approximation for basic design purposes*" (DesignBuilder, 2014). The C_p data is for low rise buildings (i.e. buildings of 3 storeys or less) with square surfaces (aspect ratio 1:1) and for 3 levels of site exposure to wind: sheltered, normal and exposed. The data is given in 45° increments. In this study, C_p data was chosen from DesignBuilder's database considering normal site exposure. Figure 5-5 was adopted from CIBSE guide A (CIBSE, 2006) and shows the definition of surfaces in determining wind pressure coefficients.

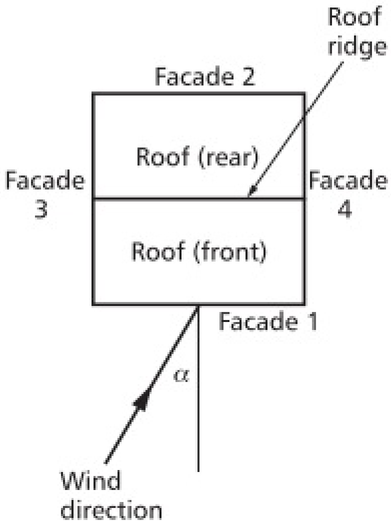

Figure 5-5: definition of surfaces in determining wind pressure coefficients (CIBSE, 2006)

Example of wind pressure coefficients over façade 1 and roof (front) for wind angels in 45º increments were presented in Table 5-6 (DesignBuilder, 2014). They were based on the slope of surfaces considering normal exposure of the site to wind and aspect ratio 1:1.

Table 5-6: Wind pressure coefficients over façade 1 and roof (front) for wind angles in 45º increments based on the slope of surfaces considering normal exposure of the site to wind and aspect ratio 1:1 (DesignBuilder, 2014)

Wind angel to surface	**Vertical**	**Slope<=10º**	**Slope 11-30º**	**Slope 31-89º**
0º	0.4	-0.6	-0.35	0.3
45º	0.1	-0.5	-0.45	-0.5
90º	-0.3	-0.4	-0.55	-0.6
135º	-0.35	-0.5	-0.45	-0.5
180º	-0.2	-0.6	-0.35	-0.5
225º	-0.35	-0.5	-0.45	-0.5
270º	-0.3	-0.4	-0.55	-0.6
315º	-0.1	-0.5	-0.45	-0.5

- **Air mass flow coefficient (C_Q) (kg/s at 1 Pa) and flow exponent (n) for each crack**

AFN requires air mass flow coefficient (C_Q) (kg/s) at a reference condition (temperature, pressure and humidity) for each crack in internal and external walls, floor/ceiling and roof defined at 1 pa pressure difference across the crack. Gaps and cracks in the building fabric cannot be accurately characterized by visual inspection as the leakage paths are often obscured by internal finishes or external cladding and are hard to follow (ATTMA, 2010). Although the air tightness of the test houses were measured at 50 Pa, it was not possible to use these values directly in the model when using AFN.

DesignBuilder uses a simplified approach which defines one crack for each surface of the building. The characteristics of these cracks are defined in DesignBuilder crack templates. There are five crack templates in DesignBuilder: Very poor, poor, medium, good and excellent which can be selected according to the leakiness level of the building under study. Since the air permeability test proven an indication of poor air tightness of the test houses (see section 3.3.6), data corresponding to “poor” crack template was chosen for the model. The crack templates has air mass flow coefficient per square meter of each surface (kg/s.m^2) at1 Pa (Table 5-7) which provides the air mass flow coefficient (C_Q) (kg/s) required in EnergyPlus by multiplying the flow coefficient per square meter of the surface by the surface area (Table 5-7). In addition, DesignBuilder’s crack templates have flow exponents (n) (equation (5-3)) for internal and external walls, floor/ceiling and roof (Table 5-7).

Table 5-7: Crack characteristics according to DesignBuilder's "poor" crack template used in the model for walls, floors and the roof

Building element	**Air mass flow coefficient (C_Q) (Kg/s.m^2) at 1Pa**	**Flow exponent (n)**
External walls	0.0002	0.7
Internal walls	0.005	0.75
Internal floors	0.002	0.7
External floors	0.001	1.0
Roof	0.00015	0.7

- **Air mass flow coefficient (C_Q) (kg/s. m crack length) and flow exponent (n) for the doors and windows when they are closed**

DesignBuilder also provides the air mass flow coefficient (C_Q) (kg/s. m crack) at1 Pa and flow exponent (n) for the cracks around the perimeter of these openings on the same five point scale (Table 5-8).

Table 5-8: Crack characteristics according to DesignBuilder's "poor" crack template used in the model for the doors, windows and vents

Building element	**Air mass flow coefficient (C_Q) (Kg/s. m) at 1Pa**	**Flow exponent (n)**
External windows	0.001	0.6
External doors	0.0018	0.66
Internal doors	0.02	0.6
External vents	0.01	0.66

- **Discharge coefficients (C_d)**

Discharge coefficient is difficult to determine and experimental values which has found for discharge coefficient varies from 0.3 to 0.8 and without a clear understanding of what causes these differences (International Energy Agency, 1992).

CONTAMW which is a multi-zone air flow and contaminant transport analysis software developed by US department of commerce (Dols & Walton, 2002) suggests a discharge coefficient of 0.6 for orifices and slightly higher for large openings in buildings. ASHRAE (ASHRAE, 2009) propose the correlation based on inter zone temperature differences as in equation (5-5) for the range of ΔTs from 0.5 to 40ºC:

$$\mathrm{Cd} = 0.4 + 0.0045\,\Delta\mathrm{T} \tag{5-5}$$

DesignBuilder's help documentation notes that "*given other uncertainties in natural ventilation calculations (wind pressure coefficients, effective areas of real-world openings and crack flows etc.), using a discharge coefficient between 0.60 and 0.65 should provide sufficient accuracy*" (DesignBuilder, 2014). Discharge coefficient of 0.65 was selected for all the openings including the horizontal openings and both opening factors.

5.4 Modelling the heating systems

This section describes the methods for modelling the heating systems for the co-heating test (section 5.4.1) and the HT1 (section 5.4.2).

5.4.1 Modelling the heating system for the co-heating test

The co-heating test (see section 3.3.6) was modelled using electric convectors with 100% efficiency in every zone of the LMP1930 building envelope model (except the unheated loft (attic) and subfloor zones). The average air temperature measured during the co-heating test in each zone was used as the set-point temperature of that zone in the model (Table 5-9).

Table 5-9: Measured average air temperature in different zones during the co-heating test; theses temperatures were used as the set-point temperature of each zone in the DTM when modelling the co-heating test

Zone	House 1 Set-point temperature (°C)	House 2 Set-point temperature (°C)
Living room	24.32	24.40
Dining room	24.64	24.10
Kitchen	25.15	24.29
Hallway ground floor	24.00	24.16
Hallway first floor	24.67	24.48
Bedroom 1	24.62	24.82
Bedroom 2	24.67	23.35
Unoccupied bedroom	24.83	24.43
Bathroom	23.53	24.20
Volumetric weighted Average for the whole house	24.50	24.82

Electricity used by circulation fans during the co-heating test was considered to end up as heat in the zone, thus there was no need to model these separately.

5.4.2 Modelling the heating systems for the space heating trials

The gas powered central heating systems were modelled to simulate the HT1: one with CC and the other one with ZC. Each heating system consisted of a gas fired condensing combination boiler and 7 radiators as described in section 3.3.4 (Table 3-3). They were modelled for each house using DesignBuilder's detailed HVAC option.

The condensing combination boilers were modelled with nominal heat output of 30 kW and mean efficiency of 84.2% and 85.7% as measured during the HT1 (see section 4.5). The normalized boiler efficiency curve of condensing combination boilers was selected from DesignBuilder's template library. The circulating hot water flow temperature was set to maximum during the HT1 which is 88°C according to the manufacturer's data (Worcester Bosch Group, 2009). In DesignBuilder, the hot water flow temperature in a wet heating system is controlled via a set-point manager which controls the hot water flow temperature according to a schedule. This was set to be always 88ºC.

Radiators were modelled using the water baseboard heater model of EnergyPlus enabling both convection and radiation heat transfer. The water mass flow rate of each radiator supplied from the primary system is calculated at each time step by determining the impact of radiator on surrounding air via convection and to the surfaces by radiation (US Department of Energy, 2012).

There will be water flow rate and therefore heat transfer from the radiator when all of the three following criteria are met: firstly, the radiator unit is "on" at that time step; secondly, there is any heat requirement remaining in the zone to be met according to the zone's set-point temperature and finally the boiler is "on" according to its schedule.

The water baseboard heater model requires a number of inputs: rated average water temperature (°C), rated water mass flow rate (kg/s) and rated capacity (W).

According to the radiators' manufacturer data: rated average water temperature was 70°C and the rated water mass flow rate (kg/s) of each radiator was calculated using equation (5-6):

$$m = H/(C_p * (t_f - t_r)) \tag{5-6}$$

Where:

m= rated water mass flow rate (kg/s)

H= rated capacity of radiator (W) selected from Table 3-3 according to the manufacturer's data

C_p= specific heat capacity of water and was approximated as 4187 J/kg.°C for the purpose of calculating water flow in radiators

t_f = standard water flow temperature (°C) = 75°C

t_r = standard water return temperature (°C) = 65°C

The radiant fraction of the radiators is the portion of the power input transferred to the occupants and surfaces as radiant heat and was considered to be 0.3 for all the radiators according to Oughton & Hodkinson (2008).

A constant speed pump was modelled for the circulating hot water supply loop of each house with a maximum loop flow rate of 0.00034 m^3/s and minimum loop flow rate of zero and a rated pump head of 6000 pa according to the specifications of the central heating pumps in the houses. The control type of the pump was selected as intermittent control. This enabled the modelled pump to shut down when no heating was required. When there was heat demand, the pump selected a flow rate somewhere between the maximum and minimum user defined flow rates in order to meet the heating requirements. Rated energy consumption of the pumps was left as “autosize” and default value of 0.9 was selected for the motor efficiency of the pumps as the electricity consumption of the houses was not studied in this research.

All the pipes in the system were assumed to be adiabatic. There was no information available regarding the pipe run in the houses and obtaining more information required removing a large amount of the floor boards on the ground and first floors which was not possible to do in this work.

The Programmable Room Thermostat (PRT) (see section 4.3) was modelled using the boiler operation availability schedule of DesignBuilder’s circulating hot water loop data. The radiators availability schedules were set to be always “on”.

The default control strategy of a wet heating system in a multi zone building model in EnergyPlus and DesignBuilder is that each zone has its own room thermostat which could be scheduled to assign set-point and set-back temperatures throughout a day. However, this control strategy of the heating system is inherently different from the control strategy in houses with either CC or ZC where boiler operation was controlled by a PRT located in the hallway and set-point and set-back temperatures (only in ZC) for each room are applied by TRVs (in CC) or PTRVs (in ZC). Currently, there is no solution in DesignBuilder in order to better represent the control strategy in multi zone houses with a PRT control over the boiler and overcome the problem discussed. However, Energy Management System (EMS) which is an advanced feature of EnergyPlus enables one to write custom programmes to describe specific control algorithms in a language called EnergyPlus Runtime Language (ERL) (US Department of Energy, 2013a). Such code could be added directly to the EnergyPlus's IDF file to override the existing default control. An ERL code was initially written for this purpose which could be found in appendix A.2. The code was written in order to shut down the hot water supply from the boiler at any time step when the air temperature in the ground floor hallway (where PRT was located) increased above its set-point temperature of 21 °C. However, it was found that adding such code to better represent the control strategy requires accurate predictions of the air temperature. As it will be discussed in sections 6.3 and 6.4, it was not possible to accurately predict the hallway ground floor air temperature due to complexities involved with modelling the air flow between the ground floor and first floor hallways. Therefore, after running a number of simulations and compare the predictions with the default control strategy, it was decided not to use the ERL code as it could not increase the accuracy in this case when the air temperatures could not be accurately predicted.

5.5 Modelling the occupancy

There was no occupancy during the co-heating test. All the internal doors in the model were set 100% open while all the windows and external doors were set 100% closed as was the case throughout the co-heating test. All window blinds were modelled open for the whole simulation period as it was during the test.

Modelling the occupancy for the HT1 was also straightforward as the synthetic occupancy presented was fully known. The electricity use measured in each zone was used to model the lighting and equipment gains in the modelled zone. The fan heaters used to represent heat gains in the kitchen were added as electric equipment with 100% convective heat. The oil filled radiators were also added as electric equipment but with a radiant fraction of 0.3. All the other lighting devices were added as lights with 0.42 radiant and 0.18 visible fractions.

All the external doors and windows were closed for the whole simulation period and the operation of the internal doors were set in the model according to their operation in real test houses described in section 3.3.5. Operation schedule of the window roller blinds were set according to their real schedule explained in section 3.3.5.

5.6 Weather file Construction

It is important that the weather parameters in the model represent the real weather conditions at the test houses during the experimental period for comparing the model predictions and the measured data from the experiments. The EnergyPlus weather converter programme was used to create weather files for the test periods. Hourly data derived from weather stations were: dry bulb temperature (ºC), dew point temperature (ºC), relative humidity (%), atmospheric pressure (pa), direct normal solar radiation (Wh/m^2), diffuse horizontal solar radiation (Wh/m^2), wind direction (degree), wind speed (m/s), total sky cover (tenth) and snow depth (cm).

Weather parameters required were measured on site or sourced from either: the Centre for Renewable Energy Systems Technology (CREST) weather station at Loughborough University, 2 km from the test houses; Sutton Bonnington, 7.5 km from the test houses; or Nottingham Watnall (26 km from the test houses). Sutton Bonnington and Nottingham Watnall weather data for the period of experiments were sourced via MIDAS Land Surface Observation database at the British Atmospheric Data Centre (BADC) operated by the UK Meteorological Office (2012).

Hourly dry bulb temperature was measured outside the test houses during all tests (see section 4.2). Hourly dew point temperature, wind speed, wind direction and humidity were sourced from Sutton Bonnington weather station. Cloud cover and atmospheric pressure data were sourced from Nottingham Watnall. Hourly Wind speed in Knots and the amount of cloud cover in Oktas[13] were converted to m/s and tenths respectively. The following criteria were used to convert the amount of cloud cover in Oktas to tenth (BADC, 2014):

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[13] Although cloud amount has been measured in eighths (or Oktas) since 1949 (BADC, 2014), EnergyPlus still uses the old format of cloud cover data (i.e. tenths of coverage).

Table 5-10: Conversion factors of cloud cover from Oktas to tenth

Value in Oktas	0	1	2	3	4	5	6	7	8
Equivalent value in tenths	0	2	3	4	5	6	8	9	10

Direct Normal Radiation (DNR) is the amount of solar radiation in Wh/m^2 received directly from the solar disk on a surface perpendicular to the sun’s rays; Diffuse Horizontal Radiation (DHR) is the amount of solar radiation in Wh/m^2received from the sky (excluding the solar disk) on a horizontal surface, and the Global Horizontal Radiation (GHR) is the total amount of direct and diffuse solar radiation in Wh/m^2received on a horizontal surface.

Hourly GHR and DHR were measured at Centre for Renewable Energy Systems Technology (CREST) at Loughborough University and used to derive DNR.

DNR can be calculated for each hour from GHR and DHR measurements using equation (5-7):

$$DNR = \frac{GHR - DHR}{\cos(\theta_z)} \tag{5-7}$$

Where:

θ_z = solar zenith angle and can be calculated using equation (5-8):

$$cos\theta_z = cos\emptyset cos\delta cos\omega + sin\varphi sin\delta \tag{5-8}$$

Where:

$\emptyset$ = latitude for the location where the test houses were located.

δ = solar declination and can be calculated according to equation (5-9):

$$\delta = 23.45 \sin\left(360 * \frac{284 + n}{365}\right) \tag{5-9}$$

Where:

n = day of the year.

ω = solar hour angle which is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15º per hour; morning negative, afternoon positive.

In this research DNR was automatically calculated using the weather converter programme of EnergyPlus by inserting GHR and DHR. Snow depth was considered as zero since there was no snow on the ground during the period of the experiments. Table 5-11 summarizes the sources of weather data used in this study.

Table 5-11: Summary of hourly weather parameters, their units and sources of data

Parameter	**unit**	**Source**
Dry bulb temperature	ºC	Measured locally outside the test houses
Dew point temperature	ºC	Sutton Bonnington weather station
Relative humidity	%	Sutton Bonnington weather station
Global horizontal radiation	W/m^2	Measured at Loughborough university campus, CREST
Direct normal radiation	W/m^2	Derived from global and direct normal horizontal radiation using EnergyPlus weather converter programme
Diffuse horizontal radiation	W/m^2	Measured at Loughborough university campus, CREST
Wind direction	Degree	Sutton Bonnington weather station
Wind speed	Knots	Sutton Bonnington weather station
Total sky cover	Oktas	Nottingham Watnall weather station
Snow depth	cm	Considered as zero for the whole tests period
Atmospheric Pressure	Hecto Pascals	Nottingham Watnall weather Station

These parameters were inserted into a CSV file which then was imported in EnergyPlus weather convertor programme to generate the EPW file. Latitude, longitude and elevation of the test houses were found using Google earth (2015) and inserted in a separate “definition” (.def) file. This definition file should be saved with the same name as the CSV file and is needed by the weather converter programme for the conversion process.

5.7 Summary

This chapter described the dynamic thermal modelling tools, techniques and the input parameters which were used to model the co-heating test and the space heating trial 1 (HT1). This included modelling the building envelope of the test houses, the air flow modelling strategies employed, the heating systems used during the tests and their control strategies as well as occupancy profiles. It also describes the method used to construct a weather file which was used to simulate the co-heating test and the HT1 including the weather parameters used and their sources. The results from modelling the co-heating test and the HT1 will be compared in chapter 6.

6 Comparison of the DTM predictions and measurements: DTM calibration

6.1 Introduction

In this chapter, the results from modelling the co-heating test and HT1 are compared to the experimental results. Firstly, in section 6.2, the energy uses measured during the co-heating test are compared to those predicted using each air flow modelling strategy. Then in section 6.3 the measured and predicted energy uses and indoor air temperatures of the LMP1930 test houses during the HT1 are compared. Section 6.4 describes the calibration procedure which was conducted to achieve a calibrated model. Finally, section 6.5 provides a summary of this chapter.

6.2 Comparison for the co-heating test

In this section, the measured energy use of the houses during the co-heating test are compared with the energy use predicted using the model with Scheduled Natural Ventilation (SNV) (section 6.2.1) and Air Flow Networks (AFN) (section 6.2.2).

6.2.1 Model with SNV

The total hourly electricity consumption predicted by the model for each house was compared to that measured during the 9 days of the co-heating test (Figure 6-1). The comparison showed that the predictions have a similar trend to the measurements. In both cases the electricity use decreases when the outdoor air temperature increases and vice versa. A strong negative relationship between the amount of hourly global horizontal solar radiation (W/m^2) and electricity use of the test houses was observed (Figure 6-2). During the daytime, when the solar radiation was at its peak, the energy consumption dropped to its minimum for that day. Generally, during the days when the solar radiation was higher, the outdoor air temperature was also higher and the energy consumption was lower compared to days when the solar radiation was lower. During the night, when there was no solar gain, the temperatures dropped and the amount of energy use was considerably increased.

In House 1, some discrepancies were found between the predictions and the measurements of energy use during days 7 and 8 where the model underestimated the energy use (Figure 6-1). The average wind speed during day 7 and day 8 were 4.6 m/s and 3.2 m/s, respectively, compared to the average wind speed of 2.3 m/s for the rest of the co-heating period (Figure 6-3). Therefore, the discrepancies could be explained as when the wind speed is higher, the rate of heat loss through infiltration increases while the model assumed the same rate of infiltration regardless of the wind speed.

For House 2, Figure 6-1 shows that the model slightly overestimates the energy use for the whole period. This is in line with the results of the co-heating test in section 3.3.6, where it was found that the total heat loss coefficient of the House 2 was 5.6% lower than House 1. By assuming the same construction for both houses in the model, the predicted energy use of the house 2 was higher during the co-heating test due to its lower total heat loss coefficient. It was important to model the houses with the same construction as it was not clear which parts of the fabric are responsible for the differences observed. It was unlikely that every part of the fabric contributed the same to the whole house better thermal performance.

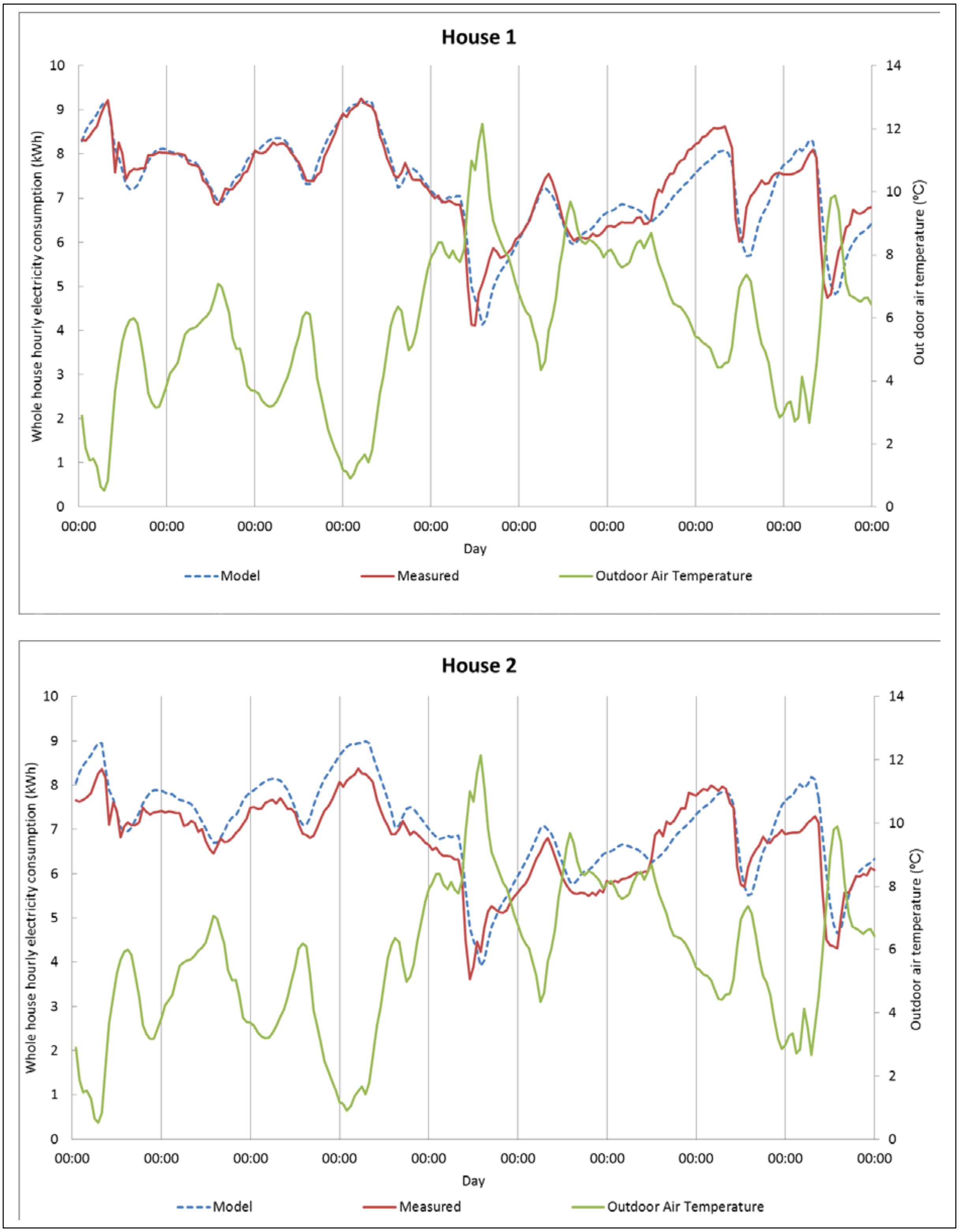


Figure 6-1: Whole house hourly electricity consumption measured in House 1 and 2 compared with the model prediction along with the hourly outdoor air temperature (SNV)

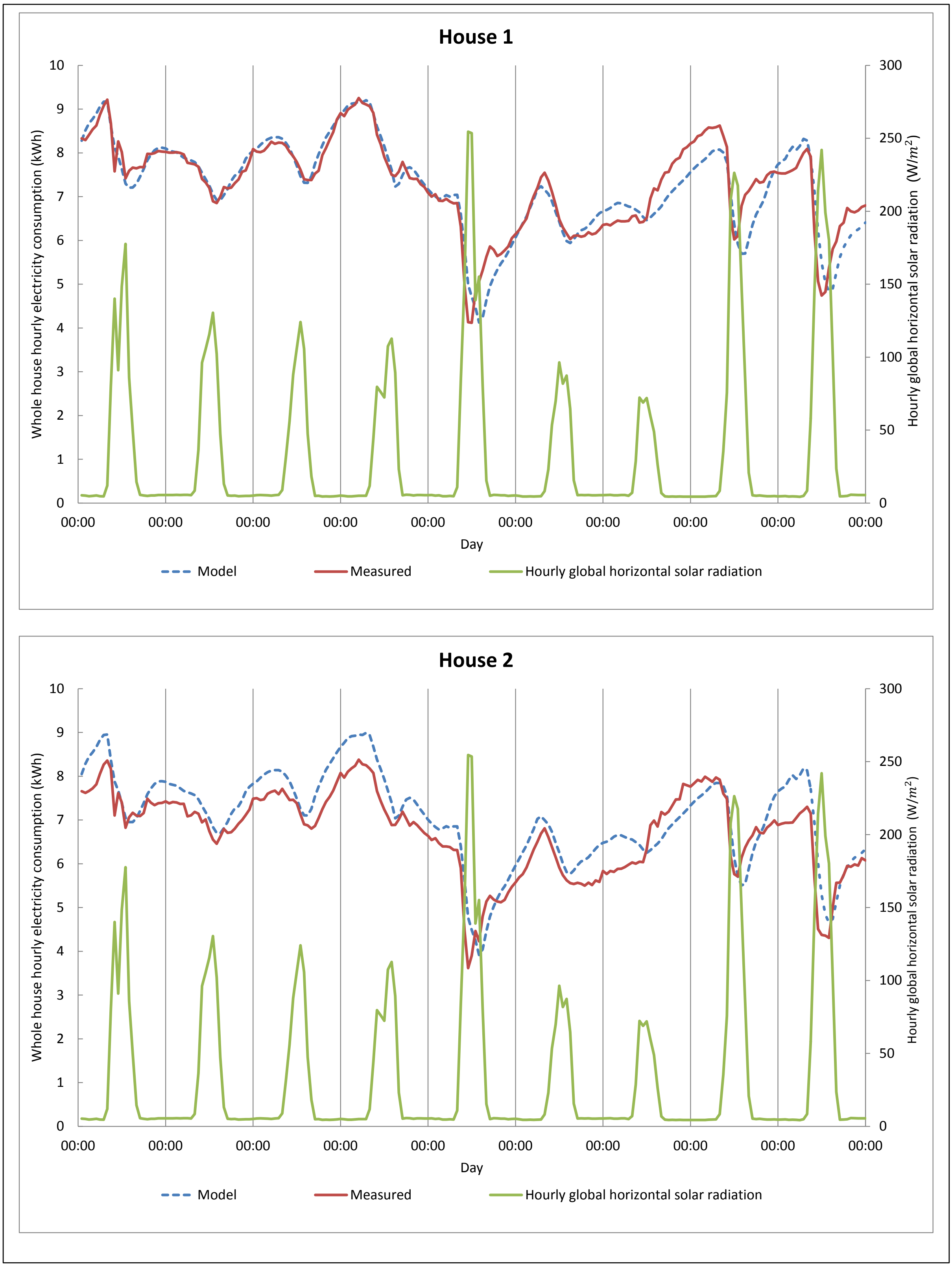


Figure 6-2: Whole house hourly electricity consumption measured in House 1 and 2 compared with the model prediction along with the hourly global horizontal solar radiation (SNV)

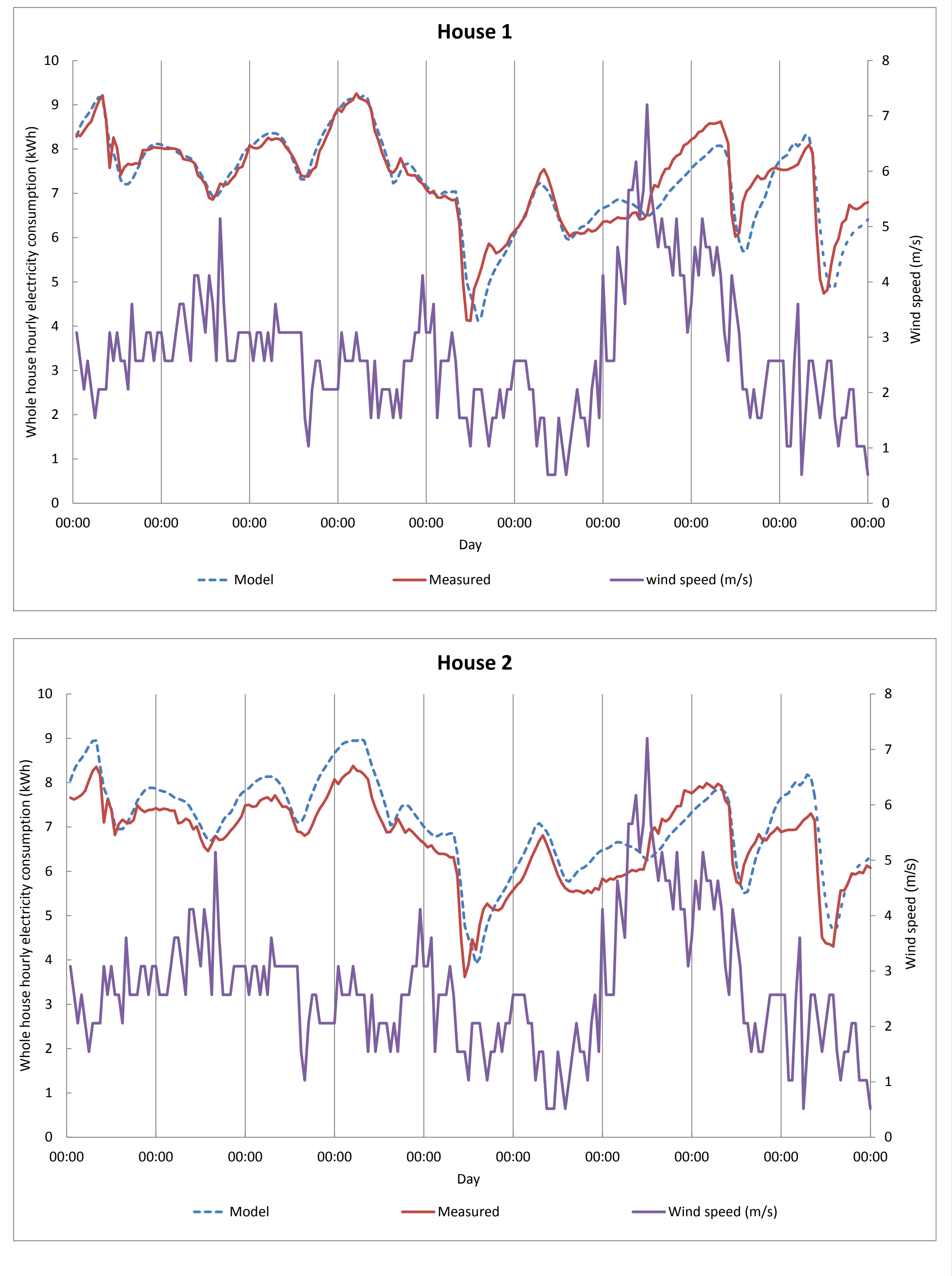


Figure 6-3: Whole house hourly electricity consumption measured in House 1 and 2 compared with the model prediction along with the hourly wind speed (SNV)

The infiltration rate of each zone in the ground and first floors was calculated by DesignBuilder as described in section 5.3.1 according to equation (5-2). The underlying assumptions of the calculation method were reflected in the results. Infiltration rate of the zones with more than one exposed surface including living rooms, hallway ground floors, kitchens, bedroom 2, unoccupied bedrooms and bathrooms were calculated as 1.3 ACH while this was calculated as 0.9 for the zones with only one exposed surface including dining rooms, bedroom 1, hallway first floors and WCs. The infiltration rates of the subfloors and the roof were 8.0 and 2.7 ACH, respectively, as they were explicitly defined.

The difference between daily electricity use predicted by the model and the measured daily electricity use varied from -6% to +1% for House 1 and from -1% to +8% for House 2 (Figure 6-4). On average, for the whole co-heating test period, the difference between daily electricity consumption predicted and measured was 0.1% and 4.8% in House 1 and 2, respectively.

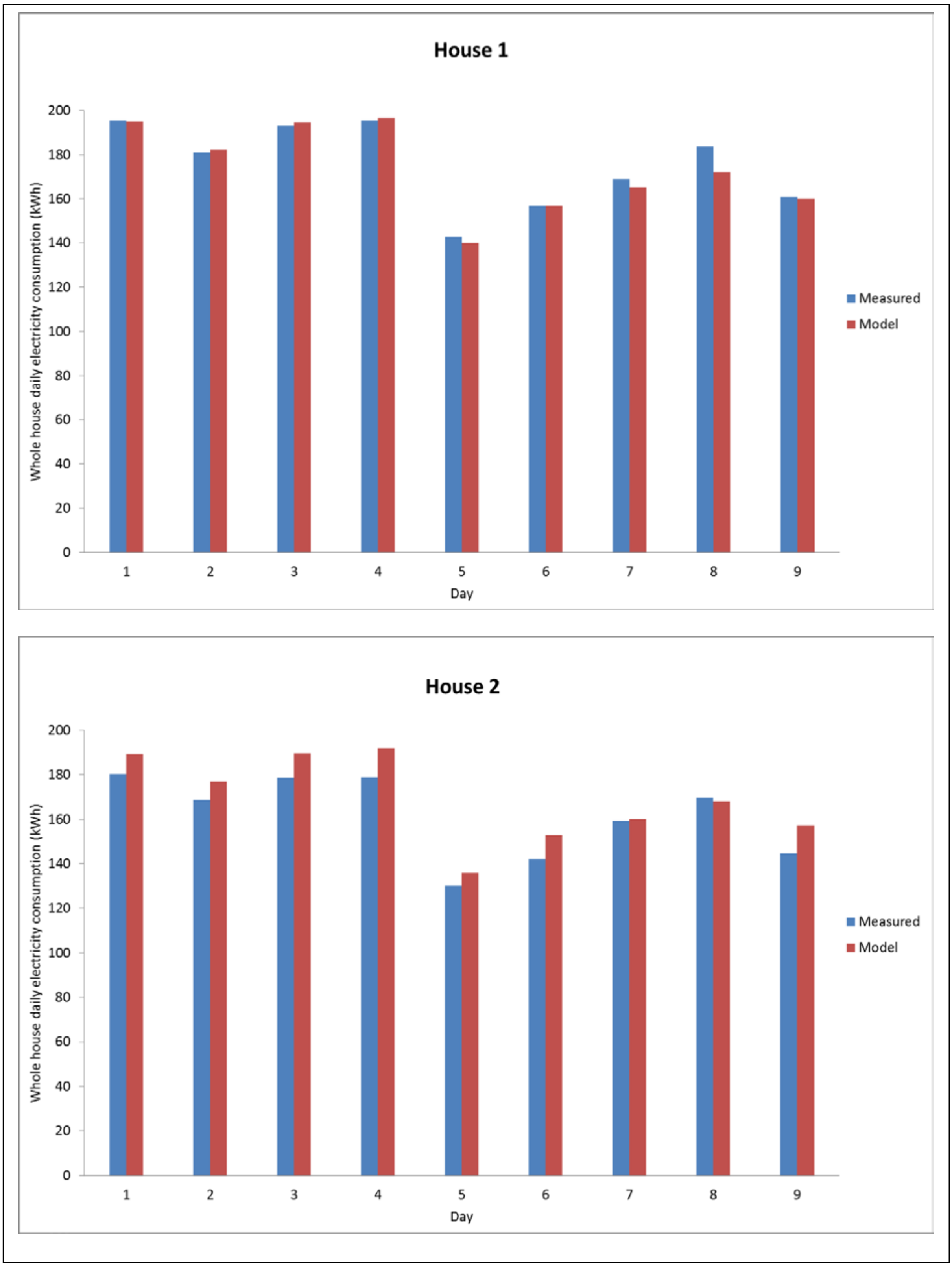


Figure 6-4: Measured and predicted whole house daily electricity consumption in House 1 and 2 during the co-heating test (SNV)

The ASHRAE acceptance criteria for the calibration of building simulation models described in section 2.7.3 showed that the models of both houses met the requirements for both criteria of MBE and CVRMSE (Table 6-1).

Table 6-1: MBE (%) and CVRMSE (%) calculated and their acceptable limit (co-heating test with SNV)

	House 1	**House 2**	**Acceptable limit**
MBE (%)	0.9%	4.9%	10%
CVRMSE (%)	5.4%	7.9%	30%

6.2.2 Model with AFN

The model was re-run using AFN instead of SNV. The predicted room by room infiltration rate and the whole house infiltration rate was not comparable to the model in SNV or measured results from the airtightness test. This was due to the different methodology of AFN for calculating air flows compared to SNV. In AFN, for each crack or opening in any exterior surface, the model predicts the air volume flow rate from outdoors to the thermal zone associated with that specific crack or opening. In addition, AFN reports the air volume flow rates in the reverse direction (i.e. from a thermal zone to outdoors). AFN also reports the air volume flow rates from each zone to its adjacent zones through interior surfaces (inter-zone air flow). These air volume flow rates in AFN are not constant like SNV and they change from one time step to another according to the variations in the wind and stack effects.

In total, there were more than 200 cracks and openings in the LMP1930 model. Hourly air flows from outdoors to each zone (m^3/hr) was calculated as the sum of hourly air flows (m^3/hr) in the direction of outdoors to indoors through all the cracks and openings in all exterior surfaces of the zone. An average air infiltration rate (ach) for the co-heating test period was achieved for each zone by averaging the hourly air flows from outdoors to the zone divided by the volume of the zone. Similarly, an average exfiltration rate (ach) for the co-heating test was calculated for each zone considering the air flows in the reverse direction (i.e. from the thermal zones to outdoors). The average infiltration and exfiltration of each zone of the LMP 1930 test houses during the co-heating test period were reported in Table 6-2.

Table 6-2: Zone by zone average infiltration rate and exfiltration rate for the LMP1930 test houses calculated by AFN

Zone	House 1		House 2	
	Average infiltration rate (ach)	**Average exfiltration rate (ach)**	**Average infiltration rate (ach)**	**Average exfiltration rate (ach)**
Living room	0.23	0.37	0.23	0.37
Dining room	0.55	0.05	0.56	0.04
Kitchen	1.65	0.25	1.2	0.4
Hallway	2.02	0.18	1.54	0.26
Hallway first floor	0.02	1.28	0	0.8
Bedroom 1	0	0.6	0	0.6
Bedroom 2	0	1.7	0	1.7
Unoccupied room	0.15	2.15	0	2.3
Bathroom	0.02	1.88	0	1.9
WC	0	3.5	0	2.1
Subfloor	21	0	21	0
Roof	0	2.1	0	2.1

As it can be seen from Table 6-2, the AFN predicted that the air was coming from outdoors to inside the building mainly through the subfloor air bricks and the ground floor cracks and openings. Average infiltration rates of near to zero for the rooms at the first floor and the roof, show that the amount of air which flows from outdoors to indoors through the first floor rooms and the roof is negligible. The air was mainly escaping to outside through the cracks in the exterior surfaces of the first floor and the roof.

The AFN predictions of how the air was flowing in the LMP1930 houses during the co-heating test proved the significant effect of stack ventilation compared to wind induced ventilation. The indoor air at temperatures of about 25°C maintained during the co-heating test was considerably warmer and thus less dense than the colder outdoor air. This causes a significant pressure difference during the whole period of the co-heating test in which the air entering the building was continuously heated. The warm, less dense air which was trying to rise and escape from the cracks at higher levels of the building (i.e. first floor and the roof) was drawing the cold dense air into the cracks at the lower levels (i.e. subfloor and the ground floor) (Figure 6-5).

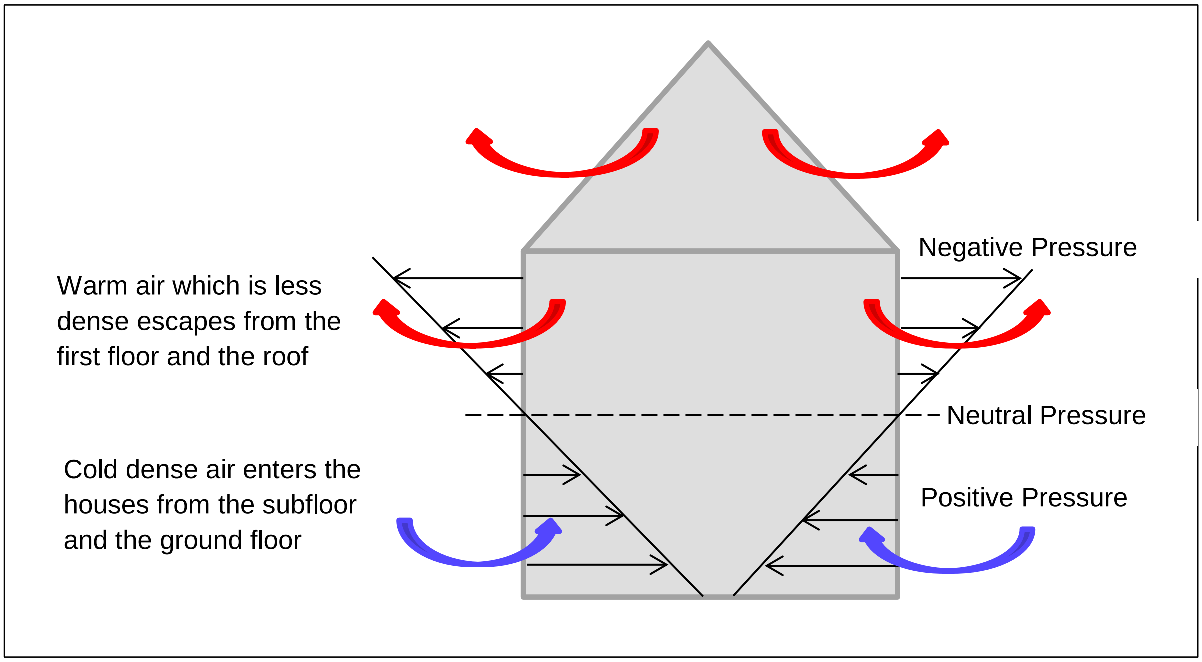


Figure 6-5: Schematic of the pressure distribution and the air flows in the LMP1930 test houses during the co-heating test

The energy use predictions by the AFN model were compared with the measurements in the same way as the predictions from the model with SNV (Figure 6-6). The AFN model underestimated the hourly electricity consumption during the whole co-heating test period for both houses. The calculated MBE and CVRMSE were higher than for the model with SNV (Table 6-3). However, the energy use predictions of the model still met the ASHRAE calibration criteria for both houses.

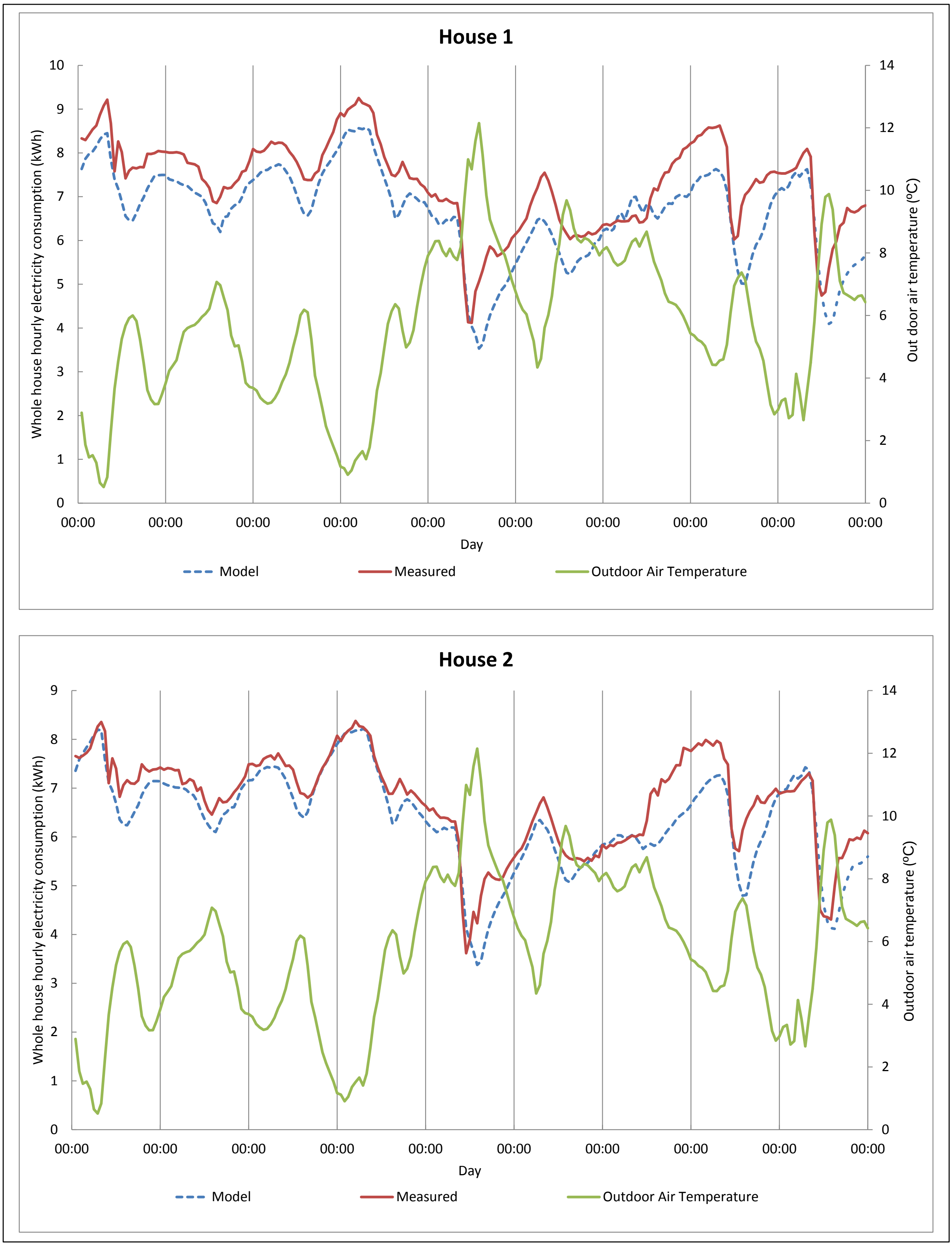


Figure 6-6: Whole house hourly electricity consumption measured in House 1 and 2 compared with the model prediction along with the hourly outdoor air temperature (AFN)

Table 6-3: MBE (%) and CVRMSE (%) calculated and their acceptable limit (Co-heating test with AFN)

	House 1	House 2	Acceptable limit
MBE (%)	9.0%	5.4%	10%
CVRMSE (%)	10.7%	8.0%	30%

Comparing the results of the models with SNV and AFN, it was concluded that in this case, AFN was better able to represent wind pressures and the stack ventilation effects. However, the magnitude of air flows and the overall building heat transfer was better represented by SNV based on the energy demand results. It was not possible to determine if this would also be the case for an intermittently heated building as in the HT1. Therefore, both air flow modelling strategies were employed to simulate the HT1 and the results compared.

6.3 Comparison for the Heating Trial 1

In this section, the measured and modelled energy demands (section 6.3.1) and indoor air temperatures (section 6.3.2) of the houses during the HT1 are compared and the potential reasons for any discrepancies are discussed.

6.3.1 Comparison of the energy demands

Daily boiler heat output measured during the HT1 was compared with model predicted daily boiler heat output using both air flow modelling strategies (Figure 6-7and Figure 6-8). In the house with ZC (Figure 6-7) the predicted daily boiler heat outputs with either of the air flow modelling strategies were lower than the measured daily boiler heat output for the majority of the days. For the whole HT1, the model with SNV under-predicted the total boiler heat output in the house with ZC by 8% while the model with AFN under-predicted by 23%.

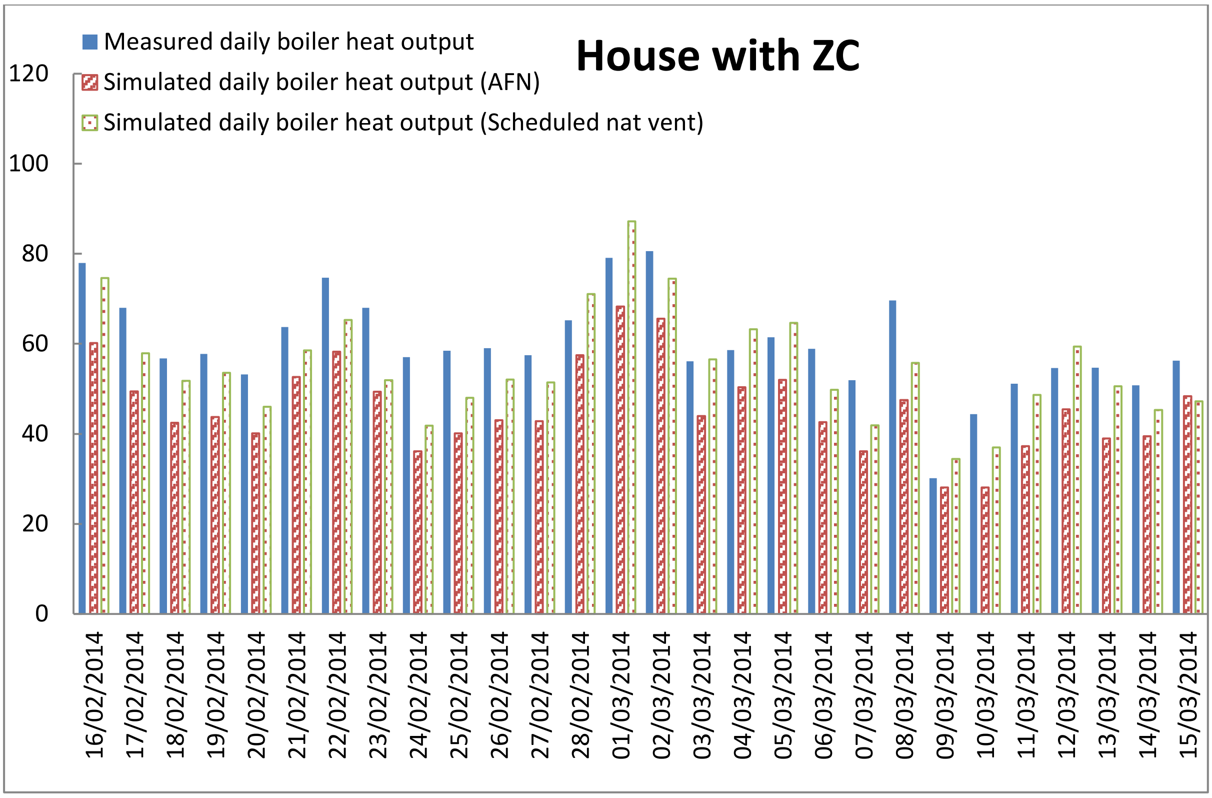


Figure 6-7: Measured and predicted daily boiler heat output during Heating Trial 1 in house with ZC

In the CC house (Figure 6-8), model predictions were closer to the measured boiler heat outputs. As for the house with ZC, the model with SNV predicted higher daily boiler heat outputs than the model with AFN. The difference between the measured and predicted boiler heat demand in the house with CC was 0.5% and 11% for the models with SNV and AFN respectively.

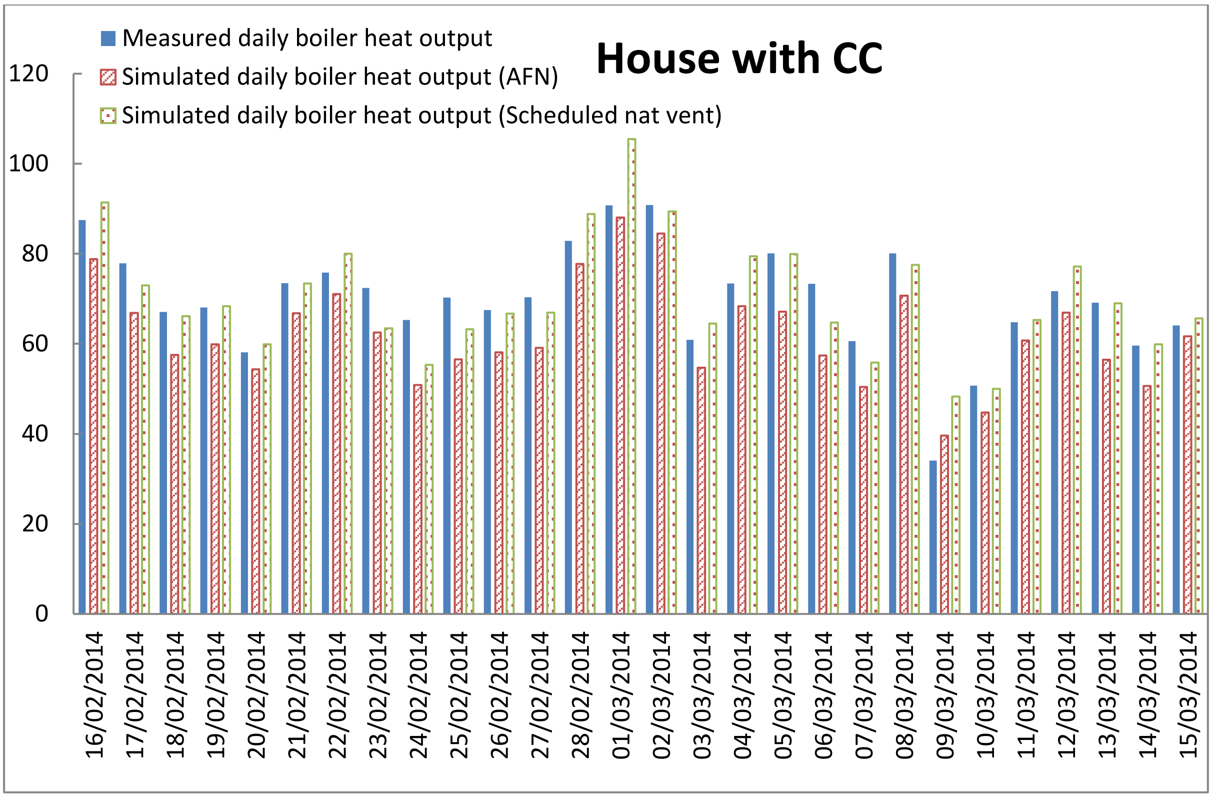


Figure 6-8: Measured and predicted daily boiler heat output during Heating Trial 1 in house with CC

Hourly analysis of the predicted and measured boiler heat outputs showed that none of the models could be considered calibrated according to ASHRAE hourly calibration criteria (Table 6-4). Although MBE (%) calculated for both houses were within the 10% limit for the model with SNV (8% and -0.4% for the house with ZC and CC respectively), they exceeded the limit for both houses using the model with AFN (23% and 11% for the ZC and CC house respectively). CVRMSE (%) calculated for both houses were above the 30% accepted limit using SNV and AFN.

Table 6-4: MBE (%) and CVRMSE (%) calculated for each house and their acceptable limit using each air flow modelling strategy

		SNV	**AFN**	**Acceptable limit**
ZC House	MBE (%)	8%	23%	10%
	CVRMSE (%)	35%	45%	30%
CC House	MBE (%)	-0.4%	11%	10%
	CVRMSE (%)	39%	44%	30%

Lower energy consumption in rooms with a radiator was predicted by most building energy simulation programs tested by Lomas et al. (1997) in the International Energy Agency (IEA) report.

The energy savings in boiler heat output of ZC predicted by the DTM with SNV and AFN were 26% and 21% respectively. These were considerably higher than the measured 14.5% and therefore further work was needed to understand the differences and calibrate the model. This was addressed in section 6.4.

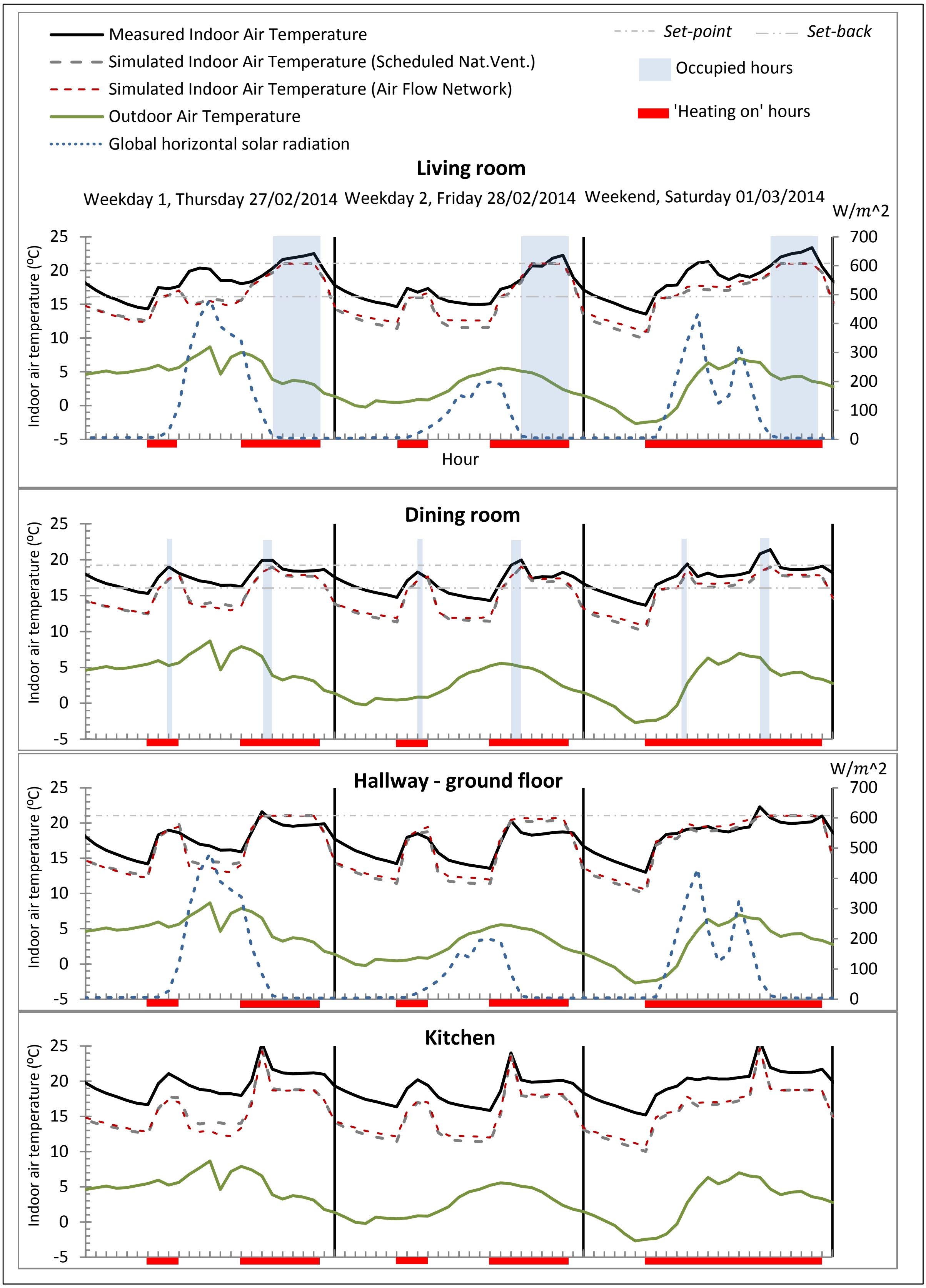
6.3.2 Comparison of the indoor air temperatures

Measured and predicted indoor air temperatures were compared for each room of the house with ZC (Figure 6-9) and the house with CC (Figure 6-10). Outdoor air temperatures, and global horizontal solar radiation for the south facing rooms, were added to the plots to aid understanding. The heating on hours, heating off hours, occupied and unoccupied hours, set-point and set-back temperatures were indicated on each plot. These plots were inspected visually to identify repeating patterns of discrepancies between the measured and predicted air temperatures.

The plots presented here were for the three consecutive days; two weekdays (Thursday 27 and Friday 28 February 2014), and one weekend day (Saturday 1 March 2014) to include different heating schedules used at weekdays and weekends. The weekdays represent days with higher (Thursday) and lower (Friday) levels of solar radiation: the average daily global horizontal solar radiation for weekday 1 and weekday 2 were 116 and 52 W/m^2 respectively compared to the average of 95 W/m^2 for the whole HT1. Daily average outdoor temperature, global horizontal solar radiation and wind speed for the selected days and the whole HT1 period were presented in Table 6-5.

Table 6-5: Weather parameters for the selected days and the whole HT1

Weather parameter	**Thursday**	**Friday**	**Saturday**	**Whole test (28 days)**
average outdoor temperature (°C)	5.2	2.5	2.5	6.2
average global horizontal solar radiation (W/m^2)	116	52	94	95
average wind speed (m/s)	4.6	2.8	1.5	3.8


Measured Indoor Air Temperature
Simulated Indoor Air Temperature (Scheduled Nat.Vent.)
Simulated Indoor Air Temperature (Air Flow Network)
Outdoor Air Temperature
Global horizontal solar radiation
Set-point
Set-back
Occupied hours
'Heating on' hours
Living room
Weekday 1, Thursday 27/02/2014
Weekday 2, Friday 28/02/2014
Weekend, Saturday 01/03/2014
W/m^2
Indoor air temperature (ºC)
25
20
15
10
5
0
-5
700
600
500
400
300
200
100
0
Hour
Dining room
Indoor air temperature (ºC)
Hallway - ground floor
W/m^2
Indoor air temperature (ºC)
Kitchen
Indoor air temperature (ºC)

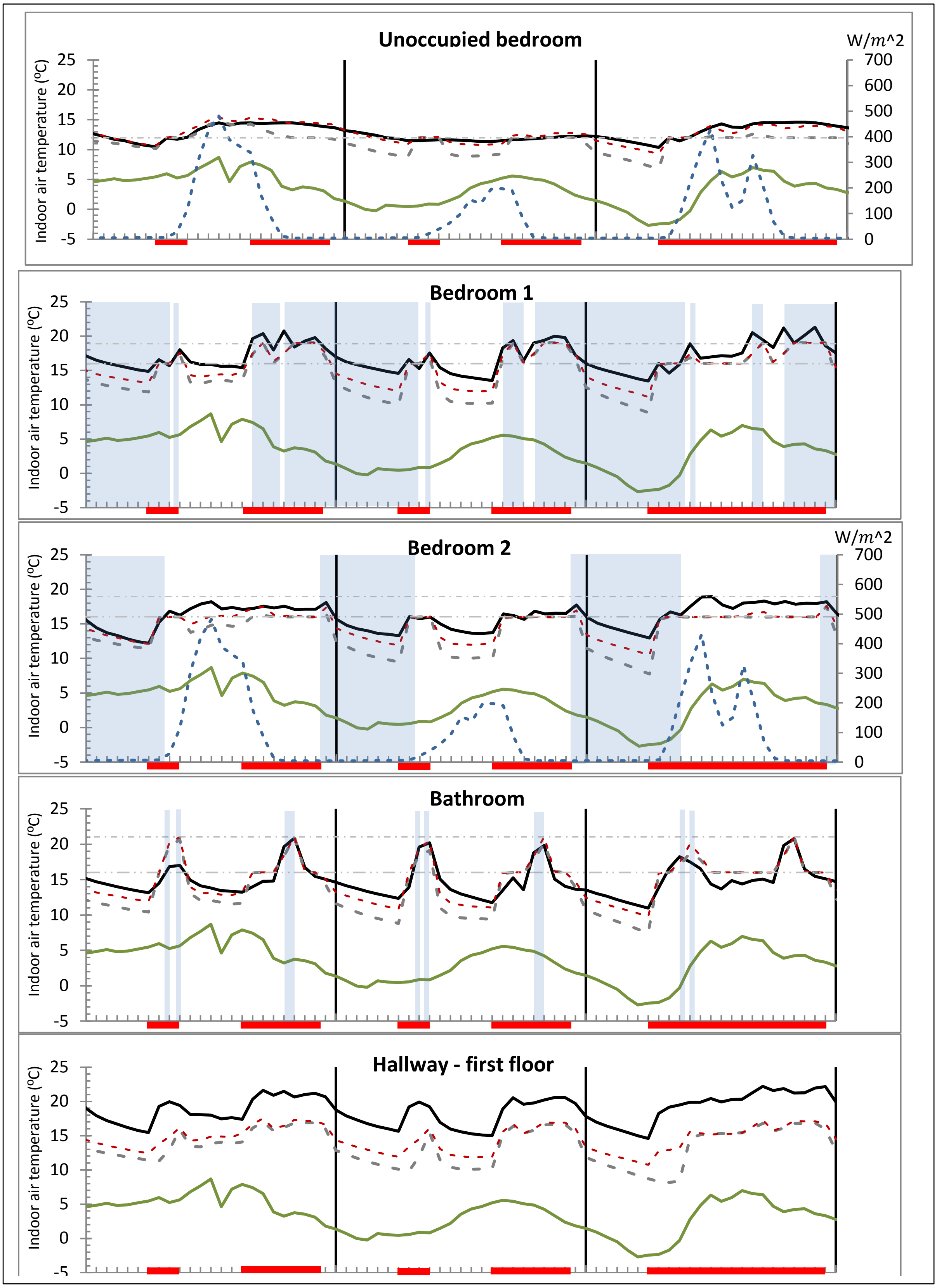
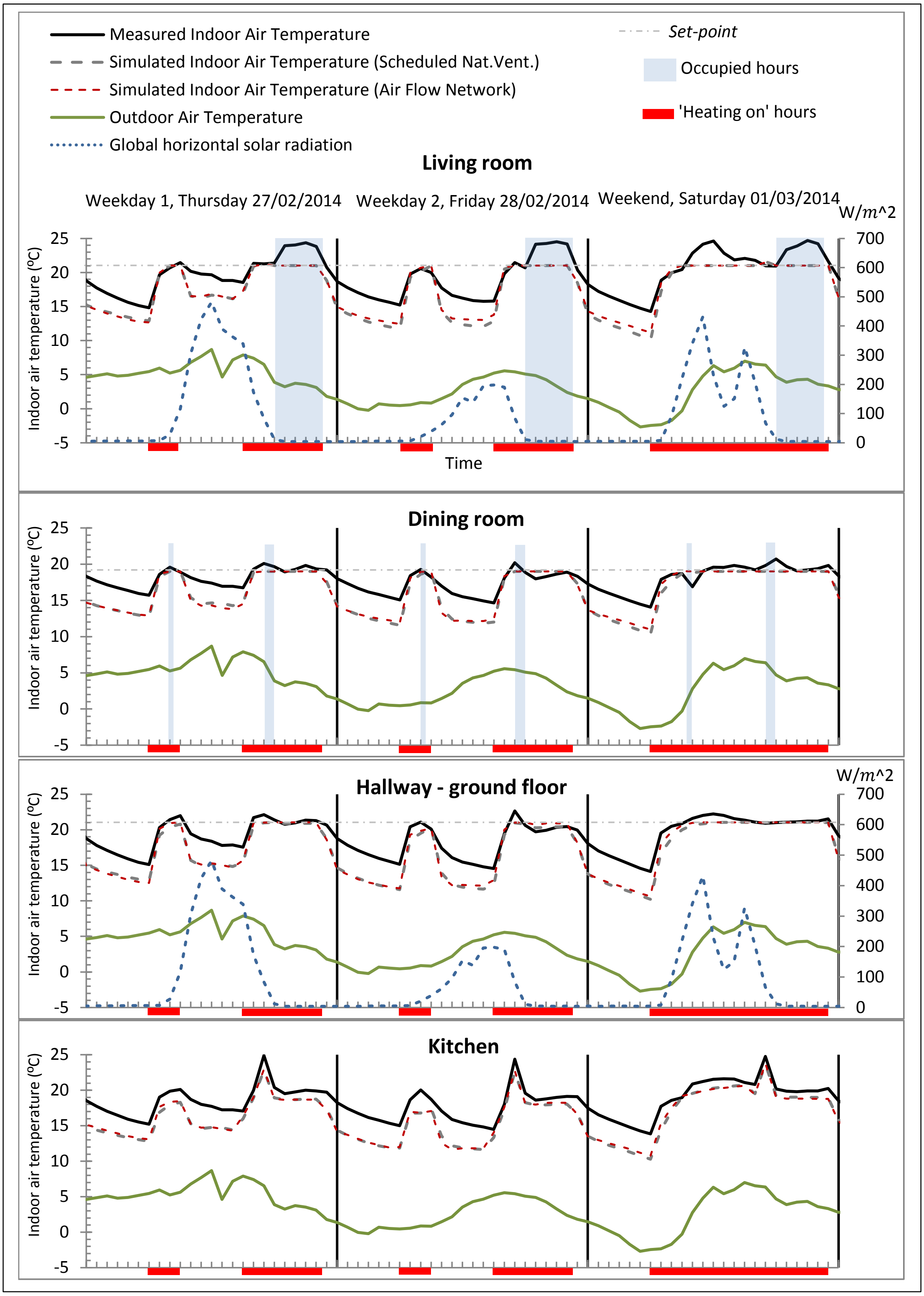


Figure 6-9: predicted and measured indoor air temperatures of the house with ZC along with measured outdoor air temperatures and global horizontal radiation; 27 Feb to 1 March 2014


Measured Indoor Air Temperature
Simulated Indoor Air Temperature (Scheduled Nat.Vent.)
Simulated Indoor Air Temperature (Air Flow Network)
Outdoor Air Temperature
Global horizontal solar radiation
Set-point
Occupied hours
'Heating on' hours
Living room
Weekday 1, Thursday 27/02/2014
Weekday 2, Friday 28/02/2014
Weekend, Saturday 01/03/2014
W/m^2
Indoor air temperature (ºC)
25
20
15
10
5
0
-5
700
600
500
400
300
200
100
0
Time
Dining room
Hallway - ground floor
Kitchen

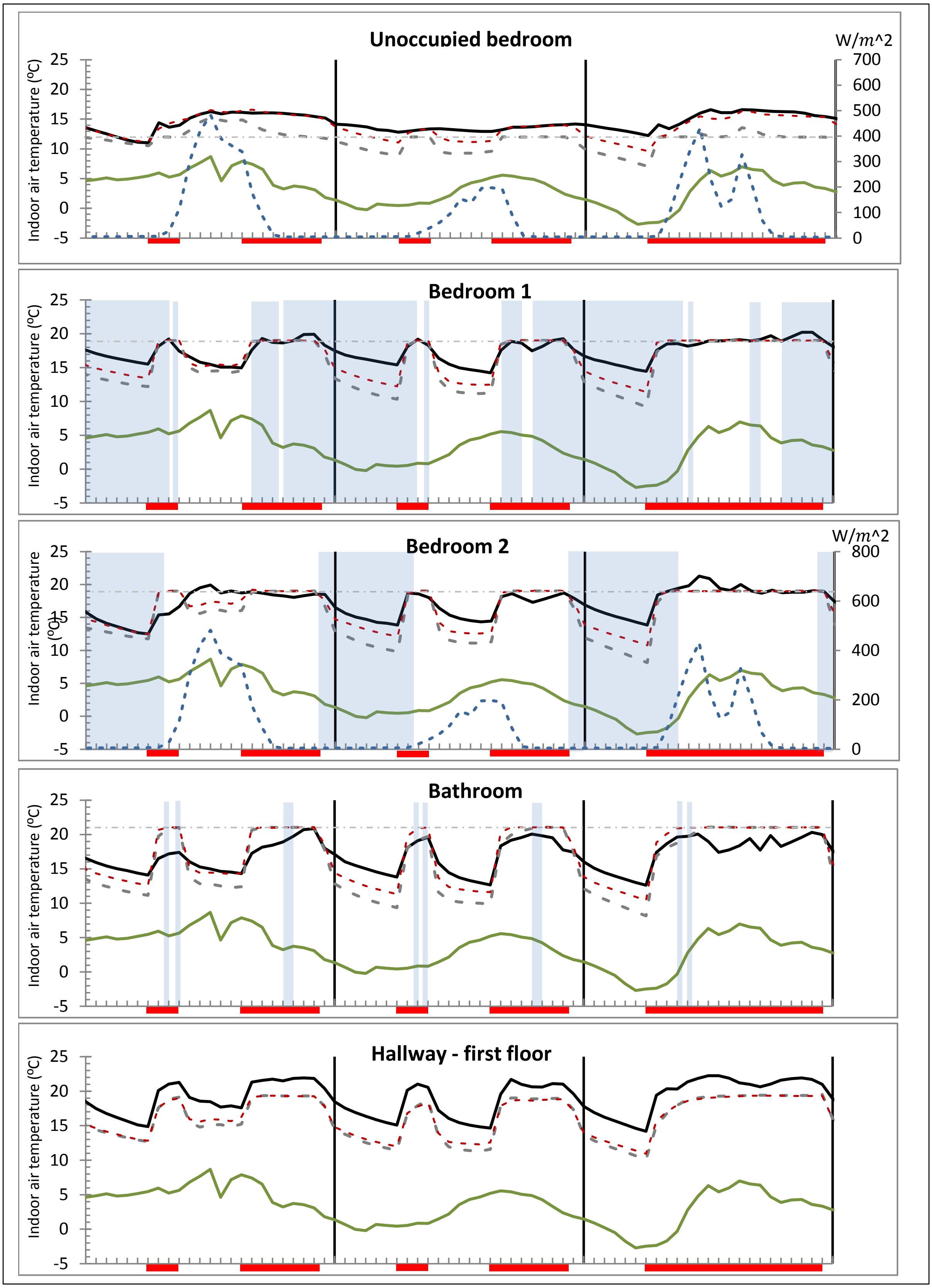


Figure 6-10: predicted and measured indoor air temperatures of the house with CC along with measured outdoor air temperatures and global horizontal radiation; 27 Feb to 1 March 2014

During the “heating on” hours, indoor air temperatures predicted using SNV and AFN followed a similar pattern to those measured in each room and in both houses. Air temperatures rise when the heating comes on, and with CC continued to increase until the set-point temperature was achieved (Figure 6-10). However, with ZC, when the room was not scheduled to be occupied, the air temperature only increased until the set-back temperature of the room was achieved (Figure 6-9). When the room was scheduled to be occupied, the room air temperature increased to its set-point temperature (Figure 6-9). This demonstrates that the heating schedules in the model were similar to those in the real test houses. However, discrepancies were observed between the predicted and measured hourly air temperatures which were persistent throughout the test period. These differences could be divided into two categories: differences during the” heating on” hours and differences when the heating was off.

- **Differences during “heating on” hours**

When scheduled to be occupied, living room air temperatures measured in both houses exceeded the nominal set-point of 21°C (Figure 6-9 and Figure 6-10) as the PTRVs and the TRVs did not maintain the room air temperatures accurately. Temperatures of up to 25°C were recorded during the evening hours when the door was closed and there was high level of internal heat gains. High temperatures were also recorded when there was high level of solar radiation. The measured radiator surface temperatures indicated that their heat output continued even when the rooms were above their set-point temperatures (see Figure 4-7).

Similarly, temperatures achieved in the dining rooms of both houses were slightly higher than the nominal set-point temperatures assumed in the model when they were scheduled to be occupied and with internal heat gains and the doors closed. During the rest of the heating on hours, predicted dining room air temperatures were relatively close to those measured.

The ability of TRVs to maintain a set-point temperature was found to vary between rooms. The measured and predicted air temperatures in bedroom 1 and 2 were similar in the house with CC, while slightly different in the house with ZC.

The unoccupied bedrooms were only heated when their air temperature dropped below 12°C. The doors were also always closed and the model using AFN better predicted air temperatures.

Detailed operation of TRVs and PTRVs cannot easily be modelled in Design Builder or EnergyPlus. This could be a significant source of inaccuracy as this difference would affect the rate of heat transfer to adjacent rooms and outdoors as well as the accuracy of the predicted air temperatures. Therefore, better predicted air temperatures might be achieved during the heating on hours by changing the nominal set-points in the model to an average of the measured air temperature for each room.

Solar gains also played a role in the differences observed between the predicted and measured air temperatures. The measured air temperatures in the south facing rooms with large windows (i.e. living room and bedroom 2) were higher than those predicted during sunny days (Figure 6-9 and Figure 6-10). Since the glazing and wooden frame area of the windows were accurately measured and inserted in the model as described in section 5.2.1, differences observed could be attributed to one or more than one of the following reasons:

a) Solar transmittance of the glazing might be assumed low in the model.
b) Solar absorptance of the floor might be assumed low in the model. (EnergyPlus assumes that all direct normal solar radiation entering a zone falls on the floor (US Department of Energy, 2012)).
c) Ground reflectance values which are used to calculate the ground reflected solar radiation might be assumed low in the model.
d) Differences between the amounts of solar radiation measured at weather station compared to actual on site solar radiation.
e) Errors involved in measuring air temperature under high solar radiation using a thin layer of aluminium foil to protect the temperature sensor from direct solar radiation.

There were two unheated rooms in each house: kitchen and first floor hallway[14]. Predicted air temperatures in both of these rooms were found to be lower than the measured air temperatures during the heating on hours. In the two houses, the boiler was located in the kitchens and the pipes were uninsulated (Figure 6-11). The additional heat gains from the boiler casing and its associated pipe work were not included in the model. The heat loss from a boiler casing and associated pipe work and fittings could be considered to be about 2% of the boiler's rated output (Vesma, 2014). This would result in 600 W additional heat gains in the kitchens when the heating was on.

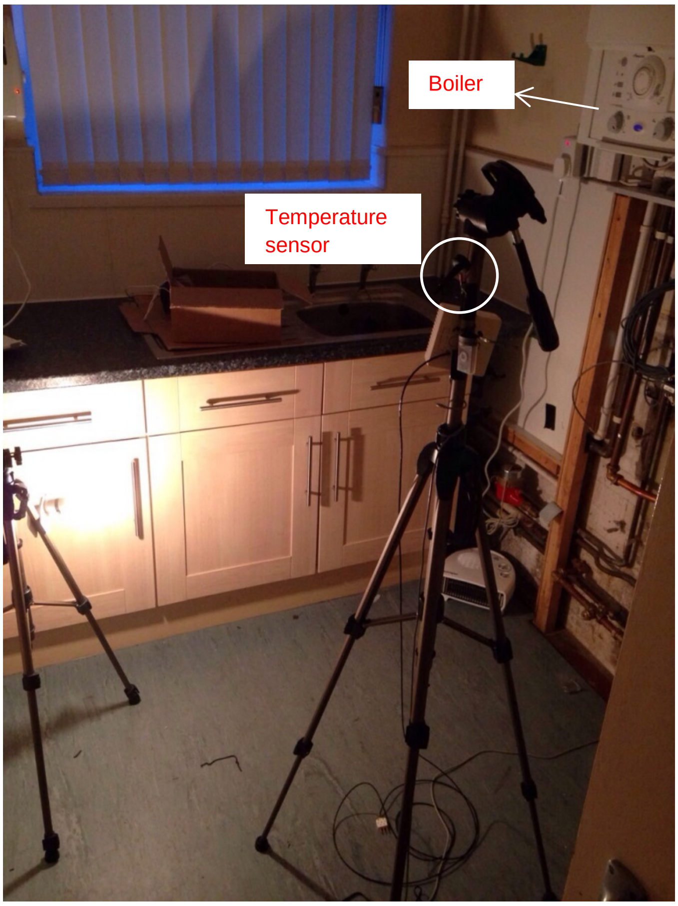


Figure 6-11: Boiler and its uninsulated pipe work and the position of temperature sensor on a tripod in the kitchen of House 2

The lower predicted air temperature of the hallway first floor compared to the measured air temperatures was believed to be due to the difficulties in modelling

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[14] WCs were ignored in this analysis due to its relatively small floor area and the fact that their air temperatures were not measured during the HT1

natural convection through the staircase which connected the ground floor and first floor hallways of each house. Both air flow modelling strategies could only very poorly represent the air flows through large horizontal openings. According to DesignBuilder's help document, "*the air flow between two floors connected by large horizontal openings (i.e. holes) could be only modelled "very approximately" when using the AFN*". According to EnergyPlus input output reference (US Department of Energy, 2013c), the AFN model is unable to model bi-directional flows through large horizontal openings at a given time step.

Inaccuracies of modelling natural convection through staircase would also cause inaccuracies in predicted air temperatures of the ground floor hallway. The measured hallway air temperature of the house with ZC was below 21°C for most of the heating period (Figure 6-9) which was lower than model prediction. This could be explained as a large proportion of the heat emitted from the radiator in the ground floor hallway was transferred to the hallway first floor and its adjacent bedrooms (as well as colder rooms in the ground floor). In the house with CC (Figure 6-10), the hallway ground floor air temperature predicted and measured during the heating on hours were very close to the nominal set-point temperature of 21°C. This can be explained as in the house with CC, since the first floor rooms were also heated during the heating on hours, the rate of heat loss from the ground floor hallway to the first floor hallway was considerably lower than the house with ZC.

One alternative method could be to consider the ground floor and first floor hallways as a single zone. However, according to EnergyPlus documentation (US Department of Energy, 2013c) AFN cannot model the air temperature stratification within a thermal zone which is the case if the hallway would have been considered as a single zone. Another alternative is to increase the air flow from the ground floor to the first floor by increasing discharge coefficient of the hole connected the two floors when using AFN or to increase the amount of air mixing between the ground floor and first floor when using SNV air flow modelling.

- **Differences during "heating off" hours**

When the heating turned off, the predicted air temperatures fell at a faster rate than was measured. This was true in all of the rooms, for both houses and regardless of the air flow modelling method. The first potential reason could be higher fabric heat loss or higher infiltration heat loss assumed in the model. However, the model showed a reasonable prediction of the overall heat loss due to fabric and infiltration when modelling the co-heating test and overall, the predicted energy use was lower than the measured energy use in both houses regardless of the air flow modelling strategy. Therefore, reducing the fabric or ventilation heat loss would not improve the model.

Figure 6-9 and Figure 6-10 show that predicted rates of heat up are also higher than measured. This could potentially be due to lower thermal mass in the model than in the real building. These fast heat up and cool down rates in rooms heated with radiators were similar to the findings of others. Zhai & Chen (2005) used experimental data from IEA annex 21/task 12[15] reported by Lomas et al. (1997) to simulate natural convection in a room with an oil-filled radiator controlled via a PID controller. They found that the difference between the predicted and measured air temperatures of the room with a radiator were significant during the heat up and cool down. Similar findings were reported by Beausoleil-Morrison (2000). Figure 6-12 which is adopted from Zhai and Chen (2005) shows the predicted and measured mean air temperature for the IEA test room with radiator for their study (a) and study by Beausoleil-Morrison (2000) (b).

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[15] International Energy Agency (IEA) annex 21/task 12 was conducted for the purpose of empirical validation of building energy simulation programs

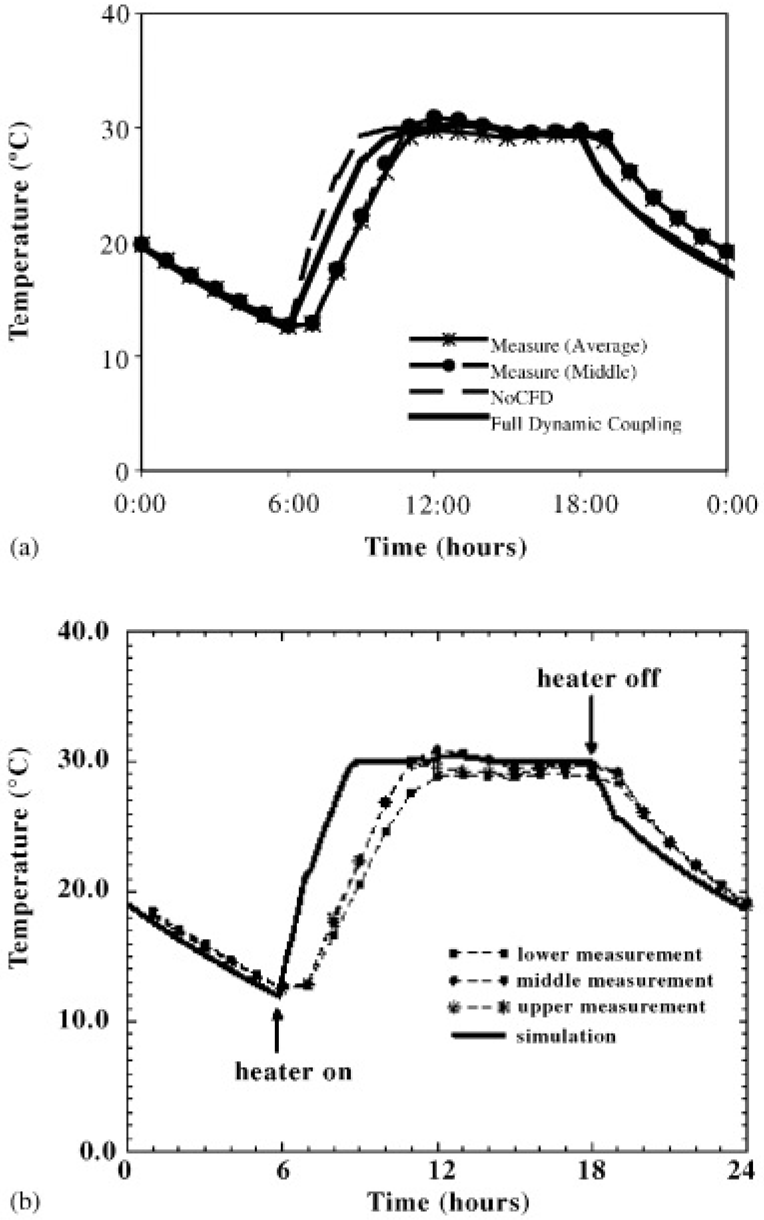


Figure 6-12: predicted and measured mean air temperature over a single day for the IEA test room with radiator for (a) study by Zhai and Chen (2005) and (b) study by Beausoleil-Morrison (2000) (Figure was reproduced from Zhai and Chen (2005)).

Zhai and Chen (2005) argue that the higher rates of air temperature change predicted in the model is because of the dynamic behaviours of the radiators: the time delay as the water warms or cools when the heater is switched on or off cannot be represented. This causes the air to heat up much faster in the model than it does in reality.

To sum up, ten input parameters were identified as those which could have potentially influenced the discrepancies observed between the predicted and measured indoor air temperatures and will be investigated further:

1. Set-point temperatures of the rooms in which the heating was controlled by TRV or PTRV
2. Unaccounted heat gains in the kitchens from the boiler casing and pipe work
3. The amount of air flow between the ground floor and first floor hallways
4. Hallway zoning strategy
5. Ground reflectance
6. Solar transmittance of the glazing
7. Solar absorptance of the floor materials
8. Building fabric heat loss
9. Infiltration heat loss
10. Thermal mass

6.4 Model calibration

Indoor air temperatures and boiler heat outputs measured during the HT1 were used to calibrate the model. The calibration procedure consisted of three steps:

1. Sensitivity analysis was conducted to evaluate the effects of the 10 parameters proposed in section 6.3.2 on improving the model's predictions of energy use and indoor air temperatures.
2. The parameters which had the potential to improve the predictions of both energy and indoor air temperature were adjusted in the base case model to generate a refined model.
3. The refined model was assessed against the acceptance criteria for hourly calibration of building energy simulation models according to ASHRAE Guideline 14. In addition, the hourly indoor air temperatures measured and predicted were plotted and inspected visually as an additional check in order to identify any discrepancies.

The calibration procedure was applied to two versions of the base case model: one using SNV, and one using AFN to model the air flows through the houses. Ten variants for the LMP1930 test house model were constructed. For each variant, all of the model inputs were exactly the same as the base case model except for the one parameter being studied. This parameter was altered, within a reasonable range, to investigate if it improved the accuracy of energy use and indoor air temperature predictions. The ten variants are described below:

Variant 1 was constructed to evaluate the effects of changing the set-point temperatures in the rooms in which the heating was controlled by TRV or PTRV: In ZC house, the nominal set-point temperatures assumed in the base case model was replaced with the average air temperature measured during the occupied hours in each room (Table 6-6). In CC house, the average air temperatures measured in each room during the heating on hours, except the first hour of each heating period (warm up periods) were replaced the nominal set-point temperatures.

Table 6-6: Nominal and new set-point temperatures which were applied for variant 1

Room	Set-point temperature ZC (°C)		Set-point temperature CC (°C)	
	Nominal	New	Nominal	New
Living room	21.0	22.1	21.0	23.0
Dining room	19.0	20.3	19.0	20.1
Bedroom 1	19.0	19.9	19.0	19.5
Bedroom 2	19.0	19.0	19.0	19.0
Bathroom	21.0	19.7	21.0	18.7

Variant 2 was constructed to evaluate the effects of adding a heat emitter to the kitchen of the two houses in order to represent the kitchen heat gains from the boiler casing and its associated pipe work. A radiator was added with a rated capacity of 600 W and was scheduled to be always on when the heating was on.

Variant 3 was constructed to evaluate the effect of increasing the air flow between the ground floor and the first floor hallways. The discharge coefficient of the opening was changed from 0.65 to 0.72 (10% increase) for the version of the model which used AFN to model the air flows. For the version of the model which used SNV, the design flow rate between the ground floor and first floor hallway increased by 10%.

Variant 4 was constructed to evaluate the effect of modelling the ground floor and first floor hallways as a single zone instead of two separate zones.

Variant 5 was constructed to evaluate the effects of higher ground reflectance by increasing the monthly ground reflectance of the model from 0.2 to its maximum value of 1.0.

Variant 6 was constructed to evaluate the effects of higher solar transmittance of the glazing by increasing it by 10% from 0.837 to 0.92.

Variant 7 was constructed to evaluate the effects of higher solar absorptance of the floor materials (i.e. carpet and timber floor) by increasing each of them by 10%.

Variant 8 was constructed to evaluate the effects of lower building fabric heat loss. The conductivities of the two layers of external walls were reduced by 30% each. This resulted in a reduction of 17% in the U-values of the external walls.

Variant 9 was constructed to evaluate the effect of lower infiltration heat loss. For the version of the model using AFN, the poor crack template was replaced by the medium crack template (Table 6-7 and Table 6-8).

Table 6-7: New crack characteristics according to DesignBuilder's "medium" crack template used in the variant 9 for walls, floors and the roof

Building element	Air mass flow coefficient (C_Q) (Kg/s.m^2) at 1Pa	Flow exponent (n)
External walls	0.0001	0.7
Internal walls	0.003	0.75
Internal floors	0.0009	0.7
External floors	0.0007	1.0
Roof	0.0001	0.7

Table 6-8: New crack characteristics according to DesignBuilder's "medium" crack template used in the variant 9 for the doors, windows and vents

Building element	Air mass flow coefficient (C_Q) (Kg/s. m) at 1Pa	Flow exponent (n)
External windows	0.00014	0.65
External doors	0.0014	0.65
Internal doors	0.02	0.6
External vents	0.008	0.66

For the version of the model which used SNV, the infiltration design flow rate of each room was decreased by 10%.

Variant 10 was generated in order to investigate the effects of assuming higher thermal mass in the model on the predictions of energy use and indoor air temperature. The "Temperature Capacity Multiplier" object of EnergyPlus was used to increase the thermal capacitance of the air in every zone. It was used in previous studies (Huchuk, Brien & Cruickshank, 2012), to account for the thermal mass of room contents. However, the value used was not mentioned in their paper. The object was also used by German et al. (2014) for calibrating a model in which the temperatures responded too quickly to outdoor environmental changes. A "Temperature Capacity Multiplier" value of 15 was found in their study to improve the rate of change of indoor air temperature. In this study, it was found that a reasonable rate of air temperature change in the model could be achieved by using a "Temperature Capacity Multiplier" of 10 for the heavily instrumented houses.

For all ten variant models MBE (%) and CVRMSE (%) for the hourly boiler heat output were calculated. In addition, the difference between the measured and predicted volumetrically weighted whole house average air temperatures (ΔTavg (°C)) was calculated (Table 6-9). For each case, the three indices were compared to the base case model: where a variant improved the prediction it was indicated by a tick mark and where it was not improved it was indicated by a cross mark.

For the model with SNV, none of the 10 variants improved the predictions of both energy and indoor air temperature. While this model could closely predict the energy use in the co-heating test, where all the zones were heated to very similar temperatures, it failed when the rooms were heated to different temperatures and the effects of natural convection were significant.

For the model with AFN, three variants improved the predictions of both energy and indoor air temperatures: 1, 2 and 10.

Table 6-9: MBE (%), CVRMSE (%) and ΔTavg (°C) calculated for each case and each house using AFN and SNV

Variant	Model with AFN						Model with SNV					
	ZC house			CC house			ZC house			CC house		
	MBE (%)	CVRMSE (%)	ΔTavg (°C)	MBE (%)	CVRMSE (%)	ΔTavg (°C)	MBE (%)	CVRMSE (%)	ΔTavg (°C)	MBE (%)	CVRMSE (%)	ΔTavg (°C)
	✓=model improved						✗=model not improved					
Base case	23	45	1.8	11	44	1.3	8	35	2.2	-0.4	39	1.8
1	20 ✓	43 ✓	1.6 ✓	8 ✓	42 ✓	1.0 ✓	6 ✓	35 ✗	2.1 ✓	-4 ✗	40 ✗	1.4 ✓
2	16 ✓	40 ✓	1.6 ✓	10 ✓	43 ✓	1.2 ✓	13 ✗	38 ✗	2.3 ✗	2 ✗	42 ✗	1.6 ✓
3	20 ✓	44 ✓	1.8 ✓	12 ✗	45 ✗	1.3 ✓	8 ✗	35 ✗	2.2 ✗	-0.4 ✗	39 ✗	1.8 ✗
4	20 ✓	44 ✓	1.9 ✗	12 ✗	44 ✗	1.2 ✓	10 ✗	40 ✗	2.2 ✓	3 ✗	47 ✗	1.6 ✓
5	28 ✗	51 ✗	1.5 ✓	17 ✗	48 ✗	1.2 ✓	14 ✗	39 ✗	2.0 ✓	6 ✗	41 ✗	1.6 ✓
6	23 ✗	46 ✗	1.7 ✓	12 ✗	44 ✗	1.3 ✓	9 ✗	36 ✗	2.2 ✓	0.0 ✓	40 ✗	1.8 ✓
7	23 ✗	45 ✗	1.8 ✗	11 ✗	44 ✗	1.3 ✗	8 ✗	35 ✗	2.2 ✗	0.4 ✗	39 ✗	1.8 ✗
8	26 ✗	48 ✗	1.7 ✓	15 ✗	46 ✗	1.2 ✓	11 ✗	37 ✗	2.2 ✓	4 ✗	40 ✗	1.7 ✓
9	34 ✗	56 ✗	1.44 ✓	25 ✗	53 ✗	1.07 ✓	11 ✗	36 ✗	2.18 ✓	2 ✗	39 ✗	1.71 ✓
10	14 ✓	28 ✓	1.39 ✓	8 ✓	33 ✓	1.06 ✓	3 ✓	30 ✓	1.87 ✓	8 ✗	29 ✓	1.48 ✓

Therefore, variants 1, 2 and 10 were combined using AFN to construct the refined model which improved the predictions of both energy and indoor air temperature (Table 6-10).

Table 6-10: Comparison of MBE (%) and CVRMSE (%) and ΔTavg (°C) between the base case model and the refined model

House	Base case model			Refined model		
	MBE (%)	CVRMSE (%)	ΔTavg (°C)	MBE (%)	CVRMSE (%)	ΔTavg (°C)
ZC	23	45	1.8	3.8	22	0.9
CC	11	44	1.3	3.9	28	0.5

These results met the acceptance criteria for hourly calibration of building energy simulation models according to the ASHRAE Guideline 14: MBE calculated for the house with ZC and CC house were reduced to 3.8% and 2.9% respectively for the refined model which both were below the 10% limit outlined by ASHRAE guideline 14; CVRMSE (%) of houses with ZC and CC were also reduced to 22% and 28% respectively which were both below the 30% acceptance limit. As can be seen from Figure 6-13 and Figure 6-14, the heating demand predictions were similar to those measured with a total difference of only 3.9% for both houses. The refined model predicted a reduction of 14.5% in heat demand for the house with ZC compared to the house with CC during the HT1, which is in exact agreement with the measured percentage of savings.

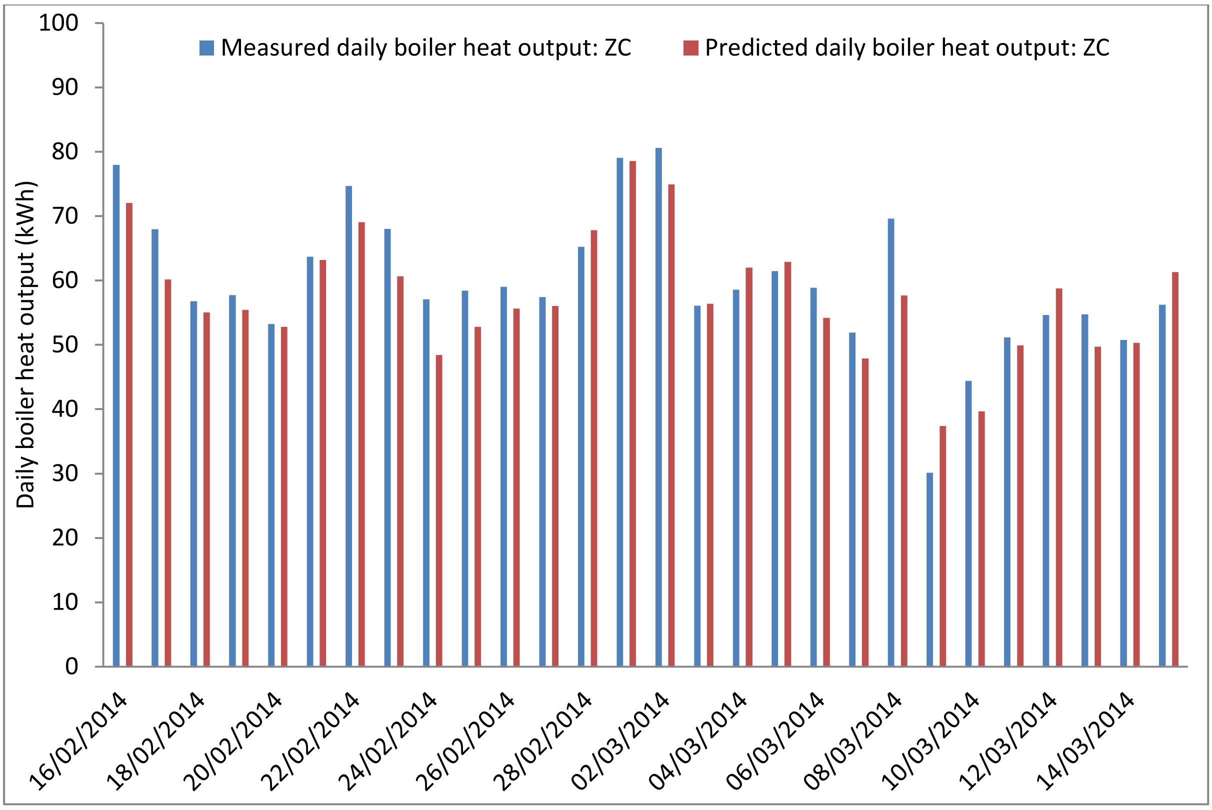


Figure 6-13: predicted daily boiler heat output against measured boiler heat output for the 28 days of HT: ZC

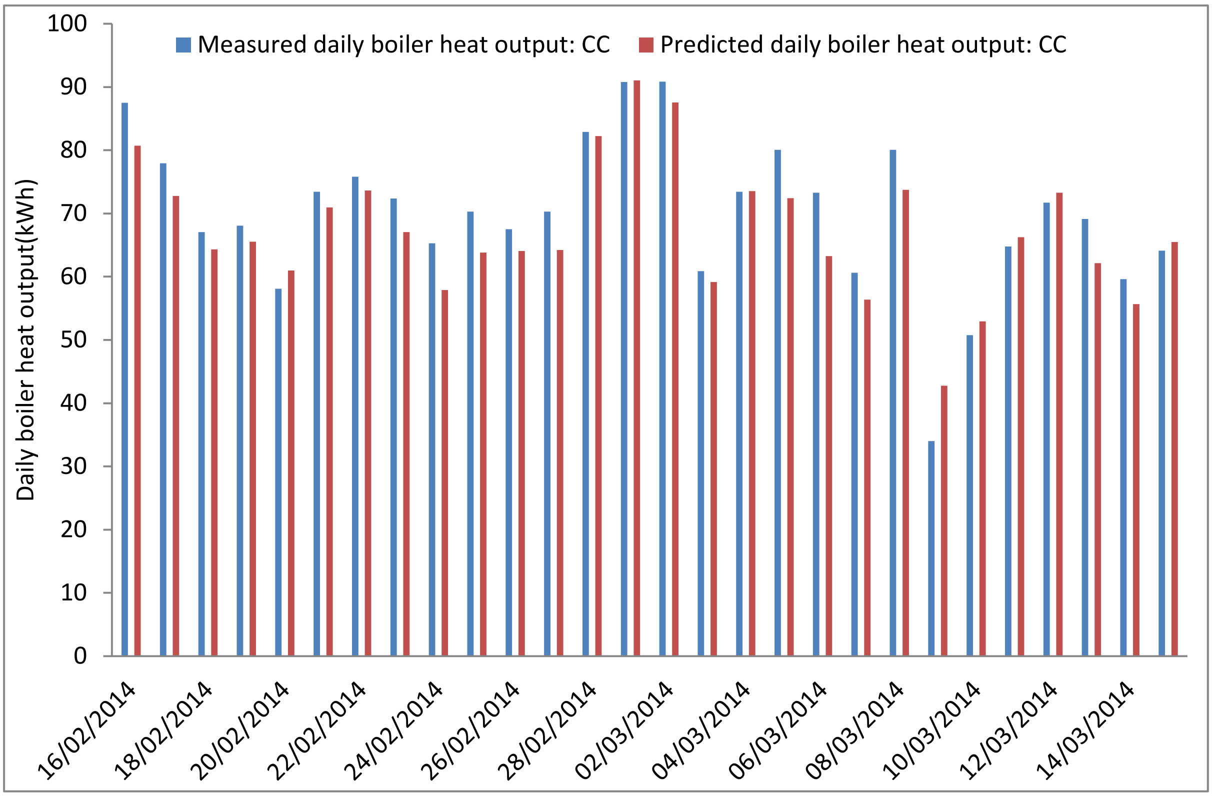
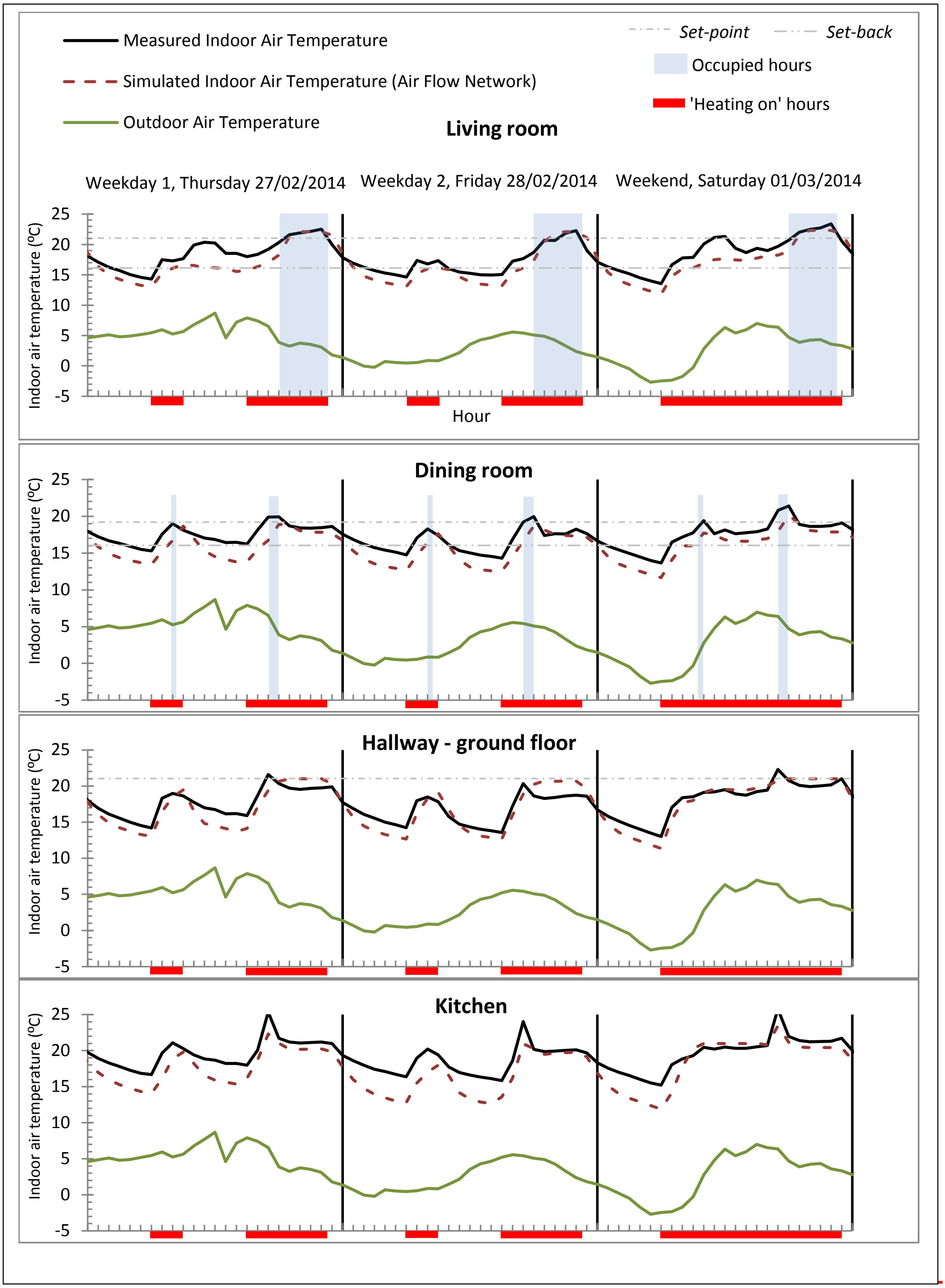


Figure 6-14: predicted daily boiler heat output against measured boiler heat output for the 28 days of HT: CC

There was a reasonable agreement between the measured and predicted indoor air temperatures of each room (Figure 6-15 and Figure 6-16). The volumetrically weighted whole house average air temperatures predicted were 0.5 °C and 0.9°C lower than those measured for the house with CC and ZC, respectively. In addition, MBE (%) and CVRMSE (%) of the predicted volumetrically weighted whole house average air temperatures before and after calibration were calculated for both houses. MBE and CVRMSE for the house with CC were reduced from 7.3% to 3.1% and 9.8% to 6% respectively. MBE and CVRMSE for the house with ZC were reduced from 10% to 5.6% and from 11% to 6.9% respectively.

The co-heating test model was re-run in order to test the implications of adding thermal mass to the energy use of the houses for the version of the model using AFN. It was found that MBE of House 1 and House 2 were reduced from 9.0 % and 5.4% respectively, to 3.8% and 0.15%, respectively. CVRMSE of the two houses were also reduced from 10.7% and 8.0% to 7.0% and 5.8% respectively. This gave further confidence in the revised model.


Measured Indoor Air Temperature
Simulated Indoor Air Temperature (Air Flow Network)
Outdoor Air Temperature
Set-point
Set-back
Occupied hours
'Heating on' hours
Living room
Weekday 1, Thursday 27/02/2014
Weekday 2, Friday 28/02/2014
Weekend, Saturday 01/03/2014
Indoor air temperature (ºC)
25
20
15
10
5
0
-5
Hour
Dining room
Hallway - ground floor
Kitchen

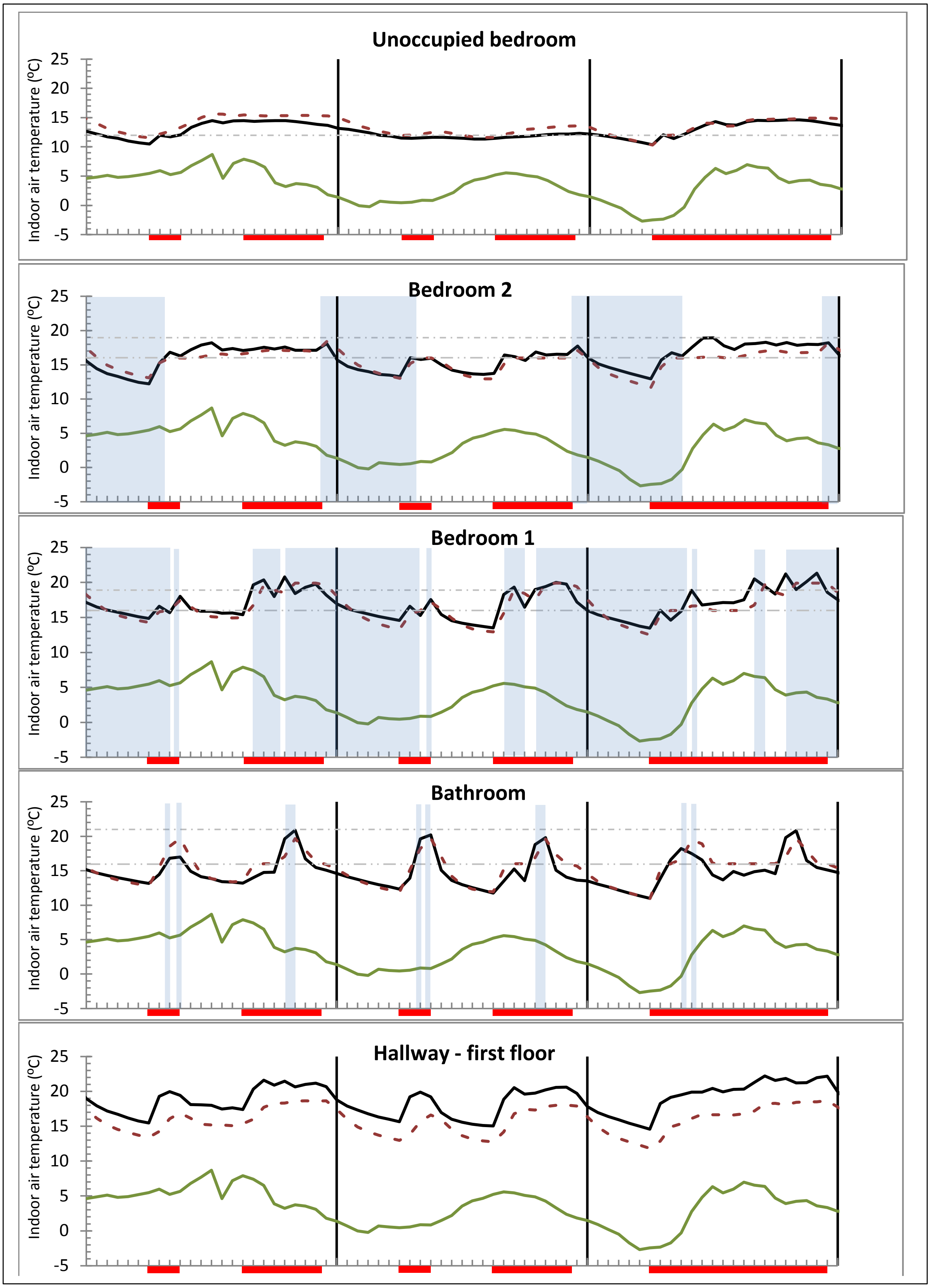
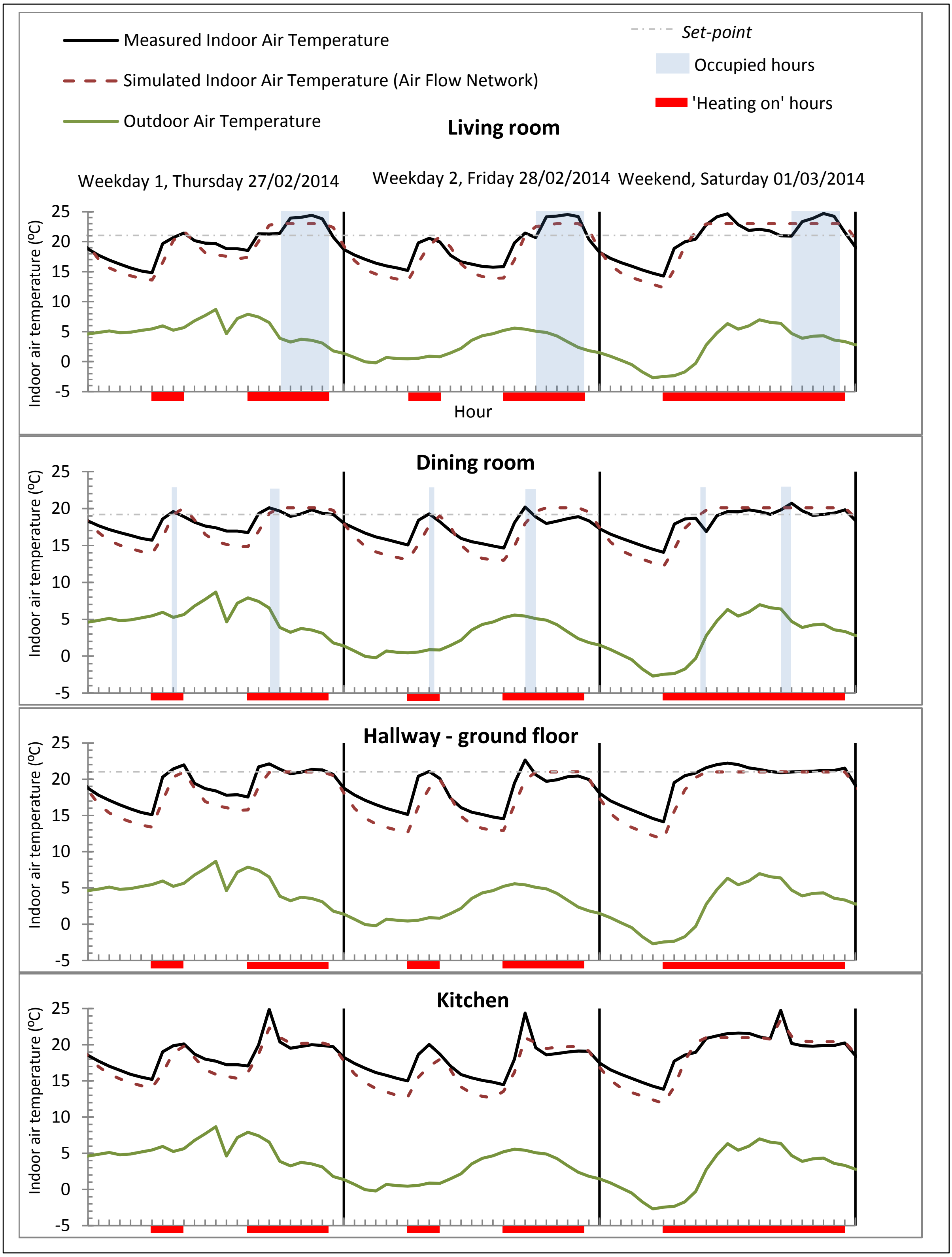


Figure 6-15: Indoor air temperatures measured and predicted by the refined model for the ZC house along with measured outdoor air temperatures; 27 Feb to 1 March 2014


Measured Indoor Air Temperature
Simulated Indoor Air Temperature (Air Flow Network)
Outdoor Air Temperature
Set-point
Occupied hours
'Heating on' hours
Living room
Weekday 1, Thursday 27/02/2014
Weekday 2, Friday 28/02/2014
Weekend, Saturday 01/03/2014
Indoor air temperature (ºC)
25
20
15
10
5
0
-5
Hour
Dining room
Hallway - ground floor
Kitchen

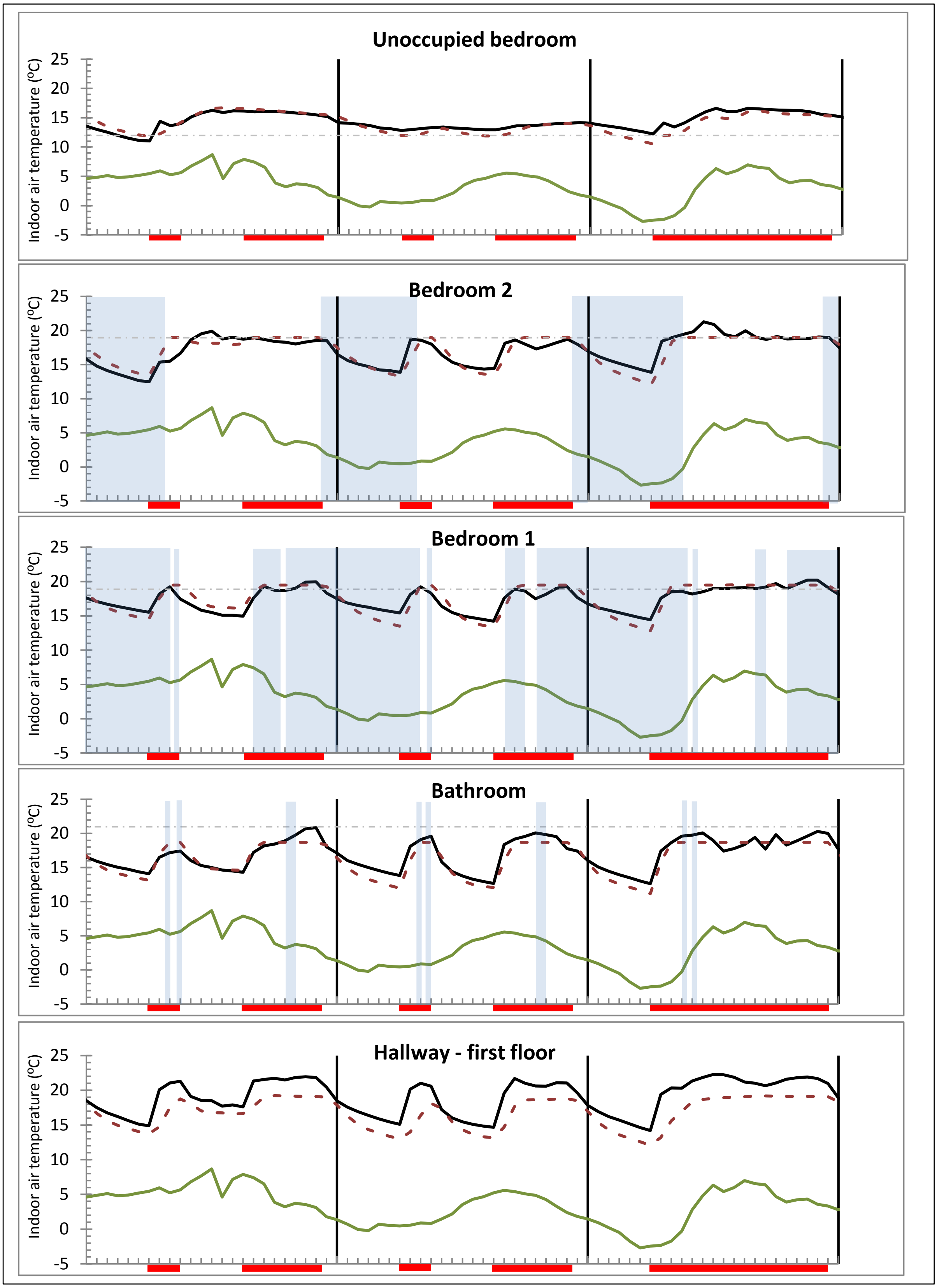


Figure 6-16: Indoor air temperatures measured and predicted by the refined model for the CC house along with measured outdoor air temperatures; 27 Feb to 1 March 2014

6.5 Summary

This chapter compared the energy use and indoor air temperatures measured at the LMP1930 test houses during the co-heating test and HT1 with those predicted by DTM using two different air flow modelling strategies: Scheduled Natural Ventilation (SNV) and Air Flow Network (AFN). The base case model could reasonably predict the energy use of both houses for the co-heating test using both air flow modelling strategies. However, the predictions were better using SNV compared to the AFN.

The base case model was not able to reasonably predict the energy use and indoor air temperatures of the test houses for the case of the HT1 using either of the two airflow modelling strategies. Differences between the measured and predicted results were investigated and potential parameters which could have contributed to the differences observed were identified. Sensitivity analysis was then conducted for these parameters and the parameters which could improve the predictions of energy use and indoor air temperatures were identified.

Based on the results of the sensitivity analysis, a refined model was calibrated against the ASHRAE guidelines for hourly calibration of building simulation programs. The model could be considered calibrated only when using AFN and it did not meet the calibration criteria when using SNV. The calibrated model could closely predict the energy savings of ZC measured during the HT1. The model will be used in chapter 7 to predict the energy savings of ZC which could be achieved in homes in different UK regions or in better insulated homes.

7 Potential savings in other UK locations and better insulated houses

7.1 Introduction

This chapter discusses the implication of the findings for the annual energy savings potential of ZC in different UK houses. Firstly, in section 7.2, the empirical results from the heating trials were evaluated for houses built and occupied in a similar way to the test houses, but located in different regions of the UK. Then, in section 7.3, the evaluations in different locations were repeated using the calibrated DTM of the test houses constructed as described in chapters 5 and 6. Section 7.3 also explores any difference between the predictions of the empirical model and DTM model and discusses the potential reasons for the discrepancies observed. In section 7.4, the calibrated DTM is used and the potential savings of ZC in better insulated homes are investigated. Finally, section 7.5 provides a summary of the findings in this chapter.

7.2 Evaluation of the empirical results for different UK locations

7.2.1 Annual heating fuel and cost savings in different UK locations

To extend the measured gas consumptions with CC and ZC to annual values, and to make an initial estimate of the effect of the weather in different parts of the UK, the results of the space heating trials were normalised and then evaluated using a Heating Degree Days (HDD) method.

Firstly, the base temperature (T_{base}) to be used for calculating the HDD was determined using the experimental results and then the relationship between the weekly HDD and the measured gas consumption was determined. This linear relationship was then used to estimate the weekly, and so annual, gas consumption for UK regions with different HDD.

7.2.2 Relationship between measured gas use and weather conditions

The measured weekly gas consumption (WGC) during the trials was strongly correlated with the weekly average outdoor air temperature (T_wao) for both ZC and CC (see Figure 7-1, ${R_{ZC}}^2 = 0.72\ and\ {R_{CC}}^2 = 0.78$). The linear relationship for the two control strategies was similar, but subtletly and importantly different. The regression lines indicate that for any average weekly ambient temperature below 13.4ºC, ZC will use less gas than CC. During the heating season, say September to April, the weekly average ambient is virtually always below 13.4ºC in all regions of the UK. It is also evident that the energy saved by ZC increases as the weekly average ambient temperature falls.

The base temperatures of the houses, i.e. the external temperature at which no heat is needed, is the intercept with the x-axis of best fit line; this was 18.2ºC for ZC and 17.3ºC for CC (Figure 7-1). However, the difference in intercepts is perhaps due to the limited range of weekly ambient temperatures, to which the two systems were exposed, leading to poor definition of the x-axis intercepts as reflected in Figure 7-1 by wide 95% confidence intervals for both systems at the x-axis intercept. Thus, the same base temperature of 17.8ºC, which is the mean value of 17.3ºC and 18.2ºC, was selected as the base temperature for houses with both ZC and CC. However, the sensitivity of energy consumption predictions to the HDD base temperature was investigated using a lower base temperature of 15.5ºC and a higher base of 20ºC and this will be presented later.

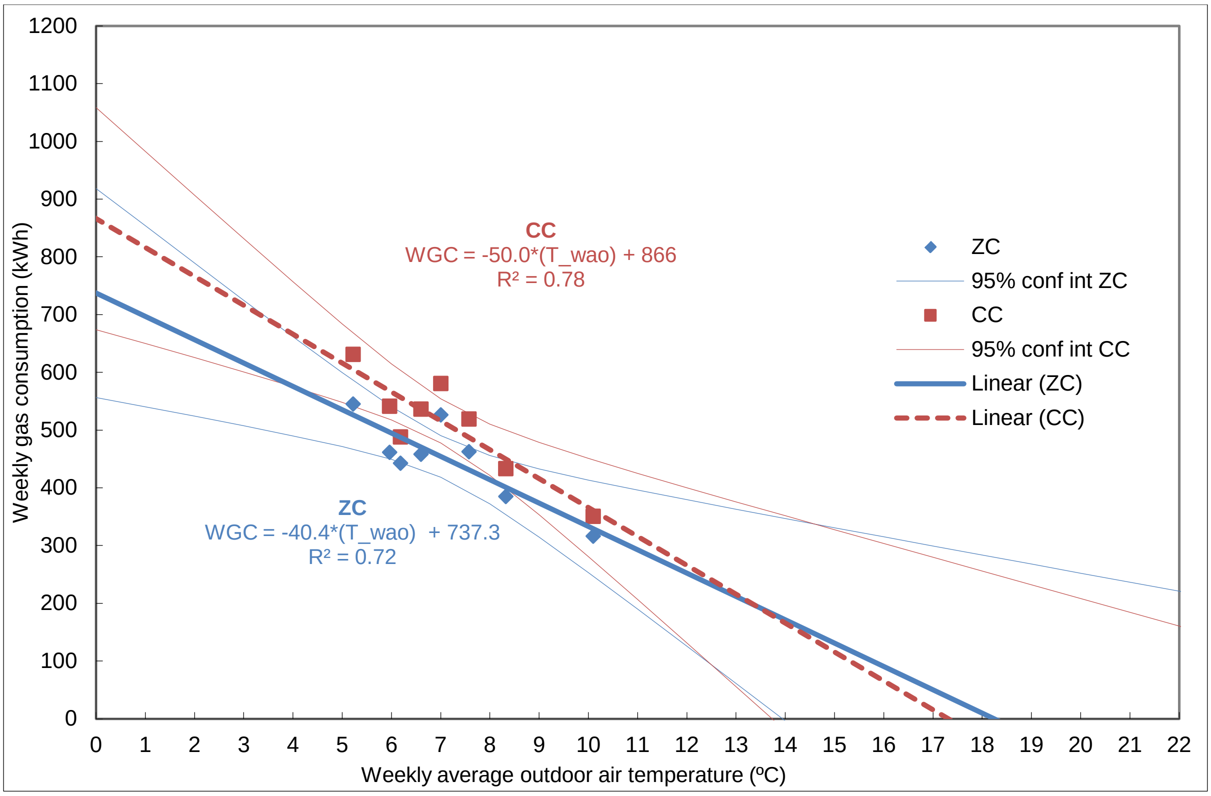


Figure 7-1: Weekly gas consumption of the houses with ZC and CC against weekly average outdoor air temperature for 8 weeks of monitoring, best fit lines and 95% confidence intervals

The base temperatures for CC and ZC were used to calculate the HDD during the heating trials (equation (7-1)).

$$Weekly\ HDD = \sum_{day\ 1}^{day\ 7} \frac{(T_{base} - T_{out})_{minutely_{((Tbase-Tout)>0)}}}{60 * 24} \qquad (7\text{-}1)$$

Where:

T_{base} = the base temperature for CC and ZC houses (i.e. 17.8ºC for this analysis)

T_{out}= outdoor air temperature (ºC) measured outside the test houses

The subscript shows that only positive differences are summed and if $(T_{base} - T_{out})_{minutely} < 0$, then it is set to 0 for that minute in equation (7-1).

Weekly HDD were used in preference to daily HDD because different heating patterns were used for weekdays and weekends. The weekly gas consumption was then plotted against the weekly HDD for each control configuration. Least squares regression analysis was used to determine the equation of the performance line.

There was a strong correlation between the 8 measured weekly gas consumption measurements and the weekly HDD for both ZC and CC (Figure 7-2, ${R_{ZC}}^2 = 0.73$ and ${R_{CC}}^2 = 0.79$). If the regression was forced through the origin, the correlation remained strong and the change in gas consumption per unit change in HDD was very similar (ZC - 6.03kWh/HDD, ${R_{ZC}}^2 = 0.73$; CC - 6.85kWh/HDD , ${R_{cc}}^2 = 0.79$).

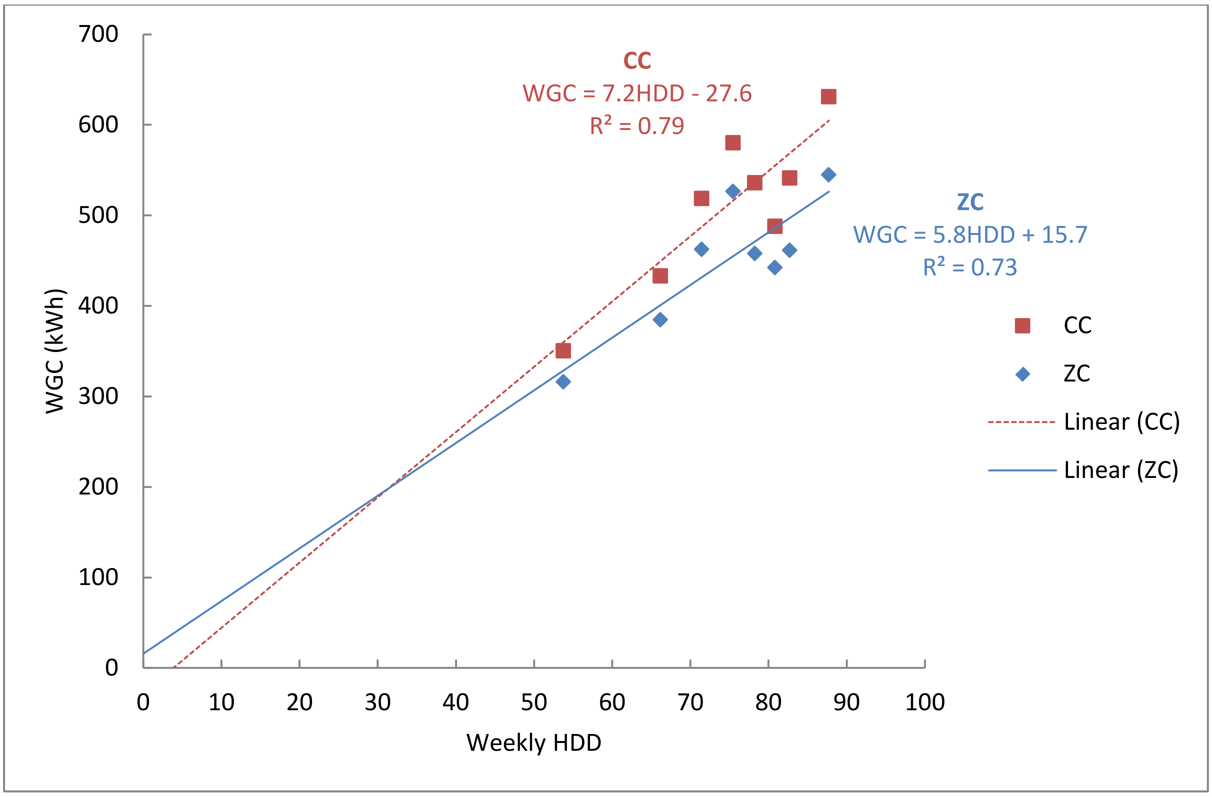


Figure 7-2: Measured weekly gas consumption plotted against calculated weekly HDD for the houses with ZC and CC

7.2.3 Effect of different UK locations

The performance lines (as in Figure 7-2 and not forced through the origin) were used to estimate the likely gas consumption for ZC and CC as if houses were built and occupied in a similar way to those measured, but were located in different regions of the UK. The HDD were calculated for seven UK regions using the base temperatures of 17.8ºC, for the heating months, October to April. To achieve this, “typical weather year” data from the International Weather for Energy Calculations (IWEC) (ASHRAE, 2001) were used for each region: London, the East of England, the West Midlands, Yorkshire, the Northwest, Northern Ireland and Scotland.

The calculated energy use for heating with each system shows that, regardless of the location, for the particular house and occupancy tested, ZC saves 11.8-12.5% of annual gas consumption for heating compared to CC (Table 7-1).

In order to explore the sensitivity of the results to different base temperatures, the calculations were repeated with a lower base temperature of 15.5ºC, as this is often used by convention for UK homes (CIBSE, 2006b) and also with 20.0°C, which, given the set-point temperature of 21°C would seem to be a plausible maximum value. The relationship between weekly gas consumption and weekly HDD was determined with these new base temperatures and the energy use recalculated. The regression coefficients with the new base temperature of 20°C were very similar to those achieved with a base temperature of 17.8°C. However, for the base temperature of 15.5°C the regression coefficients were much poorer ($R_{ZC}{}^2 = 0.55$, $R_{CC}{}^2 = 0.63$). However, it can be seen that the energy savings of ZC is not very sensitive to the base temperature selected (Table 7-1).

To estimate the impact on annual space heating costs, the Department of Energy and Climate Change (DECC, 2012b) energy & emissions projections central scenario for residential gas prices was used (Figure 7-3).

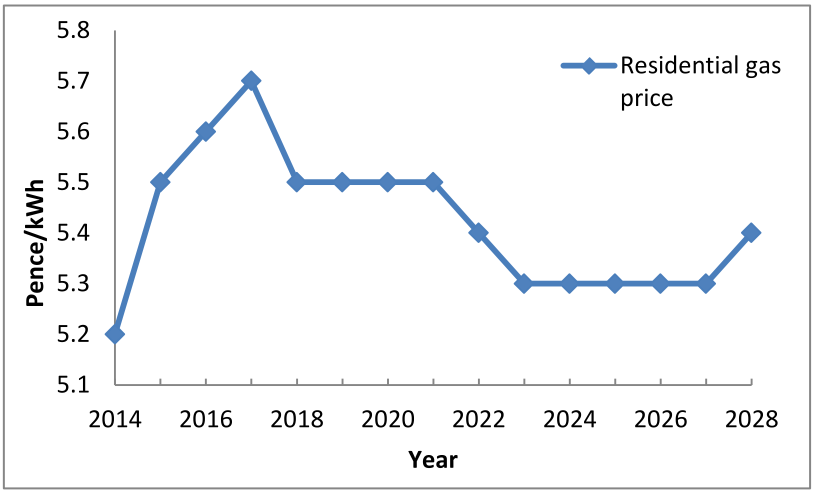


Figure 7-3: projected residential gas prices between 2014 and 2028 (DECC, 2012b)

A discounted cash flow analysis was conducted, using a modest discount rate of 5%, to calculate the Net Present Value (NPV) after 15 years (assumed lifespan of the system) of upgrading a same size house with conventional heating controls to zonal heating control in each of the 7 regions. The zonal heating kit is a recently developed commercial system and therefore the life span of the system is not exactly known, however, a typical normal TRV has a life span of 15 years and therefore a life span of 15 years was assumed for the programmable TRVs as well. The cost of batteries with a life span of two years was included in the total price of the system. The Internal Rate of Return (IRR), which stays the same regardless of the discount rate, was also calculated for each region as it is an indication of the discount rate necessary to pay back the investment within the 15 years. Two ZC systems with different capital costs were considered for the calculation of NPV: a ‘Luxury type 1’ ZC system with a touch screen central controller (which costs £1200 including installation costs) and a ‘basic type 2’ ZC system with no central controller in which PTRVs need to be programmed individually by the household (which costs £120).

The calculations show that, 15 years after upgrading to the Luxury ZC system, houses in Scotland will have a positive NPV while the houses in all other regions will have a slightly negative NPV with the houses in more Southern regions having larger negative NPVs (Table 7-1). This indicates that ZC is a more profitable energy efficiency measure for the homes in the colder more northerly parts of the UK. The IRR calculations show that discount rates of up to about 6% is imaginable for the house in Scotland, whereas the upgrade to luxury ZC would only be financially worthwhile in London at discount rates of below 3.5% (Table 7-1). In contrast, if households buy the basic ZC system, which is 10 times cheaper than the luxury system, they can save about £1000 (present value) after 15 years, regardless of the location of their house (Table 7-1).

Calculations using the base temperature of 15.5^{o}C and 20^{o}C show that the NPV and IRR are sensitive to the base temperature selected. This is due to the fact that NPV and IRR are dependent on the actual kWh of gas saved when using ZC rather than the percentages of gas savings. It was found that considering a base temperature lower than 17.8^{o}C, results in lower annual space heating energy use for both systems, thus lower kWh gas saved by ZC and correspondingly lower NPV and IRR while using a higher base temperature results in exactly opposite results. However, irrespective of the HDD base, ZC was found to be a more cost effective measure in Northern regions of the UK based on the empirical approach discussed.

Table 7-1: Estimated gas use for heating the test house, with the same occupancy, in seven different regions of the UK, using either ZC or CC and, the NPV, IRR or financial savings, for both a basic and a luxury ZC systems

Region (Weather station)	Annual heating energy use CC[1] (kWh)	Annual heating energy use ZC[1] (kWh)	Reduction in heating energy use (%)	NPV after 15 years: Luxury system[2] (£)	IRR Luxury system[3] (%)	NPV after 15 years: Basic system[2] (£)
London (Gatwick)	15685 *14884, 15950*	13839 *13217, 14053*	11.8% *11.2% , 11.9%*	-£109 *-£214, -£79*	3.4% *1.8%, 3.9%*	£971 *£866, £1001*
East of England (Hemsby)	15696 *14875,15963*	13848 *13210, 14064*	11.8% *11.2%, 11.9%*	-£108 *-£216, -£77*	3.4% *1.8%, 3.9%*	£972 *£864, £1003*
Northwest (Aughton)	15805 *14973, 16073*	13936 *13286, 14152*	11.8% *11.3%,11.9%*	-£95 *-£203, -£65*	3.6% *2.0%, 4.1%*	£985 *£877, £1015*
West Midlands (Birmingham)	16354 *15460, 16623*	14379 *13667, 14596*	12.0% *11.6%, 12.2%*	-£33 *-£140, -£2*	4.5% *2.9%, 5.0%*	£1,047 *£940, £1078*
Ireland (Belfast)	16374 *15471, 16642*	14395 *13675, 14611*	12.1% *11.6% , 12.2%*	-£30 *-£139, £0*	4.6% *3.0%, 5.0%*	£1,050 *£941, £1080*
Yorkshire (Finningley)	16507 *15604, 16774*	14503 *13780, 14718*	12.1% *11.7%, 12.2%*	-£15 *-£121, £15*	4.8% *3.2%, 5.2%*	£1065 *£959, £1095*
Scotland (Aberdeen)	17346 *16334,17616*	15180 *14349 ,15397*	12.5% *12.1% ,12.6%*	£80 *-£27, £111*	6.1% *4.6%, 6.6%*	£1,160 *£1053, £1191*

Calculated based on HDD base temperature of 17.8ºC in large regular fonts; Calculated based on 15.5ºC and 20.0ºC in *small italic font*.

[1] For a typical weather year with heating months being October to April.

[2] Based on Department of Energy and Climate Change (DECC, 2012b) energy & emissions projections central scenario for residential gas prices and discount rate of 5%

[3] Based on the life span of 15 years for TRVs

7.3 Evaluation of the DTM results for different UK locations and comparison with empirical evaluation

A calibrated DTM of the LMP1930 test houses which could reasonably predict the potential savings from ZC compared to CC during the HT1 was constructed as discussed in chapters 5 and 6. In this section, this model was used to investigate the effects of weather in different regions of the UK on potential annual space heating energy savings of ZC. These results were then compared with the results of the empirical approach described in section 7.2.

The typical weather year data used in the empirical work were also used with the DTM for the same seven UK regions: London, the East of England, the West Midlands, Yorkshire, the Northwest, Northern Ireland and Scotland. The same heating season was also considered: from 1st of October to end of April. The heating season averages of air temperature, wind speed and global horizontal radiation in each region are presented in Table 7-2. Each simulation took more than 1 hour to complete (computer used: HP ProBook 6460b, 2.5 GHz processor, 4.0 GB RAM) due to the complexity of the model and AFN calculations.

Table 7-2: Average air temperature, wind speed and global horizontal radiation in each region during the heating season

Region	Average air temperature (°C)	Average wind speed (m/s)	Average global horizontal solar radiation (Wh/m^2)
London	6.74	3.3	64.9
East of England	6.73	5.8	65.0
Northwest	6.65	4.5	59.7
West Midlands	6.3	4.0	66.7
Ireland	6.28	5.1	55.8
Yorkshire	6.2	4.5	59.5
Scotland	5.65	5.1	54.0

Annual gas use of the LMP1930 test houses predicted by the DTM was compared to annual gas use estimated by the empirical model (Table 7-3). For all the regions, the annual gas use of both houses with CC and ZC predicted by the DTM was more than the annual gas use estimated by the empirical model. The difference between the annual gas use of the house with CC predicted by DTM and empirical model varied from 8.3% in London to 15.0% in the East of England. For the house with ZC, this difference varied from 6.4% in London to 16.9% in Scotland.

The differences found between the predicted energy use by the empirical model and DTM could be explained due to their different methodology for estimating the annual gas use. The HDD method used in the empirical model took into account only the outdoor air temperature for predicting the annual energy use. Therefore, as it can be seen in Table 7-2 and Table 7-3, as the average air temperature decreased from region to region, the estimated annual gas use by the empirical model increased for both houses. In case when two regions had very similar average air temperatures (for example London and the East of England) (Table 7-2), the gas use predictions by the empirical model was also very similar (Table 7-3). However, this was not the case for the DTM. For example, although London and the East of England had about the same average air temperature during the heating season (Table 7-2), DTM predicted 7.3% more energy use for the house with CC and 9.6% for the house with ZC for the East of England compared to the houses in London. Since their average global horizontal solar radiations were also very similar (Table 7-2) for these two locations, this could be explained due to considerably higher average wind speed in the East of England (5.8 m/s) compared to London (3.3 m/s).

Another example could be observed when comparing the North West and the West Midlands regions. The air temperature was on average colder in the West Midlands by 0.35°C (Table 7-2). However, the average wind speed was lower by 11% and the average global horizontal solar radiation was higher by 10% compared to the Northwest. Since, the empirical model only considered the outdoor air temperature; it predicted higher annual gas use for house with CC in the West Midlands compared to the house with CC located in the Northwest. However, DTM which took into account the effects of wind speed and solar radiation predicted slightly higher annual gas use in the house with CC in the slightly warmer but windier and less sunny region; The North West.

As discussed, the effects of wind speed and solar radiation on the estimation of annual gas use were not considered in the empirical model. Therefore, the DTM have the advantage to take into account the variations of the solar radiation and the wind speed from region to region and could potentially provide more robust estimations.

Although the absolute amount of gas use predicted by the empirical model and DTM were up to 17% different, the predicted percentage of energy savings from applying ZC was closely matched between the two approaches for all the regions. While the empirical approach predicted the energy savings to vary from 11.8% to 12.5% among different regions of the UK, the DTM model predicts that to vary from 10.7% to 13.6%. The largest difference between the predicted percentage savings from ZC by empirical model and DTM was 1.8 pp which was found for the warmest and coldest regions (i.e. London and Scotland). This is remarkably close prediction especially when considering the differences between the two methodologies and the uncertainties involved in both models.

As discussed in section 7.2.3, the empirical model predicted that as we move towards the more northerly regions of the UK, the percentages of savings slightly increases. However, the difference between the percentages of savings from ZC in the warmest and coldest region (i.e. London and Scotland) was below 0.3 pp. DTM did not show such trend. In contrast, percentages of savings often predicted lower in more northerly regions of the UK. For example, the percentage savings in London were 2.9 pp higher than in Scotland.

These differences between the two model predictions prevent any conclusions been drawn on the effect of UK location on the potential savings. However, the effect of UK location was found to be small by either the empirical model or the DTM. More importantly, both models showed that ZC could save more than 10% of annual gas use in a typical un-furbished 1930s house regardless of the UK location.

Table 7-3: Total annual gas use for house with ZC and CC and annual percentages of savings by ZC in different regions of the UK predicted by DTM and Empirical Model (EM) and their differences

	Annual gas use (KWh) CC			**Annual gas use (KWh) ZC**			**% Savings from ZC**	
Region	**Empirical**	**DTM**	**% diff (DTM-EM)[1]**	**Empirical**	**DTM**	**% diff (DTM-EM)[1]**	**Empirical**	**DTM**
London	15685	17106	8.3%	13839	14781	6.4%	11.8%	13.6%
East of England	15696	18468	15%	13848	16351	15.3%	11.8%	11.5%
Northwest	15805	17994	12.1%	13936	15566	10.5%	11.8%	13.5%
West Midlands	16354	17985	10.0%	14379	15745	9.5%	12.1%	12.5%
Ireland	16374	19227	14.8%	14395	16980	15.2%	12.1%	11.7%
Yorkshire	16507	18468	11.9%	14503	16398	13.1%	12.1%	11.2%
Scotland	17346	19870	14.6%	15180	17741	16.9%	12.5%	10.7%

[1] Percentage difference between the predictions of energy use by DTM and Empirical Model (EM)

The cost analysis conducted using the same approach as discussed in section 7.2.3, but based on the energy savings predicted by DTM suggests that ZC is a cost effective retrofit measure across all the UK regions particularly when the basic system is employed (Table 7-4). The highest NPV after 15 years was found in the Northwest (£235 for the luxury and £1315 for the basic system) and the lowest was found in the Yorkshire (£24 for the luxury and £1104 for the basic system). In contrast with the empirical approach, DTM did not show clear relationship that suggests if the houses in the South or the North could be more financially benefited from installing the system.

Table 7-4: NPV, IRR or financial savings for both a basic and a luxury ZC systems calculated for seven different regions of the UK based on modelling results for the un-furbished houses

Region (Weather station)	NPV after 15 years: Luxury system[2] (£)	IRR Luxury system[3] (%)	NPV after 15 years: Basic system[2] (£)
London (Gatwick)	£174	7.4%	£1254
East of England (Hemsby)	£51	5.73%	£1131
Northwest (Aughton)	£235	8.3%	£1315
West Midlands (Birmingham)	£124	6.7%	£1204
Ireland (Belfast)	£128	6.8%	£1208
Yorkshire (Finningley)	£24	5.3%	£1104
Scotland (Aberdeen)	£59	5.8%	£1139

7.4 Implications for better insulated homes

To explore how savings might change in a better insulated house, the building envelope of the LMP1930 house was upgraded in the DTM. The following changes were made to the model:

- The air gap between the two layers of the external walls was filled with XPS Polystyrene (Table 7-5). This reduced the U-value of the external walls from 1.666 to 0.392 W/m^2K.
- 300 mm of mineral wool insulation was added to the roof construction, on top of the first floor ceiling (Table 7-5). This reduced the U-value of the ceiling (calculated by DesignBuilder) from 3.1 to 0.13 W/m^2K.

- All the windows were replaced by double glazed windows with 6 mm clear glass sheets and 13 mm air between the glass sheets. This reduced the U-value of the windows from 5.9 to 2.67 W/m^2K.
- Changing the windows would also improve the air tightness. As described in section 5.3.2, when using AFN, the length of the cracks are fixed (i.e. around the perimeter of the windows) and could not be changed without changing the sizes of the windows. However, the air flow coefficient (kg/s. m crack at 1 pa) could be changed to reflect the lower air leakage from the new double glazed windows. Therefore, the flow coefficients of the cracks around the windows which were adopted from DesignBuilder's "poor" template for the un-furbished model were changed to those for DesignBuilder's "good" template. This meant that the flow coefficients were changed from 0.001 to 0.00006 kg/s. m crack at1 pa.

Table 7-5: Thermal properties of the insulating materials used in the refurbished model

Material	Conductivity (W/m. K)	Density (kg/m^3)	Specific heat capacity (J/kg. K)
XPS Polystyrene	0.034	35	1400
mineral wool; stone wool rolls	0.04	30	840

The revised DTM predicted reduced annual gas use in all the regions as expected. The annual gas use of the house with CC was reduced by between 42% and 47% across different regions (Table 7-6). Similarly, the annual gas use of the house with ZC was reduced by between 42% and 46% (Table 7-6). The percentage of savings from refurbishment for houses with CC and ZC were very similar for each region. For both houses, the savings were higher in London and the West Midlands (45 to 47%) and lower in Scotland (42%).

To test the reliability of model predictions, the results were compared with those from another modelling tool: the Standard assessment procedure (SAP) (BRE, 2014). The house with CC was modelled in London and Scotland before and after refurbishment as SAP does not enable the modelling of ZC. The SAP model predicted 50% and 46% of savings after refurbishment for the house in London and Scotland respectively.

These were slightly higher than the predictions by the DTM; though remarkably close and in the same direction (i.e. higher savings after refurbishment in London compared to Scotland). Previous research by Yilmaz et al. (2014) had also shown that SAP tends to overestimate the percentages of savings which could be achieved by applying different refurbishment measures compared to EnergyPlus. This result adds confidence to the findings from the DTM.

The percentage savings of gas use from applying ZC predicted by DTM was found to be lower in the better insulated house compared to the un-furbished house in all the regions (Table 7-6). However, the percentage of savings from ZC was reduced more in the warmer regions (for example 2pp in London) compared to the colder regions (for example 0.2pp in Scotland) after refurbishment. The percentages of savings from applying ZC in the better insulated house were found to range from 9.3% in the East of England to 11.8% in the Northwest. The results from the model showed that considerable amounts of energy which is used for space heating could be saved even in refurbished (better insulated) UK houses and in all regions; although to a less extent compared to un-furbished houses.

Table 7-6: Annual gas use and percentages of savings from refurbishment for ZC and CC houses for different regions of the UK along with percentage of savings from ZC after refurbishment and its differences compared to the savings in un-furbished house

Region	Annual gas use (KWh) CC	% Savings from refurbishment	Annual gas use (KWh) ZC	% Savings from refurbishment	% Savings from ZC	pp difference in savings from ZC compared to un-furbished
London	9028	47	7981	46	11.6	-2.0
East of England	10306	44	9351	43	9.3	-2.2
Northwest	10026	44	8842	43	11.8	-1.7
West Midlands	9788	46	8672	45	11.4	-1.1
Ireland	10791	44	9756	43	9.6	-2.1
Yorkshire	10300	44	9235	44	10.3	-0.9
Scotland	11551	42	10334	42	10.5	-0.2

The cost analysis which was conducted similar to the case of un-furbished houses suggests that a luxury ZC system would not be a cost effective retrofit measure for homes when refurbished similar to this study (Table 7-7). NPV after 15 years for all the seven regions were negative; ranging from -£481 in Scotland to -£635 in the East of England. IRR was also negative for all the regions for the luxury system which shows that the investment is not profitable. However, a basic ZC system would still be a cost effective measure across all UK regions even after refurbishment as it was confirmed by positive NPV across all the regions.

Table 7-7: NPV, IRR or financial savings for both a basic and a luxury ZC system calculated for seven different regions of the UK based on DTM results for better insulated houses

Region (Weather station)	NPV after 15 years: Luxury system[2] (£)	IRR Luxury system[3] (%)	NPV after 15 years: Basic system[2] (£)
London (Gatwick)	-£581	-4.5%	£499
East of England (Hemsby)	-£635	-5.6%	£445
Northwest (Aughton)	-£500	-3.0%	£580
West Midlands (Birmingham)	-£540	-3.7%	£540
Ireland (Belfast)	-£588	-4.7%	£492
Yorkshire (Finningley)	-£570	-4.3%	£510
Scotland (Aberdeen)	-£481	-2.6%	£599

7.5 Summary

In this chapter, two models were used:

(a) An empirical model which was developed using the HDD method based on the data measured over the 8-week period of the space heating trials; and

(b) A calibrated DTM which was created as described in chapters 5 and 6.

They were used to predict the annual energy savings which could be achieved by applying ZC instead of CC in houses built and occupied in similar way to the LMP1930 but located in different UK regions.

The empirical model predicted that:

- ZC could save 11.8% to12.5% of the annual space heating gas use compared to the CC regardless of the geographical location.
- The amount of savings is likely to be more in Northern regions of the UK.

The DTM model predicted that:

- ZC could save 10.7% to13.6% of the annual space heating gas use compared to the CC regardless of the geographical location.
- There is no clear relationship between the potential energy savings of ZC and the geographical location of the house.

The differences between the predictions of DTM and empirical model were considered to be due to their different level of details incorporated in the methodology of the two models.

The DTM was also used to predict the savings for better insulated homes with cavity and loft (attic) insulation and double glazing instead of single glazing located in different regions. DTM predicted that savings from ZC would be slightly (between 0.2 to 2.2 percentage points) lower in a better insulated house across all the regions.

It was found that ZC is a profitable energy efficiency measure for both un-furbished and refurbished UK homes across all the regions when a cheap basic system is employed.

8 Discussion and future work

8.1 Introduction

Saving energy in the residential sector and in particular heating energy is essential to achieve the UK's 2050 carbon emissions reduction target. In recent years, development and deployment of new space heating control strategies, which could enable households to more efficiently control the delivery of heat, has commanded the attention by the academics, industry and the government. In the UK, two-zone space heating control has become mandatory for new homes, and the effect of time and temperature zone control has been considered in the UK government's Standard Assessment Procedure (SAP) for the energy performance assessment of dwellings. Zonal space heating control (ZC) using programmable TRVs is one of such emerging systems and allows households with low pressure wet central heating systems to heat only the occupied spaces of their house instead of all the spaces and therefore potentially save energy. A range of such products is currently available on the UK market. The systems are easy to retrofit making them a valuable energy efficiency measure provided the claimed energy savings can be realised in practice.

Prior to this research, there was no peer reviewed published literature to indicate how much energy ZC might save in UK homes. Without such information, households could only rely on the claims of the manufacturers which could be misleading. A reliable and repeatable method has therefore been developed to measure the energy saving potential of a ZC system compared to a conventional control (CC) system. The results from the measurement campaign are discussed in section 8.2. A Dynamic Thermal Model (DTM) was then used to predict the savings in the same house. The model was calibrated using the measured data. The findings from the DTM analysis are discussed in section 8.3. The potential for energy savings with ZC was then assessed for different UK houses using an empirical model based on the measured data and the DTM and their predictions were compared. The results are discussed in section 8.4. Finally, section 8.5 provides a summary of this chapter.

8.2 Measuring the energy savings potential of ZC in a UK home

To the best knowledge of the author, this is the first study that directly measured the impacts of ZC on energy use and indoor air temperatures in UK houses. The side-by-side comparison method adopted for the space heating trials is a powerful technique by which the effects of home energy efficiency measures on building energy use and thermal comfort can be independently assessed whilst controlling for the effects of the other influential factors, such as the outdoor weather, occupant behaviour and heating system characteristics. The method enables relatively small differences in energy demand caused, for example, by energy efficiency measures, to be identified. Although this method was used in the late 1970s and 1980s, for example in a couple of studies by the UK Building Research Establishment (BRE) (Rayment et al. 1983 and Rayment & Morgan 1984), the method has rarely been used since. A literature review showed that lack of such comparisons was one of the main factors which limited the availability of consistent evidence on the energy savings potential of new space heating controls (Munton et al. 2014). The lack of recent studies is believed to be because paired full-size test facilities are not widely available; they can be expensive to construct or buy, the creation of synthetic occupancy regimens is expensive and time consuming, and the need to match the buildings can take time and effort. Pairs of old un-furbished homes, as used in the trials reported here, are very hard to find and secure for research purposes.

Much effort was put into matching the two existing, un-furbished, 1930 houses, at Loughborough (LMP1930) by using the same heating systems and synthetic occupancy equipment and profiles, minimizing the effects of different morning and afternoon solar gains and by switching the space heating control strategies between the two space heating trials. However, although the houses showed remarkably close thermal performance during the characterisation tests, they cannot be considered to be 100% matched due to factors which could not be controlled such as the wind effects on the East and West facades and small inherent differences in their constructions.

The need to record occupants' behaviour when measuring the energy saving potential of heating controls was encouraged by recent studies (Munton et al. 2014). However, synthetic occupancy can eliminate the variability in the behaviour of people, which can dominate patterns of domestic energy demand. It also allows measures that are intrusive or potentially damaging to property or occupants. Examples of such disruptive measures in this study were using wired thermistors in every room, installing heat flow meters to measure boiler heat outputs, and insulating the windows in the East and West facades. However, health and safety concerns may constrain the behaviours that are simulated. For example, turning on and off gas ovens and hobs, the automatic opening and closing of doors can pose dangers when researchers are working in the house and the operation of outside windows and doors can compromise security.

A number of assumptions were made in undertaking the experiments which place caveats on the generality of the results. First of all, a single occupancy profile was considered based on the time use data (ONS, 2002). However, the way occupants behave in their houses can be very different from this. For example, it was assumed that the occupants close the doors of the living room, dining room and bedrooms when they are 'occupied'. This is perhaps the best scenario for saving energy with ZC while maintaining comfort as it minimizes the heat transfer from occupied rooms to other rooms. In reality, the occupants might not wish to change their internal door opening habits, even if they know it is the best way to get the most benefit from ZC. The effect of different internal door opening behaviours on the energy savings by ZC is a useful area for future research.

The trials assumed a household with two working adults and two children, occupying all the rooms except one, who heat their home intermittently. It was found that ZC is likely to provide the greatest benefits with intermittent heating rather than continuous heating. This suggests that, if a house is occupied by a household that spends most of its time in a heated house, then ZC would save less energy. However, if that household tended to occupy only one or two rooms, rather than the whole house, then this could increase the energy savings from ZC. Future work is needed to consolidates the findings of this study and further investigate the effects of occupants' space use on the energy savings potential of ZC.

In this study, houses could achieve adequate fresh air by infiltration through the leaky fabric and so window opening was not mimicked. In practice, however, people may choose to open windows or trickle vents even in winter, for example at night in occupied bedrooms. The additional heat loss may extend the time needed to achieve comfort temperatures after the heating has switched on, thus reducing the benefits of ZC. In addition, it would further reduce the (already low) night time bedroom air temperatures when the heating is off and so could cause thermal discomfort.

The already complex, expensive and time consuming instrumentation curtailed the use of equipment for the detailed assessment of thermal comfort. Thus, indoor air temperature was taken as a proxy for thermal comfort. However, thermal comfort is better assessed using operative temperature, which combines air temperature and mean radiant temperature (MRT) (CIBSE, 2008). Although the difference between MRT and air temperature is usually small in well insulated homes, it is likely to be greater in thermally massive buildings which are intermittently heated. Further work is needed to better understand thermal comfort implications of ZC in different types of homes.

The forgoing discussion has indicated where there is scope for further useful work in LMP1930 or similar test houses to explore different occupancy schedules, heating regimes and thermal comfort measures. There are, however, matters that might more usefully be explored in other facilities or by other types of study. For example, this study only examined the potential savings from a house with a heating system that already complied with the building regulations. If houses have poorly controlled heating systems, i.e. no TRVs, or even no thermostat (PRT), then applying ZC could save considerably more energy. Moreover, this study used type 2 ZC systems in which the boiler operation is controlled using a master room thermostat. The consequences of the boiler control mechanism used by type 1 ZC systems (in which each PTRV can call for heat) on the energy savings and boiler efficiency needs further investigation.

The 11.8% gas savings achieved by ZC compared to CC in the LMP1930 were based on data collected over an 8-week period and were only reliable for houses of the same size, type, thermal mass and thermal efficiency and under the same weather conditions. The space heating trials did not measure the annual gas savings, or savings in refurbished houses or those located in different UK regions. Conducting longer or larger field trials was not possible in this work. However, even in large field trials, results are limited only to the homes and households from which the data are gathered. Therefore, dynamic thermal modelling was employed to explore the performance of ZC more thoroughly.

8.3 Dynamic thermal modelling and calibration of a UK home with ZC

This is believed to be the first study in which a DTM has been used to simulate zonal space heating control with actual measured data being used to calibrate the model. DTM allow the performance of energy efficiency measures to be investigated. However, a large number of inputs are required to construct a model, and these are often very difficult to measure and unavailable even for well characterised buildings. Input parameters are assumed by the modeller and simplifications are inevitable. The documentations provided with DTMs provide guidance on the values that can be used, or assumptions that can be made by modellers. However, the guidance is often very general, insufficient or unsuitable for a particular building. Hence, the modeller's art is to make the "best guess" for the missing parameters in absence of any rigorous measured evidence. The inaccuracies of the assumed parameters are a major contributor to the inaccuracies of the DTM's predictions and the differences between the predicted and measured performance of buildings, known as the "performance gap".

A number of assumptions were made when constructing DTMs to simulate the co-heating test and space heating trials which their potential implications on the results should be carefully considered. For example, the party wall cavity was modelled as a partition wall. However, there is evidence in literature (Lowe et al., 2007) which shows significant heat losses from air movement through the party wall cavities. Since the overall heat loss from each house matched the measured heat loss in the co-heating test, this would suggest that the model over-predicted the heat loss by other means (e.g. conduction through external walls or infiltration) to compensate for the unaccounted heat loss through the party wall cavity. In addition, this would suggest that the model under-predicted the heat loss through the rooms adjacent to the party wall and as a result over-predicted the heat loss from other rooms to match the predicted overall heat loss to those measured. However, in this work, it was not possible to measure the heat loss from individual rooms and future work is needed to support more evidence.

A futher example of model simplifications is that chimneys and chimney breasts were not explicitly modelled. Although, passive air vents located at original fire places were sealed to minimise the air flows through chimney breasts, still air could have been escaping through small cracks. This could result in higher heat loss via infiltration in rooms which had a chimney compared to the predicted infiltration heat loss when chimney breasts were not considered. On the other hand, chimneys are non-insulated ventilated cavities which could potentially have insulating effect and therefore reduce the heat loss through the party wall. Reduced fabric heat loss and increased infiltration heat loss would have cancelling effect considering the overall heat loss of the room. In addition, the model without chimneys did not consider the thermal mass of the bricks used in construction of the chimneys which is believed to be relatively small compared to the rest of the house. To accurately model existing buildings, reconciliation of the model predictions with the known, measured, performance, which is known as model calibration, is essential. Such calibration provides greater confidence in a model’s predictions. Using test house facilities with synthetic occupancy instead of real occupied homes greatly assisted the process of model construction and calibration. It eliminated the uncertainties in model inputs related to occupancy, which determine the operation of doors, windows and window blinds as well as the time, location and magnitude of the equipment heat gains. In addition, the characteristics of the heating system components and their operation, including the heating regimes and nominal set-point and set-back temperatures, were fully known. In this research it was also possible to undertake whole house characterisation tests and use these to calibrate the DTM’s representation of the buildings’ envelope. This is not practical in occupied houses as it needs the houses to be vacated for a long period.

Modelling the performance of the houses when they were subject to a co-heating test, in which all the spaces of the house are continuously heated to the same temperature, was significantly easier than modelling multi-zone, intermittently used, wet heating systems. The base case model created in EnergyPlus showed reasonable predictions of the energy use in both houses when the co-heating test was simulated. However, when Heating Trial 1 (HT1) was simulated using the calibrated building envelope model, the model could not predict the energy use and indoor air temperatures with reasonable accuracy. The predicted energy saving of ZC was considerably higher than the measured savings. This clearly shows the risks involved in trusting predictions of complex models without rigorous calibration of the model using actual measured data.

Achieving a good model of the intermittently heated multi-zone house controlled by ZC was difficult. One of the main challenges was to model the air flows in the building. Both simplified, and a more detailed air flow modelling strategy was tested and each had its own advantages and disadvantages. A Scheduled Natural Ventilation (SNV) method which included defining the infiltration rate to each room, could not model the wind and buoyancy driven air flows but it did allow the use of the measured whole house air tightness value in the model. The simplified assumption of SNV that equal amounts of air are exchanged between zones was found to be a good approximation when all the zones were heated to the same temperature. However, in this study, SNV was found to be unsuitable for modelling the air flows in the house with ZC. For this case, inter-zone heat transfer via natural convection was better represented using an Air Flow Network (AFN). Although AFN provides a more detailed approach, it requires a large number of model inputs particularly envelope leakage and wind pressure coefficients which are difficult to measure even in test facilities. A standard blower door test provides no information regarding the distribution of air leakage paths, the ventilation rates in individual zones or inter-zone air flows. These can, in principle, be determined using tracer gas techniques or by conducting a number of air tightness tests using more than one fan (Liddament, 1996). Multi-tracer gas techniques have also been previously used to determine the air exchange between zones. However, according to Liddament (1996), "*Measurements using more than three tracers are rare and the practical maximum is probably restricted to five. This limits the number of zones in which measurements can be made*". Increasing the number of zones in a ZC house would cause the instrumentation and computer controlled feedback and injection system required for these methods to become extremely complex and bulky[16]. Given these difficulties, it was not possible to calibrate the AFN. In fact, except for a very limited number of validation projects, reconciliation of measurements with an AFN model has not been done with "any degree of scientific rigor" (Armstrong, Hadley, Stenner, *et al.*, 2001). This could place caveats on accuracy of the room-by-room infiltration rate predictions as well as inter-zone air flows. However, it should be noted that although the predicted heat loss via infiltration or heat losses from individual rooms could not be tested, the overall heat loss from the houses was in good agreement with the co-heating test. Developing improved methods which could measure the air flows in the buildings is essential for rigorous calibration of multi-zone dynamic thermal models.

It was also difficult to reliably model the thermal effects of intermittent heating. Intermittent heating requires prediction of heat up and cool down rates, which are highly dependent on accurate modelling of a building's thermal inertia as well as other parameters such as heating power and internal heat gains. Thermal inertia is a measure of the responsiveness of materials to variations in temperatures and includes the mass of the building envelope as well as partitions, furniture, equipment, etc. inside the building (Pupeikis, Burlingis & Stankevičius, 2010). These parameters are difficult to measure and accurately account in thermal models.

The radiator model in EnergyPlus is not able to model the dynamic behaviour of radiators (i.e. the time delay as the water warms or cools when the radiator is switched on or off) which resulted in much higher rates of heat up and cool down being predicted by the model than were measured. Because of this modelling error, it was difficult to accurately predict the air temperatures of the rooms during the periods of rapid changes in the load (i.e. when the heating was switched on or off). Others such as Booten & Tabares-Velasco (2012) have made similar observations. Future work is needed in this area. Accurate prediction of indoor air temperatures during the heat up periods would be particularly beneficial for the studies looking at thermal comfort in intermittently heated buildings. Without this ability, DTMs might not be able to realistically predict occupants' thermal comfort during the early hours of occupancy.

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[16] Liddament (1996) suggest the maximum number of zones that can be injected with gas is approximately ten.

Another challenge was to realistically model the performance of the Programmable Thermostatic Radiator Valves (PTRVs). Currently the operation of the PTRVs cannot be modelled in DTMs. The nominal set-point and set-back temperatures used in the base case model failed to realistically represent the variations observed in the room air temperatures during the heating hours. This was partially because the PTRVs were unable to maintain the nominal set-point temperatures in most of the rooms. This was worse when a room had closed doors or when high levels of internal heat gains were present in the room. It was due to the poor sensation of the air temperature of the room by the temperature sensors located on the PTRV heads which would be influenced by the heat from the radiators or other heat sources. Therefore, in this study, the mean air temperature measured during the occupied hours was used as the set-point temperature of each room for the purpose of model calibration. However, some discrepancies inevitably remained between the predicted and achieved air temperatures during the heating hours.

Modelling the operation of PTRVs is important for accurate predictions of energy demand and indoor air temperatures. Future research should be focused on implementing realistic TRV and PTRV operation in DTM tools. In addition, manufacturers should produce PTRVs which are able to receive temperature information from an external temperature sensor which is located in a position that better represents the mean room air temperature. Meanwhile, studies which aim to measure the energy savings which could be achieved by efficient space heating control systems could benefit from using a heating system in which the nominal set-point temperature is accurately achieved and maintained, perhaps using electrical heating. Electrical heating would also allow the heat input to each zone to be accurately and easily measured which would be beneficial for validation purposes.

Limitations and underlying assumptions in DTM tools also caused difficulties for reconciliation of the measured and predicted energy use and indoor air temperatures. For example, the AFN poorly represented the natural convective heat transfer via air flow through horizontal openings such as staircases. This was important as it did not allow accurate predictions of the air temperatures in the ground floor and first floor hallways. The ground floor hallway is where the master thermostat which controls the boiler operation is often located. Accurate prediction of the air temperature is essential for modelling heating systems with a master thermostat (such as type 2 ZC systems) as used in this study. Without accurate prediction of the air temperature of the zone with the master thermostat, EnergyPlus's Energy Management systems (EMS) could not improve the accuracy of the model predictions. Future work is needed to develop DTM tools which can accurately model the air flows through horizontal openings and allow heating systems with a master thermostat to be accurately modelled.

The core assumption of the heat balance equation in the multi-zone thermal models such as EnergyPlus is that zone air is well mixed with a uniform temperature distribution. This simplified assumption cannot reflect reality well because the room air temperature will vary throughout the room due to the various heat gain and stratification effects. In this study, the measured air temperature in the volumetric centre of each room was assumed to reasonably represent the room mean air temperature. However, using more than one temperature sensor in each room could have given more confidence in this assumption. Therefore, the comparison which was made between the measured and predicted room air temperatures should be only considered approximate. In recent years a number of advanced numerical models such as zonal models (Megri & Haghighat, 2007) have been developed and in very limited cases they were integrated into multi-zone DTMs in order to increase the accuracy of air temperature predictions within a zone. In addition, in a limited number of studies, computational fluid dynamics which is a more complex and computationally intensive method for simulating fluid flow, has been employed and integrated with DTM tools for this purpose (Negriio 1998, Beausoleil-Morrison 2000, Bartak et al. 2002 and Tan & Glicksman 2005). However, more work is needed in this area.

Differences in the weather file used in the model and the actual weather conditions during the tests also contributed to the discrepancies between the model predictions and the measured data. Except for the outdoor air temperatures, none of the input parameters used in the weather file was measured on site. Data was collected from three different weather stations which were between 2 to 26 km away from the houses. In particular, on site measurements of solar radiation could have been beneficial as discrepancies were observed between predicted and measured indoor air temperatures during the hours of high solar radiation. Global horizontal radiation can be measured on site using a pyranometer (Kotti, Argiriou, & Kazantzidis, 2014). However, it is more difficult to measure direct horizontal radiation which is measured using a pyranometer positioned horizontally on support equipped with an adjustable device such as a shadowband or shade disk that blocks the direct component from the sensor (Kotti et al., 2014). Future calibration studies should be designed to collect as many of the weather parameters as possible on site with particular attention to solar radiation data.

Of course, the precision of all the measurements made in the houses depends on the accuracy of the monitoring devices (as indicated in chapter 4) and the measurement methods adopted. This would also contribute to a part of the discrepancies between predictions and measurements.

Plotting room-by-room hourly air temperatures and inspecting the discrepancies between the measured and predicted values proved to be a useful method for identifying potential reasons for discrepancies between the measured and predicted performance. Combining this method with sensitivity analysis, which is a well established technique, would form a powerful procedure to assist with the calibration of multi-zone dynamic thermal models.

Despite the difficulties in calibration, a DTM of test houses could reasonably predict the energy use and indoor air temperatures during the first heating trial. The model predicted a very similar ZC gas savings to that actually measured. The model was validated according to the criteria recommended in ASHRAE guideline 14 (ASHRAE, 2002) for the hourly calibration of building simulation models. The model was then used to predict the savings in different regions of the UK and for a better insulated home.

8.4 Predicting the energy savings potential of ZC in different UK houses

Two different models were employed to predict the annual gas savings of ZC compared to CC in houses in different UK regions. Each model has its own advantages and disadvantages. The empirical model which was based on a Heating

Degree Day (HDD) analysis had substantial benefits over other simplified methods that use mean outdoor temperatures to calculate energy demand such as BSEN ISO 13790 (BSI, 2004) since the "*HDD method accounts for fluctuations in outdoor temperature and can capture extreme conditions in a way that mean temperature methods cannot*" (CIBSE, 2006b). The model developed was based on relationships found between the weekly gas use and the average outdoor air temperatures of each house during both space heating trials. Therefore, the empirical model's predictions did not directly take into account other influential factors such as solar radiation and wind. DTM is significantly more detailed and allows the effects of wind and solar radiation to be accounted in model predictions. However, DTM has its own limitations as discussed in section 8.3.

Employing two models for evaluation of the results was a powerful technique which allowed inter-model comparison in order to find confidence in the model predictions. The empirical model predicted that the energy savings by ZC would be greater in colder regions. It predicted that the annual gas savings of ZC varies from 11.8% in the warmest UK region (i.e. London) to 12.5% in the coldest region (i.e. Scotland). In contrast, the DTM did not show a trend for higher gas savings in colder regions. In fact, it showed lower savings in Scotland (10.7%) compared to London (13.6%). Since the results from the two models were not in agreement, this study was not able to conclude whether ZC would be more suitable for colder climates or warmer climates. Both models were based on data collected during a short winter period which did not include many warm days. This increased the uncertainty in the models used to extrapolate the measurements to warmer periods of the year and to other locations. Further trials, in milder weather conditions are needed to further investigate the effect of weather on the potential savings of ZC.

The evaluation using the DTM showed that the energy savings which could be achieved by ZC in a better insulated home would be slightly lower than for poorly insulated homes. It was estimated that ZC could save between 9.3 to 11.8% of annual gas use in a better insulated home across the UK regions. Findings were in line with previous forecasts by Utley & Shorrock (2008) that argued savings from heating certain spaces instead of the whole house could be higher for a house with poor levels of insulation while it would be lower for a well-insulated house where heat transfer from the heated spaces can often achieve the comfort temperatures throughout the house. There was a tendency for more reduction in the potential savings of ZC after refurbishment of the houses in warmer regions compared to houses in colder regions. For example, the annual gas saving of a house with ZC in London was estimated to reduce from 13.6% to 11.6% after refurbishment while it was only reduced from 10.7% to 10.5% for the house in Scotland. However, the reduction after refurbishment was small across all the regions (between 0.2 to 2.2 pp). More work using a DTM is needed to investigate the effects of different interventions on the potential energy savings of ZC.

Despite the fact that the empirical model and DTM were not in agreement regarding the effect of different UK region on the energy savings, both models predicted that ZC is able to save between 10-14% of annual gas use regardless of the UK location for the particular house and occupancy tested. In addition, the percentage of savings would not drop below 9% in any region even after the house was refurbished. This clearly shows that retrofitting of ZC to existing houses in the UK offers an opportunity for reducing energy demand for space heating. It is also much easier, cheaper, faster and non-disruptive for the households (but less energy efficient) than other retrofit measures such as external wall insulation, double glazing etc. The cost analysis also shows that upgrading to ZC could be a good investment for homes in the UK, especially when purchasing the cheaper basic system. However, the cheaper system does not have a user friendly interface with a touch screen central controller. This might influence how much households actually get involved with the control of their heating system and could shrink the potential cost savings of installing such systems. Large field trials are essential to investigate the occupants' interaction with ZC systems.

8.5 Summary

In this chapter, the results from the experimental, dynamic thermal modelling and evaluation campaigns have been discussed. The advantages of using test house facilities with synthetic occupancy rather than real occupied homes have been presented. On the other hand, this approach limits the generality of the results to other houses in other locations with different fabric energy efficiency. Areas for future work in similar test houses to further develop our understanding of the potential energy savings of ZC have been outlined.

The results of comparing predicted and measured energy use and indoor air temperatures during the heating trials have been discussed and the importance of model calibration prior to wider scale evaluation was argued. The difficulty of creating reliable multi-zone DTMs of houses with ZC have been presented and some limitations of current dynamic thermal modelling tools that could be be addressed in future work have been noted.

Finally, the strengths and weaknesses of the empirical and predictive evaluation techniques used in this study have been discussed. The results predicted by both techniques, for houses in different UK locations have been compared and the reasons for any discrepancies explored.

9 Conclusions

9.1 Introduction

In this thesis, the potential energy savings from using zonal space heating controls instead of conventional space heating controls in a UK home have been investigated and quantified. This was achieved by completing the three objectives. Firstly, a pair of test houses were instrumented and shown to be well matched in thermal performance using a side-by-side co-heating test. The houses were then automated to replicate the impacts of an occupant family (two adults and two school aged children). Over a winter period, the energy use and indoor air temperatures of the two houses were measured when the space heating had Conventional Control (CC) in one house and ZC in the other house. The control strategies were swapped half way through the test in order to avoid any differences between the thermal performances of the two houses. Then, a dynamic thermal model (DTM) of the same houses with the same occupancy pattern was constructed and calibrated against the measured data. Finally, the results from the experimental work and the DTM were evaluated and the potential energy savings of ZC in different UK climates or in better insulated homes was investigated. This chapter summarises and concludes the main findings from each of the three components of this study and provides recommendations based on this research.

9.2 Measuring the energy savings potential of ZC in a UK home

Zonal control heating was compared with conventional control in a matched pair of 1930s -era UK semi-detached houses with synthetic occupancy over an 8-week winter test period (16 February to 21 April 2015; including 9 days in which the test was stopped due to equipment failure and swapping the control strategies). It was found that:

- Daily boiler heat output of the house with ZC was lower than in the house with CC on every single day of the tests. On average, over the test period, ZC, compared to CC, provided a 14.1% reduction in measured boiler heat output.

- ZC reduced the average daily boiler efficiency by 2.4 percentage points.
- The resultant effect was that ZC produced an 11.8% saving in gas consumption over the 8-week monitoring period, compared with CC.
- The average air temperature in all of the rooms, and on average for the whole house, was lower with ZC than with CC during: the whole day, the period when the heating system was on, and the period when the heating was off. There was little or no reduction in the average air temperature in rooms while they were occupied and the occupants were awake, although during sleeping hours bedroom temperatures were up to 1.8ºC cooler on average with ZC. The average air temperatures of bedrooms in both houses during the sleeping period were below the air temperatures recommended by CIBSE.
- The average gas saving of ZC was found to be higher during the intermittently heated weekdays rather than the weekends when the houses were heated for longer periods.
- The PTRVs did not maintain their nominal set-point temperatures in most of the rooms as the average air temperature measured during the occupied period when the heating was on was different than the nominal set-point temperatures.

9.3 Dynamic thermal modelling and calibration of a UK home with ZC

A DTM of the test houses was constructed and the co-heating test and heating trial were simulated using two different air flow modelling strategies: Scheduled Natural Ventilation (SNV); and an Air Flow Network (AFN). Comparing the predicted energy use and indoor air temperatures with those measured during the tests revealed that:

- Both air flow modelling strategies were able to reasonably predict the energy use of the test houses under the co-heating test. However, for this case study, the simple SNV strategy provided energy use predictions which were closer to the measured energy use compared to when AFN was used. However, this does not provide definitive evidence on which of the two air flow modelling strategies would be more accurate or appropriate considering the assumptions and limitations incorporated in each approach.

- For the case of the heating trial, the energy use and indoor air temperatures predicted by the DTM prior to calibration were poor using either of the two air flow modelling strategies.
- Achieving a well calibrated DTM of an intermittently heated multi-zone house with a wet central heating system controlled by ZC was very difficult. This was due to: difficulties in accurately modelling air flows in the houses; limitations of the current dynamic thermal modelling tools such as difficulties in modelling the PTRV operation; underlying assumptions within the DTM regarding the fully mixed air temperature in a zone; inaccuracies of the measurements; and the availability of important model inputs.
- Hourly comparison of the measured and predicted indoor air temperatures and sensitivity analysis were found to be useful techniques for the calibration of the multi zone DTMs.

9.4 Predicting the energy savings potential of ZC in different UK houses

The potential savings from ZC for houses in different UK regions were calculated using an empirical heating degree day (HDD) method and also using the calibrated DTM. The empirical model suggested that:

- Regardless of geographic location, ZC, in houses built and occupied in a similar way to the test houses, could save about 11.8% to12.5% of the annual space heating energy, compared to CC.
- ZC is potentially a more cost-effective measure in Northern regions of the UK, compared with Southern regions. However, the financial costs and benefits of upgrading from CC to ZC are subject to many uncertainties.

The calibrated DTM suggested that:

- Regardless of geographic location, ZC, in houses built and occupied in a similar way to the test houses, could save about 10.7% to13.6% of the annual space heating energy, compared to CC.

- There is no clear relationship between the potential energy savings of ZC and the geographical location of the house.

- The DTM was also used to predict the savings for the houses after installing double glazed windows and insulating the cavity wall and the loft (attic) space. The DTM predicted that savings from ZC would be between 0.2 to 2.2 percentage points lower after refurbishment across all the regions. This was in agreement with the forecasts of previous studies.

The differences between the predictions of DTM and empirical model were believed to be because:

- The simplified HDD method employed in the empirical model only took into account the outdoor air temperature as the factor which determined the gas use while the more detailed DTM considered other influential parameters such as solar radiation and wind speed.

- Development of the empirical model and validation of the DTM model were based on data collected during a short winter period which did not include many warm days. This increased the uncertainty when extrapolating to warmer periods of the year and to other locations.

9.5 Overall conclusions and recommendations for future work

Annual gas savings of ZC compared to a house heated conventionally is in the range of 10-14% for a typical un-insulated 1930s UK family home. ZC is likely to save more energy in un-insulated and intermittently heated homes compared to refurbished, continuously heated homes. ZC could be considered as a cost effective energy efficiency measure for UK homes in all regions particularly when cheaper ZC systems are employed. Further studies in the Loughborough matched pair homes are suggested to enable the effects of different occupancy and heating schedules on energy savings to be investigated. Further work, using a dynamic thermal model calibrated against data which is measured for long period including warmer periods, will enable the energy saving potential of zonal control to be explored more fully.

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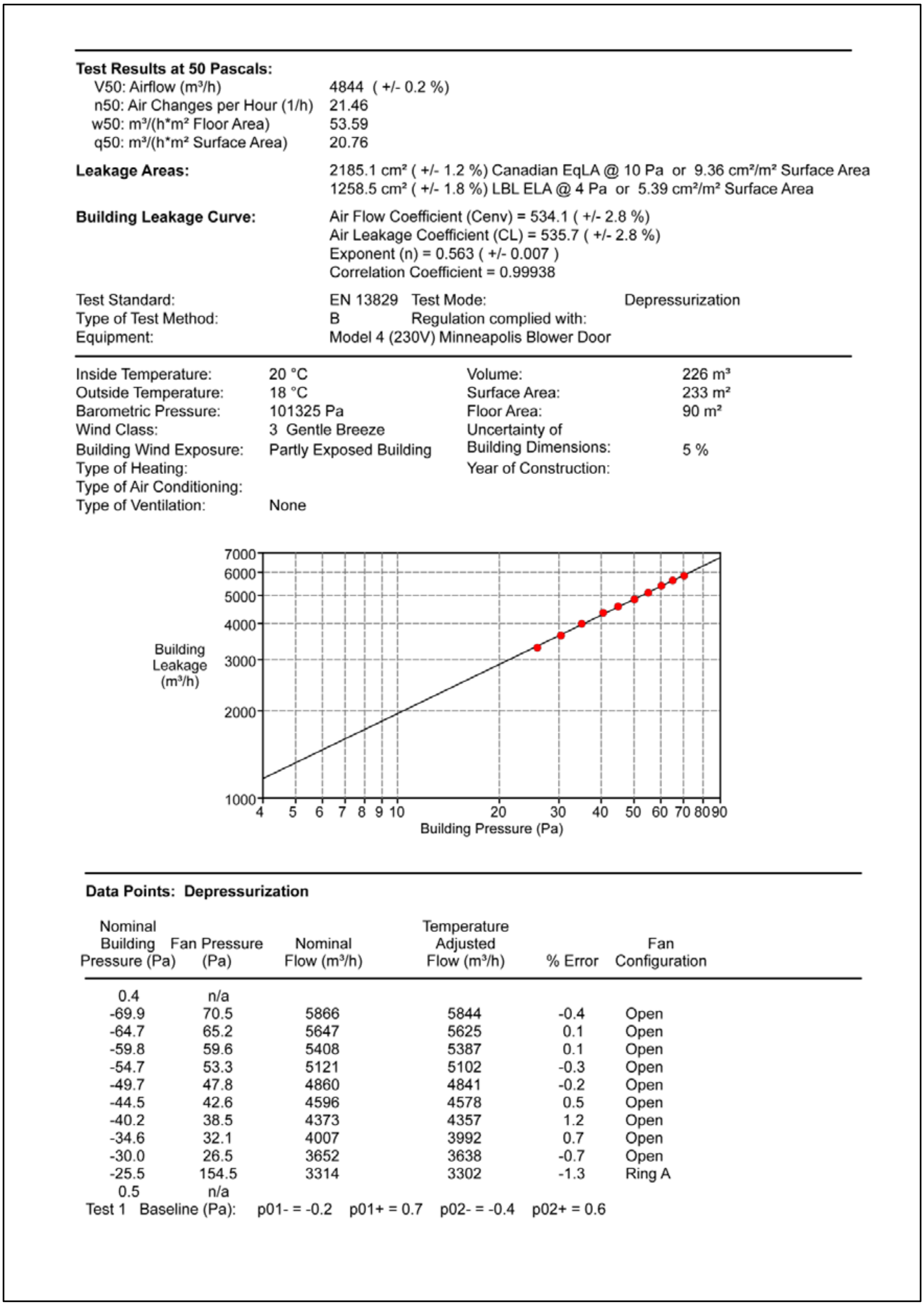
A.1 Appendix 1: Blower door test reports

A.1.1 House 1



Test Results at 50 Pascals:

V50: Airflow (m³/h)	4844 (+/- 0.2 %)
n50: Air Changes per Hour (1/h)	21.46
w50: m³/(h*m² Floor Area)	53.59
q50: m³/(h*m² Surface Area)	20.76

Leakage Areas:	2185.1 cm² (+/- 1.2 %) Canadian EqLA @ 10 Pa or 9.36 cm²/m² Surface Area 1258.5 cm² (+/- 1.8 %) LBL ELA @ 4 Pa or 5.39 cm²/m² Surface Area
Building Leakage Curve:	Air Flow Coefficient (Cenv) = 534.1 (+/- 2.8 %) Air Leakage Coefficient (CL) = 535.7 (+/- 2.8 %) Exponent (n) = 0.563 (+/- 0.007) Correlation Coefficient = 0.99938

Test Standard:	EN 13829	Test Mode:	Depressurization
Type of Test Method:	B	Regulation complied with:	
Equipment:	Model 4 (230V) Minneapolis Blower Door		

Inside Temperature:	20 °C	Volume:	226 m³
Outside Temperature:	18 °C	Surface Area:	233 m²
Barometric Pressure:	101325 Pa	Floor Area:	90 m²
Wind Class:	3 Gentle Breeze	Uncertainty of Building Dimensions:	5 %
Building Wind Exposure:	Partly Exposed Building		
Type of Heating:		Year of Construction:	
Type of Air Conditioning:			
Type of Ventilation:	None		

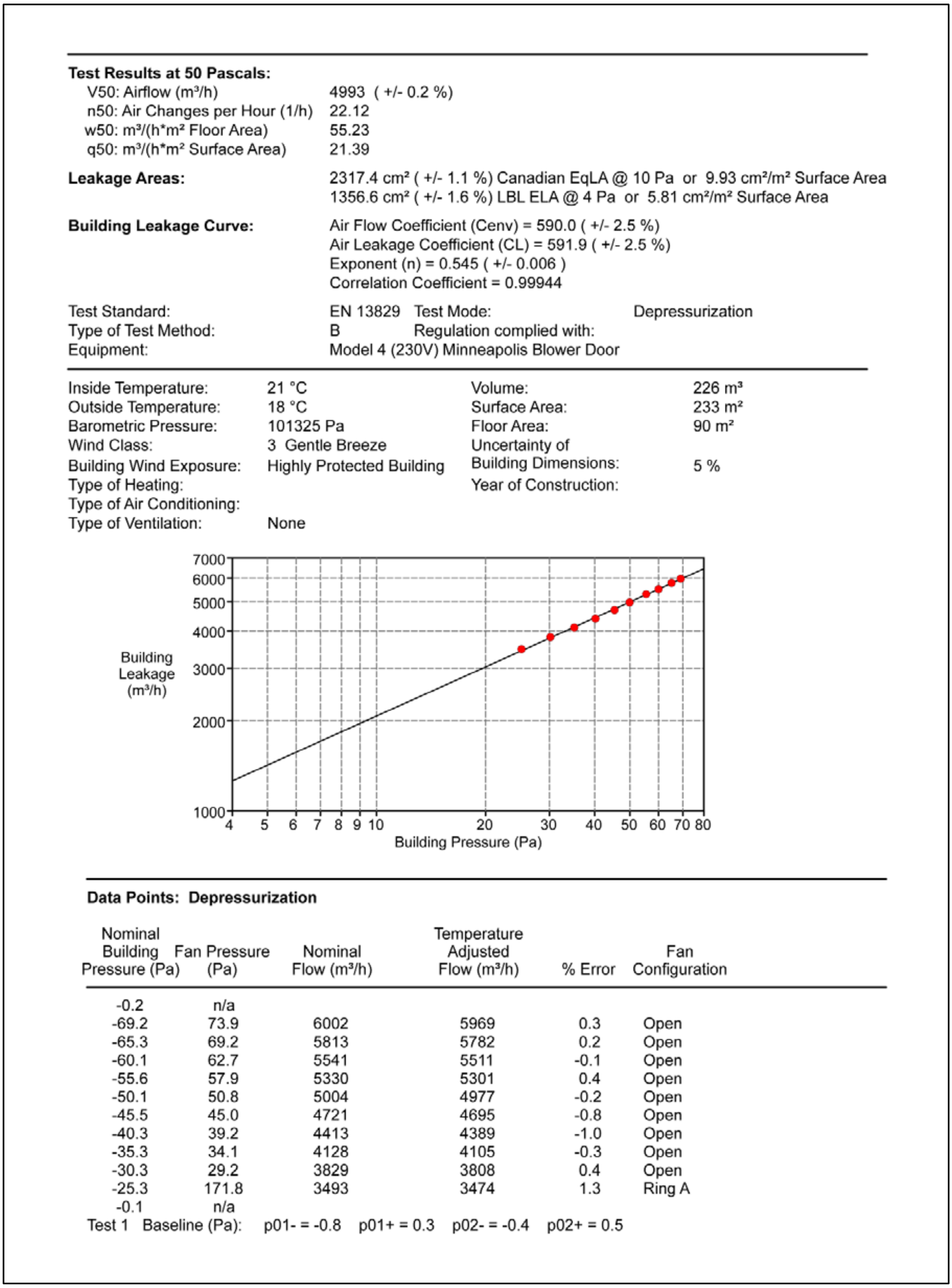
Data Points: Depressurization

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (m³/h)	Temperature Adjusted Flow (m³/h)	% Error	Fan Configuration
0.4	n/a				
-69.9	70.5	5866	5844	-0.4	Open
-64.7	65.2	5647	5625	0.1	Open
-59.8	59.6	5408	5387	0.1	Open
-54.7	53.3	5121	5102	-0.3	Open
-49.7	47.8	4860	4841	-0.2	Open
-44.5	42.6	4596	4578	0.5	Open
-40.2	38.5	4373	4357	1.2	Open
-34.6	32.1	4007	3992	0.7	Open
-30.0	26.5	3652	3638	-0.7	Open
-25.5	154.5	3314	3302	-1.3	Ring A
0.5	n/a				

Test 1 Baseline (Pa): p01- = -0.2 p01+ = 0.7 p02- = -0.4 p02+ = 0.6

Figure A-1: Blower door test report for House 1

A.1.2 House 2



Test Results at 50 Pascals:

V50: Airflow (m³/h)	4993 (+/- 0.2 %)
n50: Air Changes per Hour (1/h)	22.12
w50: m³/(h*m² Floor Area)	55.23
q50: m³/(h*m² Surface Area)	21.39

Leakage Areas:	2317.4 cm² (+/- 1.1 %) Canadian EqLA @ 10 Pa or 9.93 cm²/m² Surface Area 1356.6 cm² (+/- 1.6 %) LBL ELA @ 4 Pa or 5.81 cm²/m² Surface Area
Building Leakage Curve:	Air Flow Coefficient (Cenv) = 590.0 (+/- 2.5 %) Air Leakage Coefficient (CL) = 591.9 (+/- 2.5 %) Exponent (n) = 0.545 (+/- 0.006) Correlation Coefficient = 0.99944

Test Standard:	EN 13829	Test Mode:	Depressurization
Type of Test Method:	B	Regulation complied with:	
Equipment:	Model 4 (230V) Minneapolis Blower Door		

Inside Temperature:	21 °C	Volume:	226 m³
Outside Temperature:	18 °C	Surface Area:	233 m²
Barometric Pressure:	101325 Pa	Floor Area:	90 m²
Wind Class:	3 Gentle Breeze	Uncertainty of Building Dimensions:	5 %
Building Wind Exposure:	Highly Protected Building	Year of Construction:	
Type of Heating:			
Type of Air Conditioning:			
Type of Ventilation:	None		

Data Points: Depressurization

Nominal Building Pressure (Pa)	Fan Pressure (Pa)	Nominal Flow (m³/h)	Temperature Adjusted Flow (m³/h)	% Error	Fan Configuration
-0.2	n/a				
-69.2	73.9	6002	5969	0.3	Open
-65.3	69.2	5813	5782	0.2	Open
-60.1	62.7	5541	5511	-0.1	Open
-55.6	57.9	5330	5301	0.4	Open
-50.1	50.8	5004	4977	-0.2	Open
-45.5	45.0	4721	4695	-0.8	Open
-40.3	39.2	4413	4389	-1.0	Open
-35.3	34.1	4128	4105	-0.3	Open
-30.3	29.2	3829	3808	0.4	Open
-25.3	171.8	3493	3474	1.3	Ring A
-0.1	n/a				

Test 1 Baseline (Pa): p01- = -0.8 p01+ = 0.3 p02- = -0.4 p02+ = 0.5

Figure A-2: Blower door test report for House 2

A.2. Appendix 2: EMS Code for boiler control

```
! Boiler thermostatic control of 207 house
EnergyManagementSystem:Sensor,
  Hallway_Air_Temperature207,                          !- Name
  GroundFloor:Hallway207,                                    !-
Output:Variable Index Key Name
  Zone Mean Air Temperature;                                 !-
Output:Variable Name

EnergyManagementSystem:Actuator,
 Actuator_Loop,                                        !- Name
 HW LoopZC,                                                  !- Actuated
Component Unique Name
 Plant Loop Overall,                                         !- Actuated
Component Type
 On/Off Supervisory;                                         !- Actuated
Component Control Type

EnergyManagementSystem:Actuator,
 PumpFlowOverride,                                           !- Name
 HW LoopZC Supply Pump,                                      !- Actuated
Component Unique Name
 Pump,                                                       !- Actuated
Component Type
 Pump Mass Flow Rate;                                  !- Actuated Component
Control Type

EnergyManagementSystem:GlobalVariable,
 PumpFlowOverrideReport;

EnergyManagementSystem:OutputVariable,
 EMS Boiler Flow Override On [On/Off],                       !- Name
```

```
  PumpFlowOverrideReport,                              !- EMS Variable
Name
  Averaged,                                        !- Type of Data in
Variable
  SystemTimeStep;                                  !- Update Frequency

EnergyManagementSystem:ProgramCallingManager,
  HW LoopZC OnOff Management,                                  !-
Management type
  InsideHVACSystemIterationLoop,                       !- Calling time
  BoilerControl;                                   !- Program

EnergyManagementSystem:Program,
  BoilerControl,                                   !- Name
  IF (Hallway_Air_Temperature207 > 21.0),              !- Conditional
statement
   SET Actuator_Loop = 0.0,
   SET PumpFlowOverride = 0.0,
   SET PumpFlowOverrideReport = 1.0,
  ELSE,
   SET Actuator_Loop = Null,
   SET PumpFlowOverride = Null,
   SET PumpFlowOverrideReport = 0.0,
  ENDIF;
  Output:Variable,
  *,
  EMS Boiler Flow Override On,                         !- Output
variable name
  Hourly;

! Boiler thermostatic control of 209 house
EnergyManagementSystem:Sensor,
   Hallway_Air_Temperature209,                         !- Name
```

```
   GroundFloor:Hallway209,                                   !-
Output:Variable Index Key Name
   Zone Mean Air Temperature;                                !-
Output:Variable Name

EnergyManagementSystem:Actuator,
  Actuator_Loop1,                                   !- Name
  HW LoopCC,                                                 !- Actuated
Component Unique Name
  Plant Loop Overall,                                        !- Actuated
Component Type
  On/Off Supervisory;                                        !- Actuated
Component Control Type

EnergyManagementSystem:Actuator,
  PumpFlowOverride1,                                         !- Name
  HW LoopCC Supply Pump,                                     !- Actuated
Component Unique Name
  Pump,                                                      !- Actuated
Component Type
  Pump Mass Flow Rate;                                       !- Actuated
Component Control Type

EnergyManagementSystem:GlobalVariable,
  PumpFlowOverrideReport1;

EnergyManagementSystem:OutputVariable,
  EMS Boiler1 Flow Override On [On/Off],                     !- Name
  PumpFlowOverrideReport1,                                   !- EMS Variable
Name
  Averaged,                                         !- Type of Data in
Variable
  SystemTimeStep;                                   !- Update Frequency
```

```
EnergyManagementSystem:ProgramCallingManager,
  HW LoopCC OnOff Management,                                              !-
Management type
  InsideHVACSystemIterationLoop,                                 !- Calling time
  BoilerControl1;                                      !- Program

EnergyManagementSystem:Program,
  BoilerControl1,                                      !- Name
  IF (Hallway_Air_Temperature209 > 21.0),                        !- Conditional
statement
   SET Actuator_Loop1 = 0.0,
   SET PumpFlowOverride1 = 0.0,
   SET PumpFlowOverrideReport1 = 1.0,
  ELSE,
   SET Actuator_Loop1 = Null,
   SET PumpFlowOverride1 = Null,
   SET PumpFlowOverrideReport1 = 0.0,
  ENDIF;
  Output:Variable,
  *,
  EMS Boiler1 Flow Override On,                                  !- Output
variable name
  Hourly;
```