A THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

# UNDERSTANDING THE INTERACTIONS BETWEEN OCCUPANTS, HEATING SYSTEMS AND BUILDING FABRIC IN THE CONTEXT OF ENERGY EFFICIENT BUILDING FABRIC RETROFIT IN SOCIAL HOUSING

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June 2014

# DECLARATION

I, Jennifer Anne Love, declare that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

*June 2014*

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# ACKNOWLEDGMENTS

There are many wonderful people without whom I would not have been able to finish this thesis.

I would firstly like to thank my supervisors, Tadj Oreszczyn and Andrew Smith, for their guidance, insight and care over the years of my PhD, overcoming the challenges that it brought by their astounding intelligence and regular provision of assorted confectionary.

I would like to acknowledge the support I received from the "People Energy and Buildings: Distributions, Diversity and Dynamics" project (EP/H051112/1) jointly funded by the Engineering and Physical Sciences Research Council (EPSRC) and EDF Group. In particular I would like to thank the staff at EDF ECLEER for their encouragement and advice during my PhD.

I am extremely grateful for the help I received from Adam Cooper who guided me as I strayed out from my home discipline of physics into an unknown realm of combining social and physical approaches. I hope to see this carried out more and more in our field in the future.

Many other academics at UCL Energy Institute have provided help in all kinds of disciplines. I would especially like to thank Bob Lowe, Frank Smith, Phill Biddulph, Lai Fong Chiu, Cliff Elwell, Gesche Huebner, and David and Michelle Shipworth. I would also like to thank several fellow students in particular for helping with technical problems: Joel Guilbaud, Gwyneth Bradbury, David Veitch and David Polson.

I would like to thank some UCL staff who provided invaluable non-academic support: John Walden for keeping me from hitting my computer, and everyone in the UCL Energy Institute admin office.

The data collection would have not been possible without the RSL who let me monitor their site and went out of their way to help me and allowed me to present the results truthfully. It would also not have been possible without all the incredibly generous occupants who gave their time and shared their lives with me. It was a privilege to get to know them.

I would like to thank everyone who helped make sensors, and everyone who accompanied me on site, especially those who came in the snow. I feel that David Dijemeni and Lucy Aldous deserve a special mention, as they gave up their plans for me at zero notice to be ushered onto on a train, as does Virginia Gori who endured staying the night with me in an incredibly cheap hotel.

I would like to thank Penny Dunbabin at DECC, for the opportunity to take a break at a difficult time during my PhD and work with her on a different project, as this was a major turning point for me and my PhD. I would also like to thank all of my proofreaders who gave up their time at short notice.

Thank you to Mum and Dad, never stopping their support, letting me monitor them with all kinds of sensors, providing all kinds of academic support but also love which is more important.

Most importantly, inexpressible thanks and praise to almighty God and his son Jesus, in whom I find my joy, my purpose, my value and my identity, and who has taught me so much about himself throughout this PhD.

# ABSTRACT

In order for the UK to meet its 2050 carbon targets there needs to be a major energy efficient retrofit of the UK dwelling stock, of which one fifth is social housing. Evidence suggests that retrofit often leads to an increase in mean internal temperature at the expense of energy savings. Research has quantified this effect but little investigation has taken place regarding why temperature increase occurs.

This thesis measures the temperature change after installation of external wall insulation in social housing and attempts to separate out the causal influences of the building fabric and occupant behaviour. A longitudinal mixed physical and social methodology was used to collect data from 13 case study social housing dwellings. Physical variables of air and radiator temperature, relative humidity, secondary heating and use of space were measured in each room in the property, and combined with occupant interviews, in two consecutive winters before and after insulation was applied.

Mean internal temperature was observed to increase after retrofit: the majority of this was attributed to insulated properties cooling down more slowly. Observed changes in occupant behaviour consisted mostly of reduction in daily hours of heating, and no occupants increased the thermostat setting. Only a minority of homes purposefully increased their demand for heat. This is contrary to assumptions normally made about occupants deliberately 'taking back' energy savings as increased comfort.

However, the temperature during heated periods did increase in most dwellings. In several it appeared to have been previously constrained by the ability of the heating system to deliver sufficient heat.

The current algorithms for predicting mean internal temperature in models such as SAP and BREDEM are a simplification of the complex physical and social reality in most dwellings. This research gives recommendations as to how domestic heating use could be better modelled and controlled.

# PUBLICATIONS

Some ideas and figures have appeared previously in the following publication:

*Mapping the impact of changes in occupant heating behaviour on space heating energy use as a result of UK domestic retrofit*, presented at Retrofit 2012, January 2012, University of Salford

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# NOMENCLATURE

**Acronyms**

*A.H.H.* Approximate Heated Hours

*BREDEM* Building Reseach Establishment Domestic Energy Model

*C.H.* Central Heating

*C.O.P.D.* Chronic Obstructive Pulmonary Disease

*CARB* Carbon Reduction in Buildings

*CERT* Carbon Emissions Reduction Target

*CESP* Community Energy Saving Programme

*DUKES* Digest of UK Energy Statistics

*E.P.S.* Expanded Polystyrene

*E.W.I.* External Wall Insulation

*ECO* Energy Company Obligation

*EFUS* Energy Follow Up Survey

*HVAC* Heating, Ventilation and Air Condtioning

*M.I.T.* Mean Internal Temperature

*M.R.T.* Mean Radiant Temperature

*MVHR* Mechanical Ventilation with Heat Recovery

*P.H.P.* Potential Heating Period

*P.I.R.* Passive Infrared (sensor)

*R.F.I.D.* Radio-frequency Identification

*R.H.* Relative Humidity

*R.M.S.* Root Mean Square (error)

*S.H.E.U.* Space Heating Energy Use

*T.R.V.* Thermostatic Radiator Valve

*TRNSYS* Transient System Simulation Tool

**Definitions**

*Self − report methodology* A methodology involving data collected by asking occupants.

*Achieved demand temperature* Highest temperature achieved during a heating period.

*Alternative Secondary Heating* Secondary heat sources used instead of primary sources.

*Approximate Heated Hours* Time per day that the heating system is doing work

*Backfire* An increase in energy use following retrofit

*Background temperature* The model input representing the temperature when the heating is off, resulting from incidental heat gains and the heat loss of the building.

*BREDEM demand temperature* The temperature required by the occupants during the heating period (BRE 1997)

*Concurrent mixed methods* The use of several empirical methods at once.

*Convenience sampling* Sampling carried out on the basis of availability and ease of data collection.

*Cooling curve* Section of temperature timeseries from the end of the evening heating period, as a dwelling cools overnight.

*Cross − sectional* Referring to all of the housing stock at one point in time.

*Daily occupancy plot* A histogram of hourly occupancy events over the day, constructed from data from one occupancy sensor (normally that which best represents movement around the dwelling)

*Decrement delay* The time lag between the timing of the internal temperature peak and the peak heat flow out of the external surface (ARUP 2010)

*Dry − bulb temperature* The temperature of air measured by a thermometer freely exposed to the air but shielded from radiation and moisture.

*Fabric retrofit* Retrofit measures which increase the thermal resistance of the building fabric

*Fuel spend ratio* Ratio of actual to normative (modelled) fuel expenditure.

*Heating behaviour* An umbrella term for the set of five variables consisting of setpoint temperature, heating schedule, number of rooms heated, ventilation behaviour and use of secondary heating.

*Inter − room temperature gradient* The difference in temperature between the warmest and coolest room in a dwelling

*Longitudinal* Referring to data from one or more dwellings over time.

*M.I.T. Increase* Increase in mean internal temperature after retrofit calculated according to the procedure in Section 7.5.

*Manual heating control* Where heating is controlled by occupant pressing 'on' and 'off' at the programmer, or turning the thermostat down to zero and back up again, in order to turn the heating on and off (as opposed to using a timer).

*Mean internal temperature* Volume-weighted mean of the temperatures of the living room, bedrooms, kitchen and hall, over the time period of 1 day unless otherwise stated

*Metric* A variable constructed to convert empirical data into a useful quantity for this thesis

*Microgeneration* Retrofit measures enabling generation of low carbon energy on site.

*Mixed methodology* The use of methods from different methodologies.

*Mixed methods* The use of more than one method which can be drawn from the same methodology.

*Modelled daily heated hours* The model input representing the number of hours per day in which the primary (central) heating is switched on.

*Modelled demand temperature* The model input representing the temperature during the entirety of the heating period. Assumed also to be the temperature desired by the occupants during the heating period.

*Modelled mean internal temperature* The modelled value representing dwelling mean internal temperature, produced by calculation in BREDEM or SAP.

*Natural temperature increase* Temperature increase following building fabric retrofit which is solely as a result of an increase in thermal resistance of the building fabric, and not as a result of occupant change in behaviour

*Normative model* A model which uses a set of normative assumptions about occupant heating behaviour.

*Operative temperature* A resultant temperature experienced by an occupant, arising from a combination of convective and radiative heat transfer.

*Physical Data* Data collected through methods belonging to a physical methodology, for example occupancy data collected using passive infrared sensors.

*Potential Heating Period* Time per day that the heating system is switched on at the programmer

*Practice* A collection of sayings and doings associated with a behaviour - for example, clothes washing practices.

*Programmable thermostat* An integrated programmer and thermostat.

*Programmer* The wall-mounted panel from which heating can be switched on and off, either maunally by buttons or through use of an automatic timer.

*Responsiveness* A variable in BREDEM and SAP representing how long the delivered heat output takes to fall to zero once the heating is switched off.

*Room thermostat* A central thermostat, normally located in the living room or hall.

*Sequential mixed methods* The use of one empirical method followed by another, often so that findings from the first can be incorporated into the design of the second.

*Services retrofit* Retrofit measures which increase the efficiency of conversion of fuel to an energy service, for example heat or light.

*Sociall Data* Data collected through methods belonging to a methodology involving occupants reporting their perception of phenomena, for example data on thermal comfort collected using interviews.

*Stabilised demand temperature* Highest temperature during a heating period if the temperature plateaus over two or more measurements.

*Supplementary Secondary Heating* Secondary heat sources used at the same time as primary sources.

*Thermal admittance* Ability of a material to exchange heat with the environment when subjected to cyclic variations in temperature

*Thermostat* Shorthand for room thermostat

*Thermostatic Radiator Valve* Control on an invididual radiator to regulate its temperature.

*Timer* Device which can be programmed to automatically turn on an off the heating at certain times of day.

*Transient heating* A heating pattern in which the heating is on during some hours of the day and off during the remaining hours.

**Symbols**

$\epsilon$ Efficieny of an energy service

$\sum_d$ Sum over all days in one monitoring period for a given dwelling.

$\tau$ Thermal time constant, hours

$\eta_{I\varepsilon}$ Efficiency elasticity of demand for an energy service

$\eta_{IP}$ Price elasticity of demand for an energy service

$\triangle T_0$ Internal-external temperature difference at time = 0, degrees C.

$C$ Thermal mass of a dwelling, J/K

$E$ Energy use for space heating, J

$G$ Free useful heat gains (composed of solar gain and internal gains), W

$H$ Heat loss coefficient of a dwelling, W/K

$H_2$ BREDEM heat loss coefficient of zone 2, W/K

$H_3$ BREDEM inter-zone heat loss coefficient, W/K

$P_E$ Unit price of energy for space heating, £

$Q$ Delivered power from space heating, W

$r$ Three dimensional space (x,y,z) in a dwelling.

$RH'_{in,post}$ Post-retrofit mean internal relative humidity adjusted to pre retrofit external conditions, per cent

$S$ Energy service demand, J

$SVP$ Saturation vapour pressure, kPa

$T'_{ex}$ Mean external temperature plus temperature lift caused by free heat gains, in other words the minimum temperature the dwelling would cool to if left, degrees C

$t_{\frac{1}{2}}$ Thermal half-life, hours

$T_{diff}$ BREDEM demand temperature desired difference between zones 1 and 2, degrees C

$T_{ex}$ Mean external temperature, degrees C

$T_h$ Internal temperature during heated hours, degrees C

$t_h$ time during which the heating is on.

$T_h(d_{post})$ Temperature during heated hours of a post retrofit day, degrees C

$T'_{in,post}$ Post-retrofit mean internal temperature adjusted to pre retrofit external conditions, degrees C

$T_{in}$ Dwelling mean internal temperature, degrees C

$T_{post,line}(T_{ex} = 5)$ Point on the post-retrofit internal temperature line, when external temperature = 5 degrees, degrees C

$T_{post}$ Post-retrofit mean internal temperature, degrees C

$T_{pre}$ Pre-retrofit mean internal temperature, degrees C

$T_{uh}$ Internal temperature during unheated hours, degrees C

$t_{uh}$ time during which the heating is off, hours

$T_{uh}(d_{post})$ Temperature during unheated hours of a post retrofit day, degrees C

$Tctl$ BREDEM level of independence of zone 2 heating control from zone 1

$Td_1$ BREDEM demand temperature in zone 1, degrees C

$Td_2$ BREDEM demand temperature in zone 2, degrees C

$VP_{ex}$ External vapour pressure, kPa

$VP_{gen}$ Excess vapour pressure (generated within a dwelling), kPa

$VP_{in}$ Internal vapour pressure, kPa

t Number of hours during a day which have switched from heated pre retrofit to unheated post retrofit

t Time, hours unless otherwise specified

# 1

# INTRODUCTION

## 1.1 MOTIVATION FOR THIS THESIS

The factors determining energy use in buildings are complex and often poorly understood (Oreszczyn and Lowe (2010)). This lack of knowledge is concerning, as meeting national $CO_2$ targets requires a near-zero carbon retrofit of the domestic sector, costing billions of pounds. It is therefore very important to understand the likely impacts of retrofit. The UK government traditionally uses a physics-based model derived from the Building Research Establishment's BREDEM tool to make predictions about energy use and $CO_2$ savings. There is a growing awareness that such models do not fully represent occupant behaviour, including how it could change as a result of retrofit. However, there is a lack of data about if and how behaviour changes after retrofit, and what impact this might have on energy consumption and internal temperatures.

This thesis focuses on one type of retrofit strategy - increasing the efficiency of the building fabric - and one type of outcome - change in mean internal temperature. It uses a novel longitudinal mixed physical and social methodology to explore how and why change in mean internal temperature occurs in real dwellings. Monitored data of air temperature and heating system operation in all rooms are gathered both before and after installation of external wall insulation, and combined with occupant-reported data. This is then used to investigate the interactions between occupants, heating systems and building fabric which result in the observed temperature change.

## 1.2 LAYOUT

In this introductory chapter, a context is presented to show how the study of retrofit could be further advanced by a new type of in-depth empirical methodology which combines physical and social data. Chapter 2 presents the building physics theory needed throughout the rest of the thesis and examines how it is operationalised in current modelling tools used to simulate retrofit. A literature review follows in Chapter 3, much of it concerning behavioural variables and how they may change following retrofit. In Chapter 4 physical and behavioural aspects of energy use are then combined in a single model to give an indication as to how much change in behaviour might matter to space heating demand.

Once a foundation of theory, literature and modelling has been presented, research questions and methodology are developed in Chapter 5, and empirical methods are developed and described in Chapter 6. Chapter 7 explains how empirical data was analysed and variables developed to represent key quantities, such as change in temperature following retrofit.

There are three results chapters in this thesis. Chapter 8 addresses how mean internal temperatures change following retrofit. Chapter 9 addresses the reasons for this change, presenting three example case studies followed by a cross case comparison. Chapter 10 then addresses other interactions between occupants, heating systems and building fabric uncovered by the empirical study.

The findings are related back to the theory, literature and modelling context in the Discussion in Chapter 11. Finally, the Conclusion in Chapter 12 summarises the key findings and gives a critical reflection on the research design used in the thesis.

## 1.3 DEFINITIONS

The literature devoted to domestic energy use often mixes the popular use of terms with stricter scientific definitions, which can lead to problems in interpreting the results of research. In order to avoid this type of confusion, the following three conventions are used in this thesis:

- Terms used in their popular sense, whose meaning can be unclear, are given in single quotes. For example, from Section 3.2.4, "The term 'demand temperature' has also now come to be used to refer to empirical findings from real dwellings."

- Terms referring to a particular qualitative definition are both accompanied by a definition and emboldened the first time they are used. They are also listed in the Nomenclature section on page 27. Any further use of that term then refers to the strict definition. For example, from Section 1.4, **fabric retrofit** is defined as any intervention on an existing building which is designed to decrease the heat loss of the building fabric.

- Terms referring to a strictly-defined mathematical construct, formed from data in this thesis, are italicised every time they are used. For example, from Section 7.4.1, "...the *mean internal temperature* of a dwelling is defined in this thesis as volume-weighted mean temperature of the living room, bedrooms, kitchen and hall". They are also listed in the Nomenclature section. These terms often have modelled equivalents, not formed from data collected in this thesis, which are preceded by the word 'modelled' and not italicised. For example, from Section 2.3.2, "An influence diagram showing how modelled mean internal temperature is determined in BREDEM is shown in Figure 4."

Please note that all acronyms used in this thesis are written out in full in the Nomenclature section beginning on page 27.

## 1.4 WHY IS DOMESTIC RETROFIT NECESSARY?

'Low carbon retrofit' can refer to one of three types of interventions on an existing building: those which decrease the fabric heat loss (**fabric retrofit**), those which increase the efficiency of conversion of fuel to delivered energy, for example heat or light (**services retrofit**) or those which enable generation of low carbon energy on site (**microgeneration**). The first part of this chapter will consider all of these types of retrofit together as they often coexist in policy (Section 1.5) and analysis of interventions to date (Section 1.7). However from Section 1.9 onwards, the focus will be on fabric retrofit as this is the subject of the thesis.

The UK dwelling stock consists of approximately 27 million properties (Palmer and Cooper (2012)), many of which were built before energy performance was formally included in the building regulations. It is now acknowledged that the UK *"suffers from the poor thermal efficiency of a significant proportion of its housing stock"* (DECC (2011a)), and that fabric retrofit is a therefore required to increase the thermal efficiency of at least this part of the stock. The main motivations for this are described below.

The primary motivation for domestic retrofit is to reduce space heating energy use and hereby the emission of greenhouse gases which impact on the earth's climate. The gas which has received the most policy attention to date is carbon dioxide ($CO_2$), as its long atmospheric lifetime leads to accumulation and therefore increased radiative forcing over time (IPCC (2001)). The amount of $CO_2$ released into the atmosphere must be drastically reduced to reduce the risk of dangerous climate change: the 2008 Climate Change Act mandates an 80% cut in emissions by 2050 (HMSO (2008)). In the short term, the UK has a target of a 34% cut in 1990 greenhouse gas emissions by 2020 and five-year carbon budgets until 2050 (European Commission (2011)).

Emissions reduction is a huge undertaking which will affect every end-use sector, but the domestic sector is often identified as a sector with more cost-effective opportunities than others (IPCC (2007)). As a consequence, most developed countries have programs to reduce domestic energy use. In the UK, 15% of total $CO_2$ emissions are attributed to domestic space heating (DCLG (2007)), since most of this heat demand is supplied by the combustion of fossil fuels (natural gas, oil, coal). Strategies to reduce space heating demand and other emissions associated with the domestic sector involve both new builds and existing homes: the UK's Carbon Plan proposes that new homes are to be built as 'zero carbon' by 2016 (DCLG (2010)), and that retrofit of existing homes is a significant and urgent part of the nation's decarbonisation strategy (HM Government (2011)). The Fourth Carbon Budget stipulates ongoing energy efficiency improvement through the 2020s, including cumulative insulation of 3.5 million solid walls by 2030 in the residential sector (CCC (2010)).

A second, more localised, motivation for domestic retrofit is the effect on the occupants. For many households, the combination of inefficient dwellings and low income means that they either cannot heat their homes to a comfortable or healthy standard or do so at the expense of other necessary purchases. The term representing high relative necessary fuel expenditure is **fuel poverty**. The most appropriate method for quantifying the extent and the depth of the problem has been a topic of debate for many years, but under the low income-high cost indicator defined in Hills (2012), 2.4 million households (9%) were fuel poor in England in 2011 (the most recent year for which this information is available). The government, whilst still in the process of specifying a target for alleviation of fuel poverty, proposes to focus its efforts primarily on ensuring that those households who are fuel poor attain a certain standard of energy efficiency in their homes (DECC (2013a)).

Other justifications for retrofit of the dwelling stock include decreasing peak heat demand and increasing energy security through reduced demand, but climate change and

fuel poverty have received the most policy attention to date in the UK. The next section presents the government's existing schemes to address these issues.

## 1.5 how is domestic retrofit incentivised in the uk?

The UK government's response to the need to reduce energy consumption in existing dwellings consists of two policies in conjunction: the Green Deal and the Energy Company Obligation (ECO). The Green Deal scheme involves granting householders access to capital to fund energy efficiency works, which they gradually repay out of money saved on their energy bills. ECO, on the other hand, is an obligation placed on energy suppliers to reduce $CO_2$ emissions. This is effected by subsidising retrofit.

There are three areas in which subsidies provided by ECO funding are granted. The first is measures for 'hard to treat' housing, such as insulation for dwellings with solid walls, in which the loan repayment period for such measures under the Green Deal scheme would be very long. The second aims to reduce $CO_2$ emissions in neighbourhoods with a prevalence of low income households, and the third also targets vulnerable and low income households but is focussed on affordable heating as opposed to $CO_2$ emissions reduction. For the latter two components of the ECO, an effective way for energy suppliers to reach a high number of low income households at once is to partner with a local authority or a social landlord.

The combination of Green Deal and ECO schemes is designed to cover owner-occupied, social and private rented housing. These three sectors have not received equal policy attention to date. Social housing, representing 18% of the stock, is the primary sector in which policy driven large scale retrofit is currently being undertaken and is also the most energy efficient section of the stock. Privately-rented housing is on average older and contains a high proportion of the least energy efficient properties (DCLG (2013)).

Combinations of measures per dwelling vary, but in all of the sectors mentioned above measures cover upgrades to the building fabric, new space and water heating systems, energy efficient ventilation and lighting, and microgeneration (DECC (2011b)). It is often cost-effective to install multiple measures simultaneously. For example, the scheme preceding ECO (known as CESP) was set up in such a way as to incentivise installation of more than one measure per dwelling at once; as of 2011 there were around 2 measures installed per dwelling (calculated from figures in OFGEM (2011)).

## 1.6 WHY IS THE STUDY OF RETROFIT IMPORTANT?

It has been estimated that retrofit of the UK dwelling stock will cost £500 billion (IfS (2012)). It is essential that an understanding is gained of how to best invest this money to improve health and comfort, reduce $CO_2$ emissions and fuel costs and avoid unintended consequences (Davies and Oreszczyn (2012)). Between now and 2050 there is only enough time to undertake a national scale retrofit programme once, and therefore it needs to be successful. Therefore, the ability to set reasonable targets and then achieve them, whether energy and carbon savings or improvements in thermal conditions, is important from a policy and investment point of view. A prerequisite for the above is an evidence base of high quality data to identify the effect of previous interventions (Hamilton et al. (2013)), discussed in the next section.

## 1.7 THE UK STOCK AND THE EFFECTS OF RETROFIT TO DATE

Two metrics often used to represent the energy efficiency of dwellings are heat loss coefficient and SAP rating; the construction of the latter is explained in Section 2.3.1. The two metrics are calculated from information about the physical fabric of the dwellings and the installed energy services but do not take account of how occupants use energy in their homes.

Table 1 presents some key figures on the evolution of the UK housing stock, its efficiency and its energy use since 1970, summarised from Palmer and Cooper (2013) (where the % Change column contains 'N/A', this indicates that calculating the percentage change in the particular variable is not meaningful).

| | 1970 | 2012 | % Change |
|---|---|---|---|
| Number of dwellings, millions | 19.0 | 27.4 | +44% |
| Number of households, millions | 18.8 | 27.1 | +44% |
| Mean SAP rating | 17.6 | 56.7 | N/A |
| Mean dwelling heat loss, W/K | 376 | 290 | -23% |
| DUKES total UK domestic demand, TWh | 429 | 502 | +17% |
| Modelled annual space heating energy use per dwelling, kWh | 13,000 | 10,200 | -22% |
| Modelled annual $CO_2$ emissions per dwelling, tonnes | 10.3 | 4.5 | -56% |
| Modelled mean winter internal temperature, °C | 13.7 | 17.7 | N/A |

Table 1: The UK housing stock in 1970 and 2012, summarised from Palmer and Cooper (2013).

It can be seen from Table 1 that the average SAP rating has significantly increased over the last 40 years, and energy use and $CO_2$ emissions per dwelling have decreased. Palmer and Cooper state that the improvement in average SAP rating across the stock is mainly due to upgrades to existing homes. It can be attributed to more efficient boilers, improved glazing and cavity and loft insulation amongst other factors. However, mean internal temperature has increased, suggesting that higher demand for heat in homes may have offset some of the energy saved through these interventions.

From stock level data it is difficult to determine the change in energy use due to retrofit measures alone, as other variables which have evolved since 1970, such as household size, must be controlled for. However it has recently become possible to combine energy use data with records of energy efficiency interventions on a per-dwelling level (Hamilton et al. (2013)). Furthermore, the effects of the interventions can be compared to modelled predictions from SAP. Table 2 from Hamilton et al. (2014) shows the median monitored and modelled savings from different interventions: boiler upgrades and a combination of boiler and building fabric upgrades, compared to a base case group where no interventions were carried out (whose energy use fell on average over the period of study). It can be seen that the interventions produced an effect beyond the base case, but that the actual savings fell short of predicted savings for all types of intervention.

| Intervention | Median annualised gas consumption, kWh | Actual change from 2005 | Actual change from trend | Predicted savings, kWh |
|---|---|---|---|---|
| All 2005 | 17,567 | - | - | - |
| No energy efficiency measures installed between 2005 and 2007 | 16,243 | -7.5% | - | - |
| Boiler upgrade only, 2007 | 14,501 | -17.4% | -9.9% | -20.0% |
| Loft insulation and boiler upgrade, 2007 | 14,494 | -17.6% | -10.0% | -25.2% |
| Cavity wall insulation and boiler upgrade, 2007 | 14,172 | -19.4% | -11.8% | -41.1% |

Table 2: Monitored versus modelled energy savings from efficiency measures, from Hamilton et al. (2014).

Further insight can be gained by visualising the distribution of percentage change in gas demand following retrofit for the different combinations of efficiency intervention, as in Figure 1 which is also from Hamilton et al. (2014). The red line has been added by the author of this thesis to represent the median change for the control group of

dwellings. Everything to the right of this line then represents an increase in gas use following retrofit. It can be seen that for all types of intervention there is a part of the distribution where the gas use increased afterwards. However, the fact that this also occurred in the 'no efficiency measure' group is a reminder that there are many reasons why energy use might increase from one year to the next. An outstanding question is whether any proportion of the increase in the intervention groups occurred as a result of installation of the measures.

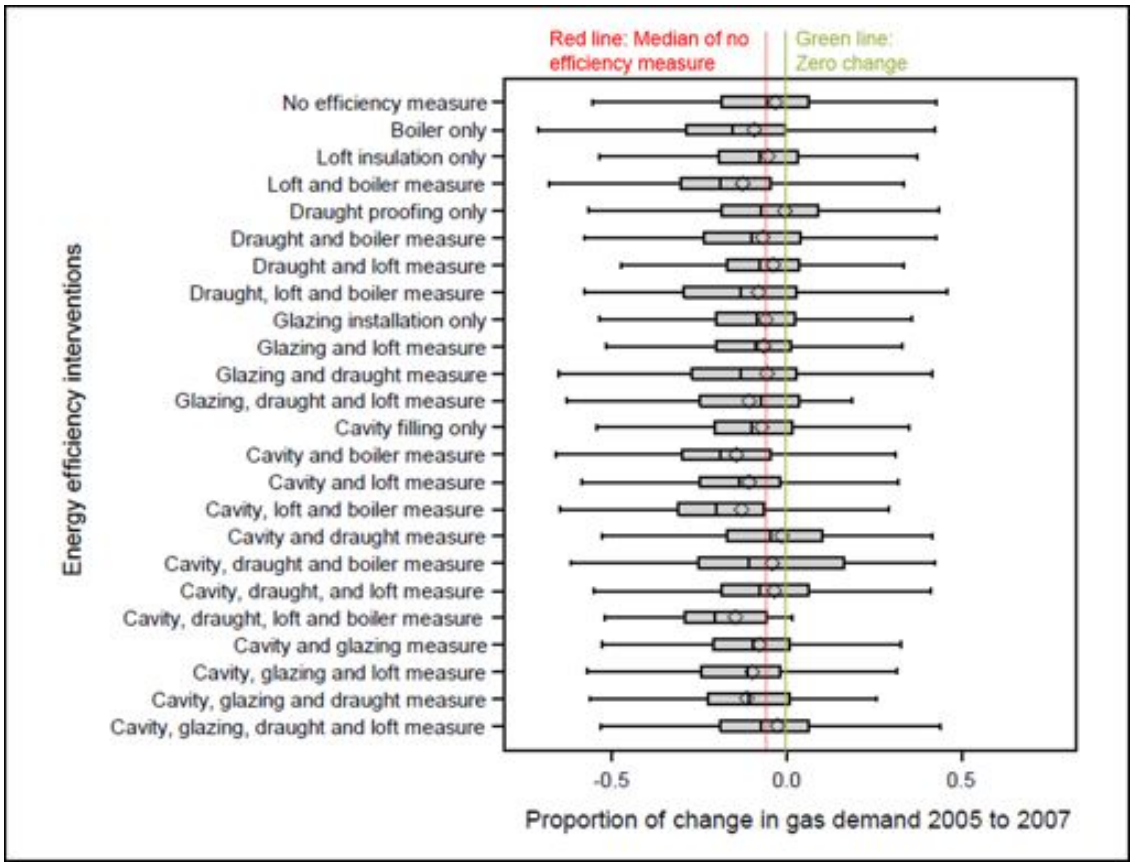



Figure 1: Percentage change in gas demand in the year following different interventions, from Hamilton et al. (2014).

Table 2 and Figure 1 together demonstrate two challenges for predicting and achieving energy savings from retrofit. Firstly, there exists a discrepancy between predicted and actual energy savings following installation of energy efficiency measures. Secondly, there is a wide distribution of outcomes including increases in energy use after retrofit. Potential causes of these issues will now be introduced.

## 1.8 ACTUAL VERSUS PREDICTED ENERGY SAVINGS

The dominant methodology for predicting the potential savings from retrofit interventions is bottom-up physics-based modelling, normally using tools based on the BREDEM family of models (of which SAP, introduced above, is a member). This methodology can be applied at any scale, from an individual dwelling to a national building stock. For example, a stock-level model within this methodology was used to produce the right hand column of Table 2. It was previously noted that these predicted values are higher than the 'actual' savings; the latter being constructed using a different methodology involving longitudinal metered data. This discrepancy has now come to be expected: Sorrell et al. (2009) completed a meta-review of studies relating to predicted and actual savings, which concluded that standard physics-based models may overestimate the energy savings from heating improvements by around one half, and possibly more in low-income households. Sanders and Phillipson (2006) term the discrepancy the **Reduction Factor**. The known reasons for the Reduction Factor all involve the fact that models do not capture what actually occurs in a building before, during and after retrofit. The reasons can be grouped into two categories: equations, and inputs.

#### 1.8.0.1 *Equations*

Attempting to describe any aspect of the real world as a mathematical model or set of equations necessitates simplification of the actual physical processes taking place. Heat transfer in buildings is no exception: even the most comprehensive models which represent conduction, convection and radiation in time and in three dimensions still approximate the physics occurring in reality. An example of this type of simplification is the historic assumption within domestic energy models that party walls have zero heat loss and thus do not need to be modelled. However, modern party walls have been shown by Lowe et al. (2007) to lose large amounts of heat through convection up the cavity.

#### 1.8.0.2 *Inputs*

The second source of discrepancy is found not in the model structure itself but the error on the values used for the parameters. This can occur in a number of ways. Firstly, measured data is sometimes missing for some variables, such as the heat loss

of building elements. For example, recent evidence has emerged indicating that the average U-value of solid walls is lower than had been previously assumed (Stevens and Bradford (2013)). Secondly, some aspects of a retrofit are often not carried out as well in reality as is modelled (sometimes termed 'installation error' or 'loss factor'). Thirdly, the temperature demand in time and space is rarely accurate. This latter variable is a function of occupant behaviour and the capability of the heating system. A set of inputs around occupant heating schedule and desired temperature in each room during the heating period are usually left unmodified from their default values in the SAP model (Chapter 2 explores this in more detail); not only have these assumptions remained largely untested until recently, there has also been no consideration as to whether the values of these variables may change following retrofit.

One possible mechanism in which the values of behavioural variables may change after retrofit is through a change in demand for thermal comfort - specifically, temperature - following retrofit. Two paradigms through which this could be investigated will now be explored.

## 1.9 CHANGE IN DEMAND FOR ENERGY SERVICES FOLLOWING RETROFIT

Studying change in demand for energy services such as temperature following retrofit is useful beyond simply aiding explanation of the difference between monitored and modelled savings. This is because understanding why this type of change may occur, and whether occupants actually intend to change their demand for temperature, could potentially help realise more energy savings.

There exists a set of terms commonly used in the literature to describe increase in demand for temperature following retrofit. Their qualitative definitions are as follows:

- **Takeback** (sometimes **temperature takeback**): the extent to which unrealised predicted energy savings converted into increased internal temperature.
- **Comfort-taking**: same as takeback.
- **Rebound**: the general term for an increase in efficiency of an energy service leading to an increase in demand for that service.
- **Backfire**: where rebound occurs to the extent that energy use actually increases following the efficiency increase.

The above terms are often used in the literature without clear definition, and expressed in a variety of units. In this thesis, they will not be ascribed quantitative definitions; rather, alternative strictly defined empirical-based metrics are used instead (Chapter 7).

The most well-known approaches to express and measure change in demand following retrofit originate from the fields of Economics and Physics. From this point onwards the discussion will focus on building fabric retrofit as opposed to other retrofit strategies.

### 1.9.1 *Change in demand as an economic elasticity*

Economists often use the term 'demand' assuming an underlying premise of rational choice. Demand for goods or for a particular service has an associated elasticity; this means that if the price of the service decreases, occupants choose to purchase more of it. The exact proportion of increase in demand depends on the value of the elasticity. Retrofit can be expressed in this language as follows. There is a pre-existing demand for an energy service (e.g. a particular internal temperature for a particular length of time). When fabric retrofit is carried out, there is an associated efficiency elasticity ($\eta_{|\varepsilon}(S)$): a change in energy service demand ($S$) coming about with a change in efficiency of delivering that energy service demand ($\varepsilon$). This definition is stated in Equation 1, from Sorrell and Dimitropoulos (2008):

$$\eta_{|\varepsilon}(S) = \frac{\varepsilon}{S}\frac{\partial S}{\partial \varepsilon} \tag{1}$$

Equation 1 is rearranged in Sorrell and Dimitropoulos (2008) to derive Equation 2 whose left hand side is now price elasticity of an energy service ($\eta_{|P}(S)$):

$$\eta_{|P}(S) = \frac{P_S}{S}\frac{\partial S}{\partial P_S} \tag{2}$$

The qualitative meaning of Equation 2 applied to a fabric retrofit context is that occupants may be expected to react to a decrease in the price of one unit of heat by using more heating. Although this thesis is not situated within the economic paradigm, the above piece of microeconomic theory is important as it has shaped the way in which researchers in the energy and buildings field often talk about occupants. For example,

a common assumption is that after retrofit occupants realise it is cheaper to heat their house after retrofit, so they turn up the thermostat. This use of language implies that any increase in demand for heat is a result of the rational choice of the occupants. As such, when predicted energy savings are not realised, there is sometimes an implicit assumption that this is the occupants' fault. However, the aforementioned rational choice assumption leading to these occupant-implicating statements remains untested.

### 1.9.2 *Change in demand observed through mean internal temperature*

#### 1.9.2.1 *Methodology*

An alternative approach to calculating change in energy service demand, termed 'quasi-experimental' by Sorrell et al. (2009), does not use Equation 1 as a starting point, nor does it predict theoretical savings using models and try to compare observed data to the results. Instead, the approach begins by monitoring the physical variables of internal temperature and/or energy consumption before and after (any type of) retrofit, and goes on to compare the change to a counterfactual, whose value should ideally be obtained without the use of modelling.

In a fabric retrofit context, internal temperature is a more meaningful variable than energy consumption to observe using the quasi-experimental approach. This is because arguably the energy service being demanded is a certain internal temperature during certain time periods through the day. Then, zero change in demand for energy service can be represented by internal temperature during these periods staying the same post retrofit, and the extent of increase in demand can be measured by the increase in internal temperature. On the other hand, creating a counterfactual unchanging energy service demand expressed through energy use is difficult, since a lack of change in energy service demand after fabric retrofit should lead to a decrease in energy use, the value of which is not possible to discern without invoking a building physics model and thus introducing the set of uncertainties described in Section 1.8 above. [1]

1 For example, Milne and Boardman (2000) and Martin and Watson (2006) attempt to relate empirically observed internal temperatures and energy use via Equation 3:

$$\text{temperature takeback} = 100\% \text{ x} \frac{\text{predicted energy savings} - \text{actual energy savings}}{\text{predicted energy savings}} \tag{3}$$

Obtaining the parameters for Equation 3 requires determining the predicted energy savings using empirical data. To do this, one would need to find a dwelling in which the temperature stayed the same after retrofit, and monitor the decrease in energy consumption. Milne and Boardman (2000) and Martin and Watson

This thesis aims to avoid uncertainties introduced by comparing model results with monitored data by focussing on internal temperatures determined empirically before and after retrofit.

#### 1.9.2.2 *Example of the quasi-experimental approach: Warm Front*

The most comprehensive study of the effect of different energy efficiency measures on internal temperatures is Hong (2011). This study used data from the UK Warm Front scheme, in which low-income households could apply for various efficiency measures to be undertaken in their homes. The data consisted of a time series of temperatures in two rooms and energy consumption from about 800 dwellings (in which longitudinal comparisons were possible in about 250) for around 3 weeks during the winters before and after the measures were installed.

Derivation of change in internal temperature following retrofit was carried out by standardising internal temperatures pre and post retrofit to account for external temperature. There are multiple methods of doing this which will be discussed in Section 7.5.0.1. In this particular example, monitored external temperatures were subtracted from the internal ones.

Hong's results are reproduced in Table 3, where 'mean internal temperature' refers, *in this instance,* to the average over the two monitored rooms.

| Measure | Increase in mean internal temperature (±95% C.I.), °C | Statistically significant? |
|---|---|---|
| Draught-proofing | 0.39 (-0.03, 0.81) | No |
| Full insulation | 0.73 (0.26, 1.20) | Yes |
| Installation of gas central heating | 2.28 (1.81, 2.75) | Yes |
| Central heating and insulation | 3.11 (2.25, 3.98) | Yes |

Table 3: Monitored mean internal temperature increase by measure, summarised from p. 185 of Hong (2011).

(2006) present methods which claim to empirically determine the maximum theoretical energy saving from retrofit and thus allow expression of the actual energy saving as a proportion of that. However their methods would not work in practice as the physical data is not properly standardised according to the external temperature.

#### 1.9.2.3 *Other studies within the physical paradigm*

Several other studies have carried out physical monitoring before and after (different types of) retrofit, to measure the change in internal temperature. Some key studies are summarised below:

- Dinan and Trumble (1989) found a non-statistically significant temperature increase of 0.2°C following retrofit. However, the nature of the retrofit is not clear, and it is also unclear whether internal temperatures were standardised to account for differing external temperatures pre and post retrofit.

- Henderson et al. (2003) found a temperature increase of 0.4°C following retrofit, but again there were several types of measures applied, some involving the building fabric and some the heating system, and the resulting temperature increase was not differentiated by measure. The authors were surprised that the temperature change was as low as 0.4°C, and proposed that one explanatory factor was increased window opening as occupants had little control over the functioning of their (electric) heating systems.

- Martin and Watson (2006) found a temperature increase of 0.6°C following installation of insulation (cavity wall or loft) in 88 dwellings, of which 57 were occupied by low income households. Again, it is not clear how the increase was adjusted to account for external temperature.

- Milne and Boardman (2000) carried out a meta-review of retrofit schemes in low income housing. Mean temperature increases across studies ranged from 0.5°C to 3.5°C. Although the authors do differentiate between interventions, they do not give information on methodological considerations such as how 'mean internal temperature' was calculated in each of the studies, rendering cross-case comparison difficult.

Hong (2011) emerges as the most methodologically robust study of change in mean internal temperatures following retrofit, as changes in external temperature are taken into account, the sample size is reasonable even though the study is not entirely longitudinal, and the results are differentiated by retrofit measure. It can be seen from Table 3 that there was a difference between the changes in temperature following measures which only involved the building fabric and those involving installation of central heating. Hong attributes much of the latter to a step-change in heating strategy: changing from heating one room pre retrofit to all rooms post retrofit. Since by default central

heating heats all rooms unless the occupants intervene and turn off individual radiators, this change in demand for space heating could occur almost by default, without the occupants making a rational choice to increase their demand for heat.

One important difference between the physical paradigm and the economic one is that, within the former, the term 'demand' is not necessarily associated with rational choice. That is, if a change in internal temperature or energy use is observed, there is no judgment made as to whether the occupants brought this about by their behaviour or not, and whether it was intended or is even consciously recognised. The type of data collected does not extend to the formation of such claims. Indeed, very little is known about exactly how increases in mean internal temperature come about following different types of retrofit - and within this, the role of the occupant. This knowledge gap is the subject of the next section.

## 1.10 PEOPLE, ENERGY AND BUILDINGS

Studies discussing increases in temperature following fabric retrofit differ on the main phenomenon to which they propose it is attributed. Deurinck et al. (2012), which will be critiqued in detail in Chapter 3, provides modelling evidence that the observed change in temperature is of the order of magnitude to be expected if the occupants did not change any aspect of their heating behaviour. Conversely, as stated by Deurinck et al, some authors *"assume in their analysis that any temperature rise is to be a voluntary behavioural change"*. This is shown in the language used in the following extract from Tweed (2013):

*"There is no doubt, therefore, that the householders have opted for increased temperatures rather than greater energy and cost savings. This behaviour is borne out by other studies that suggest that people prioritize their comfort, and lean towards the warmer side of this, as long as they feel able to afford it."*

Similarly, Dinan and Trumble (1989) use language around occupant choice in the context of a discussion about the location of their temperature loggers:

*"If households choose to 'take back' energy savings after a retrofit by maintaining higher temperature levels in the non-central parts of the home, we cannot observe this."*

In reality, it is unlikely that the observed outcomes of retrofit (change in temperature and energy use) come about by either a purely physical mechanism or a purely be-

havioural one. The following quotation in Lowe et al. (2012) illustrates the complexity inherent with the phenomenon of domestic retrofit:

*"The interactions between the different components (heating and ventilation systems, solar thermal etc) and the physical envelope of the dwelling, and with the people who retrofit and inhabit it, form a complex system whose behaviours cannot always be predicted, particularly during times of rapid change."*

This quotation denotes retrofit as more than simply the installation of an energy efficient measure leading to a particular outcome. Since the retrofit takes place in the context of a pre-existing set of interactions between occupants, heating systems and buildings - that is, a socio-technical system - the outcome will depend on how those interactions are changed by the retrofit and co-evolve afterwards. Understanding the interactions in their pre and post retrofit forms, and understanding any changes which took place due to the retrofit, are then prerequisites for understanding why a given outcome came about.

## 1.11 A NOVEL TYPE OF STUDY

This thesis will examine the interactions between occupants, building fabric and heating systems before and after building fabric retrofit, and use these to explain observed changes in internal temperature. This is a novel approach for four reasons:

Firstly, many studies do not include pre retrofit data as part of the research design. If this is included, it is normally limited to temperature or energy data, and does not capture what occupants do and why. This thesis will use a longitudinal research design to enable change in certain variables to be identified.

Secondly, studies tend to focus on either occupants or the building fabric exclusively. That is, data is collected from either the occupants' perspective or by physical monitoring, but not both. A subset of studies do collect both physical and occupant-reported data, notably Warm Front study and Retrofit For The Future. However, they do not go on to combine the physical and occupant data to understand the interactions between physical phenomena and occupant behaviour.

The study coming closest to this type of research is Gram-Hanssen (2010). It does not focus on retrofit per se, but attempts to understand how different household heating practices may result in variation between dwellings' energy consumption. Qualitative

interviews were used to uncover how occupants attempt to control heating to suit their needs, and this qualitative data was very superficially compared with physical monitoring of energy use and internal temperature. Although the latter comparison formed a small part of the publication, it found a useful result: that some households thought they maintained low internal temperatures and energy use because of their perceived behaviour, whereas physical data showed their temperatures and energy use to be relatively high. This highlights that simply asking the occupants how they heat their home is not an adequate study of interactions; it is not that occupants are giving false information, but that the process by which occupant practices translate into energy consumption involves the heating system and the dwelling fabric. Thus the occupants might not be able to describe these interactions. This gives a justification for collecting data from both the occupants and the building in order to be able to reconstruct what actually changes following retrofit.

Thirdly, in many studies the effect of the building fabric and heating system on the outcomes of retrofit is impossible to separate, as the retrofit involved upgrades to both. In this thesis, the intervention on which the study is based involves the building fabric retrofit only, to keep the aforementioned effects separate.

Fourthly, many studies only collect temperature data in one, two or three rooms of a dwelling. This limits findings on the effects of retrofit to whether particular spaces have increased in temperature, and misses effects such as parts of the dwelling warming in relation to others, or previously unused rooms becoming occupied. In this thesis as many rooms as possible are monitored in order to capture such effects.

## 1.12 NEXT STEPS

This chapter has highlighed the lack of understanding around why the outcomes of energy efficient retrofit of domestic building fabric are not as predicted, and some paradigms within which this is studied. It was proposed that a new approach combining physical and social data could provide better understanding of what actually changes after retrofit takes place.

In order to be able to interpret physical and social data collected in a retrofit context later on, the theoretical framework needs to be set out. One aspect of this is the physical theory of retrofit. The next chapter will explain the physical basis from which mean internal temperature may be expected to change following upgrade to the building fabric, and how this is represented in physics-based models.

# 2

# PHYSICAL THEORY OF RETROFIT

## 2.1 INTRODUCTION

Since this thesis concerns how and why mean internal temperature might change following building fabric retrofit, it is useful to explain some physical theory associated with retrofit and how mean internal temperature may be expected to change afterwards, both if occupant behaviour is held constant and if it is assumed to change. It is also useful to explain how members of the BREDEM family of models operationalise this physical theory, and to describe which variables are included and which are omitted. This chapter can then be drawn from when interpreting and discussing empirical results later on in the context of theory and current modelling assumptions.

## 2.2 PHYSICAL THEORY

### 2.2.1 *Mean internal temperature*

The mathematical definition mean internal temperature (M.I.T.) of a space is the mean temperature over time and space, as in Equation 4. Please note that all of the symbols used in equations in this thesis are listed in the Nomenclature section beginning on page 27.

$$\int_0^t \int_0^r T_{in}(t,r)\ dr\ dt \tag{4}$$

In a real space, there are several different types of mean internal temperature which one might wish to measure. These include the temperature of the air, the radiant temperature, and the combination of these two which represents the temperature experienced by an occupant within the space, known as the **operative temperature**. The difference between these categories of temperature are further expounded upon in Section 6.2.2.

M.I.T. evolves in time according to the heat input, storage and loss from a space. A simplified[1] differential equation describing this is given in Equation 5. All of the physical principles in this chapter will be derived from this equation.

$$C\frac{dT_{in}(t)}{dt} = Q(t) + G(t) - H(T_{in}(t) - T_{ex}(t)) \tag{5}$$

Having defined M.I.T. and the mathematical form of its evolution, the effects of building fabric retrofit can now be considered.

### 2.2.2 *Physics of retrofit*

Building physics suggests three causes of increase in M.I.T. following fabric retrofit. Since they are all caused by physical principles alone and not the behaviour of the occupant, they can be categorised as **natural temperature increase**. To derive equations which describe them, some simplifying assumptions have to be made, the nature of which will be explained in each subsection.

#### 2.2.2.1 *Retention of internal gains*

Starting from Equation 5, setting $Q(t)$ to zero for all time (i.e. no space heating) and assuming a steady state scenario yields Equation 6:

$$G = H(T_{in} - T_{ex}) \tag{6}$$

1 One simplification consists of the heat loss coefficient $H$ being assumed constant in Equation 5 and therefore in all subsequent equations derived from it in this chapter. In reality, $H$ varies with internal-external temperature difference, wind speed and properties of the building element surfaces.

Rearranging Equation 6 gives Equation 7:

$$T_{in} = T_{ex} + \frac{G}{H} \tag{7}$$

Equation 7 suggests that following fabric retrofit, represented by a decrease in $H$, the internal temperature will naturally be higher as internal gains are more effectively retained within the dwelling. However, some types of fabric interventions could reduce the value of $G$ through reduction in solar gains. For example, external wall insulation could decrease the effective solar aperture.

#### 2.2.2.2 *Decrease in rate of cooling*

The second way in which M.I.T. might be expected to increase following fabric retrofit is through a decrease in the rate of cooling when the heating is switched off. Starting from Equation 5 and setting $Q(t)$ to zero as the heating is off, and letting $T'_{ex}$= $T_{ex} + \frac{G}{H}$ to represent the temperature that $T_{in}$ would fall to eventually (as in Equation 7 above), yields Equation 8:

$$\frac{d\left(T_{in}(t) - T'_{ex}\right)}{dt} = -\frac{H\left(T_{in}(t) - T'_{ex}\right)}{C} \tag{8}$$

The solution to Equation 8 is Equation 9:

$$T_{in}(t) = T'_{ex} + \left(T_0 - T'_{ex}\right) e^{-\frac{t}{\tau}} \tag{9}$$

The thermal time constant, $\tau$, has units of time. Equation 9 rearranged in terms of $\tau$ yields Equation 10:

$$\tau = \frac{t}{ln(\frac{T_{in}(t) - T_{ex}}{T_0 - T_{ex}})} \tag{10}$$

$\tau$ is made up of the thermal resistance ($H$) and capacitance ($C$) of the dwelling as in Equation 11:

$$\tau = \frac{C}{H} \tag{11}$$

As $H$ decreases after building fabric retrofit, then from Equation 11 the thermal time constant should increase. Subsequently, from Equation 9 this decreases the rate at which $(T_{in} - T'_{ex})$ falls when the heating is switched off. The thermal half life, $t_{\frac{1}{2}}$, is the time after which $(T_{in} - T'_{ex})$ falls to half of its original value, and is equal to $\tau ln2$.

The above description of the effect of retrofit on the thermal time constant presupposes that the thermal mass, $C$, is unchanged following retrofit. This is approximately true when the retrofit measures are installed outside the original inner sufaces of a dwelling, for instance in the case of external wall insulation. Internal wall insulation, on the other hand, shields the thermal mass from temperature waves within the space, which are instead reflected from the insulation back into the space. In this case, it is not expected that building fabric retrofit would increase the thermal time constant.

At this point two simplifications which have been made to describe real buildings in these terms will be made explicit. Firstly, as described in Lowe (2009), there are actually two time constants acting in a space: one representing the entire building element and one representing its inner surface. Assuming a periodic heating and cooling down of the space, the frequency of this function determines whether there is time for heat to reach beyond the inner suface of the wall to the mass, and as such which time constant should be used. This will not be further considered in this thesis, for simplicity. Secondly, no mention has been made thus far of the temperature-time evolution as a buildings warms up when the heating is switched on. This could be represented by an equation similar to Equation 9 with an extra term for the heat input into the space. Well insulated dwellings should warm up more quickly than poorly-insulated dwellings as heat loss during this time is decreased. Although this could potentially be observable in data, reproducing the effect using mathematical modelling requires knowledge of the heat input into the space, which is often not measured.

#### 2.2.2.3 *Inter-room temperature gradient*

The third physical principle to be introduced concerns **inter-room temperature gradient**, which is defined in this thesis as the difference in temperature between the warmest and coolest room in a dwelling over a specified time interval. It is relevant to the study of M.I.T. before and after fabric retrofit since, in certain circumstances to be described below, some rooms may warm more than others.

Starting from Equation 5 and considering a steady state situation ( $\frac{dT_{in}}{dt} = 0$) yields the steady state heat balance equation which can be thought to apply to each room in a dwelling under steady state assumptions:

$$Q + G = H(T_{in} - T_{ex}) \tag{12}$$

Assuming that all rooms in a dwelling are heated and that a central thermostat controls the temperature in all the rooms[2], there are likely to be differences between the air temperatures in each room. These differences will originate from either the heat loss coefficient of each room being slightly different, or radiator balancing and/or internal gains providing different amounts of heat per unit volume in each room. A simple theoretical example of the former situation is illustrated in the left hand picture in Figure 2, representing a situation in which the thermal resistance ($R$) of the right hand wall of room 4 is double that of room 2 for an unspecified reason. The location of the thermostat is represented by the red 'X'.

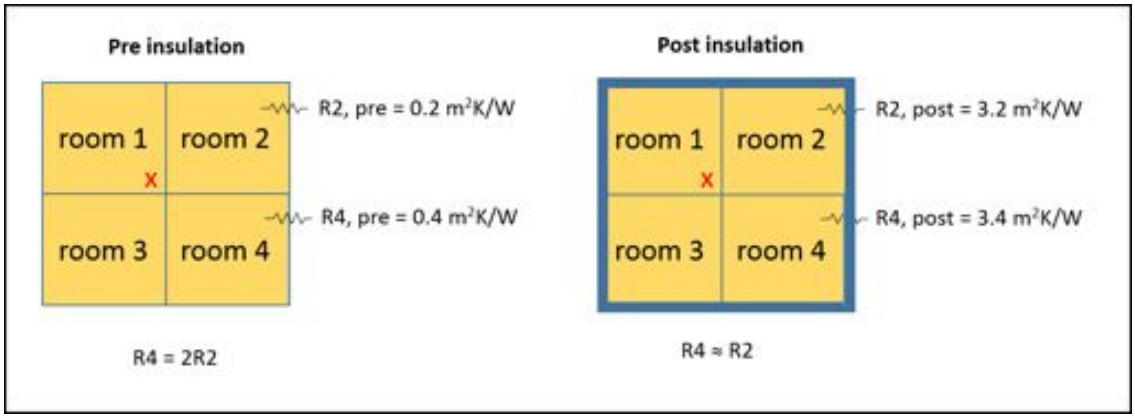



Figure 2: Two theoretical built forms, plan view.

If insulation is then applied to the external building fabric, the thermal resistance of the wall increases. In fact, external wall insulation will be shown later on in this thesis to increase the resistance (in theory) by almost an order of magnitude[3]. As shown on the right hand picture of Figure 2, the insulation then dominates the resistance (R-value) and thus the U-value of the wall. Any prior differences in R-value matter less once insulation has been applied. The U-values of the walls of interest in rooms 2 and 4 are

2 These assumptions in fact originate from later on in the thesis when the case study dwellings are described.
3 60 mm of EPS external wall insulation has an R-value of 3.0, and changes the resistance from to 0.4 to 3.4 $m^2K$.

closer together post retrofit than they were pre retrofit, as their prior differences have essentially been smoothed out. From Equation 12, this will bring the temperatures of the two rooms closer together.

It should be stated that calculating the expected change in inter-room temperature gradient is complicated as there are heat loss processes at work in multiple dimensions, so this argument will be kept qualitative and simply conclude that there is expected to be a reduction in inter-room temperature gradient following a building fabric efficiency upgrade.

If there are unheated rooms in the dwellings then the inter-room temperature gradient may be expected to be larger and possibly change more post retrofit than if all rooms are heated.

### 2.2.3 *Possibility space of effect of retrofit on M.I.T.*

Having set forth some physical principles above, the next concept to introduce is that of the **possibility space**. Used on several occasions in this thesis, it is a bounded space encompassing the possible set of relationships between a dependent variable and one or more independent variables. Any empirically observed relationship should theoretically fall within the possibility space.

For example, there is a bounded space describing possible values of internal temperature versus external temperature, shown in Figure 3. The laws of physics create bounds for how cold a dwelling can be, and human physiology places a limit on the maximum likely maintained internal temperature; anything in between is theoretically possible. These limits can be derived as follows:

- The lower constraint is derived from the assumption that heating is never switched on. Setting $Q = 0$ in Equation 12 and assuming a steady state scenario yields Equation 7), in which the internal temperature is proportional to the external temperature, plus a temperature lift caused by free heat gains. The value of this temperature lift was shown in Section 2.2.2.1 to increase following retrofit.

- The upper constraint is taken from Kavgic et al. (2012), in which internal temperatures were monitored in winter in a residential block with a district heating system of which occupants had no control; however the windows were openable.

Indirect evidence from a questionnaire and relative humidity measurements suggested that occupants were opening the windows in order to regulate the temperature and avoid overheating: across the sample, the mean temperature was 22.8°C in the living room and 22.3°C in the bedroom. Assuming that windows could be opened as wide as the occupants required (not explicitly stated in the study), this is a useful finding as it indicates the existence of a maximum comfortable temperature in winter, at (or possibly below) which demand for heat is satisfied. This temperature will be rounded up to 23°C in the Figure below.

Figure 3 shows the possibility space (shaded), bounded by the limits set out above. The range of external temperatures on the x axis represents the heating season.

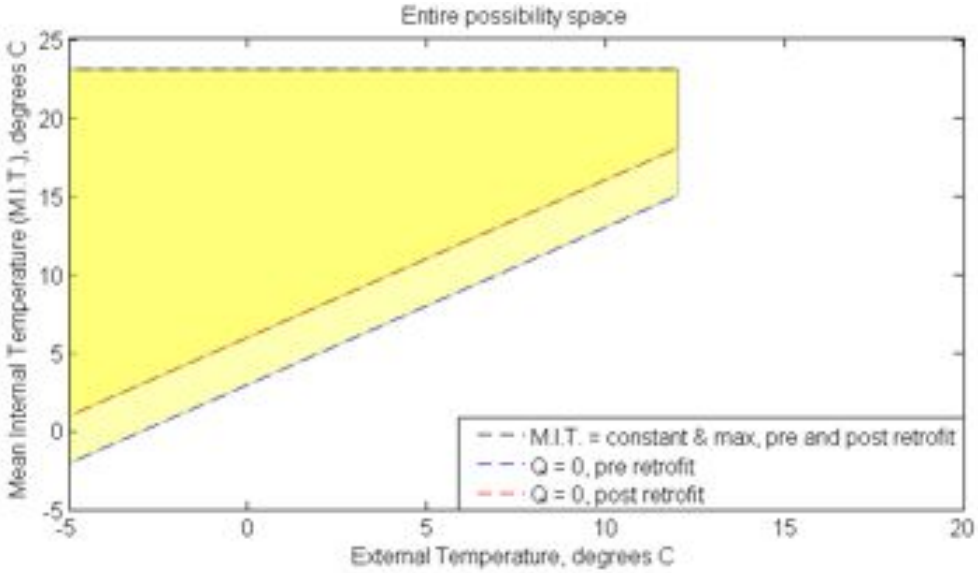



Figure 3: Bounded possibility space of internal versus external temperatures during the heating season.

Figure 3 will be returned to shortly, after a brief discussion of models.

## 2.3 MODELS

Much of this thesis is concerned with determining the mechanisms through which mean internal temperatures gain their values, and through which these values might change following retrofit. Since the findings will be compared to standard modelling assumptions, this next section of the chapter describes how SAP, and its parent model BREDEM, calculate mean internal temperature, and how retrofit is represented in the calculation.

### 2.3.1 *BREDEM and SAP*

BREDEM and SAP are constructed from similar equations, since they belong to the same family of models. However, a major difference is as follows. Since the original purpose of SAP was a compliance tool to allow buildings to be compared independent of occupant behaviour, the values of certain behaviour-related parameters are fixed to represent a normative situation, whereas in BREDEM these defaults are less likely to be the case. Furthermore, while both BREDEM and SAP give an output of energy use, SAP then converts this into a score called the SAP rating. The conversion between normalised energy use and SAP rating is through an equation. This equation is a logarithmic function designed not to represent a physical process but to increase the reward in terms of SAP rating as buildings become more efficient and thus further savings are more difficult to make. This last point is important as the SAP rating is then not proportional to the actual efficiency of the building, and as such should not be used as a proxy.

### 2.3.2 *Mean internal temperatures in the BREDEM family of models*

BREDEM uses a calculation of mean internal temperature to then calculate energy use, through the steady state heat loss equation (Equation 12). An influence diagram showing how mean internal temperature is determined in BREDEM is shown in Figure 4. This diagram is based on the documentation by Anderson et al. (1997).[4]

4 There is another variable in BREDEM, not shown in Figure 4, known as **responsiveness**: this represents how quickly the delivered heat output falls to zero when the heating is switched off. In this thesis, the primary heat source is always gas central heating and the secondary sources are gas/electric fires and electric fan/halogen/bar heaters. All of these systems have a responsiveness of 1.0 in BREDEM, meaning that an assumption is made that they deliver no extra heat after being turned off. As such, responsiveness is a constant and does not influence any other variables in Figure 4. For this reason, responsiveness is omitted from the diagram.

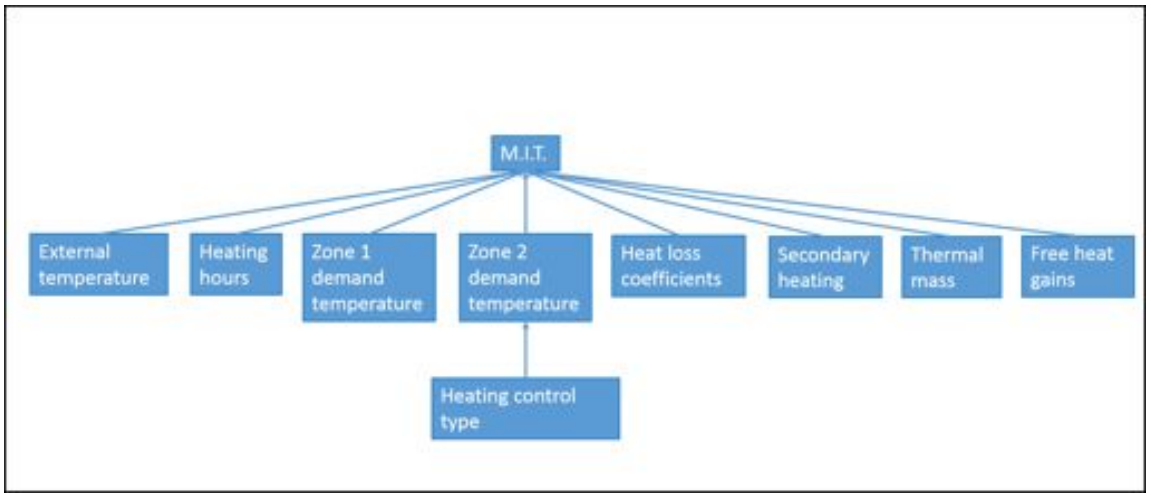



Figure 4: Influences to M.I.T. in BREDEM

From here onwards, mean internal temperature as calculated in BREDEM or SAP is termed **modelled mean internal temperature** to differentiate it from results obtained using empirical data. Figure 4 shows that the BREDEM method of calculating modelled mean internal temperature depends on a set of physical variables (heat loss coefficients, external temperature), a set of behavioural variables ('demand temperature' and 'heating hours'), and free heat gains which arise from a combination of physical and behavioural factors.

More detail will now be given as to how the independent variables in Figure 4 determine the modelled M.I.T. The starting assumption is temperature demand, in the form of the BREDEM internal temperature-time profile reproduced in Figure 5:

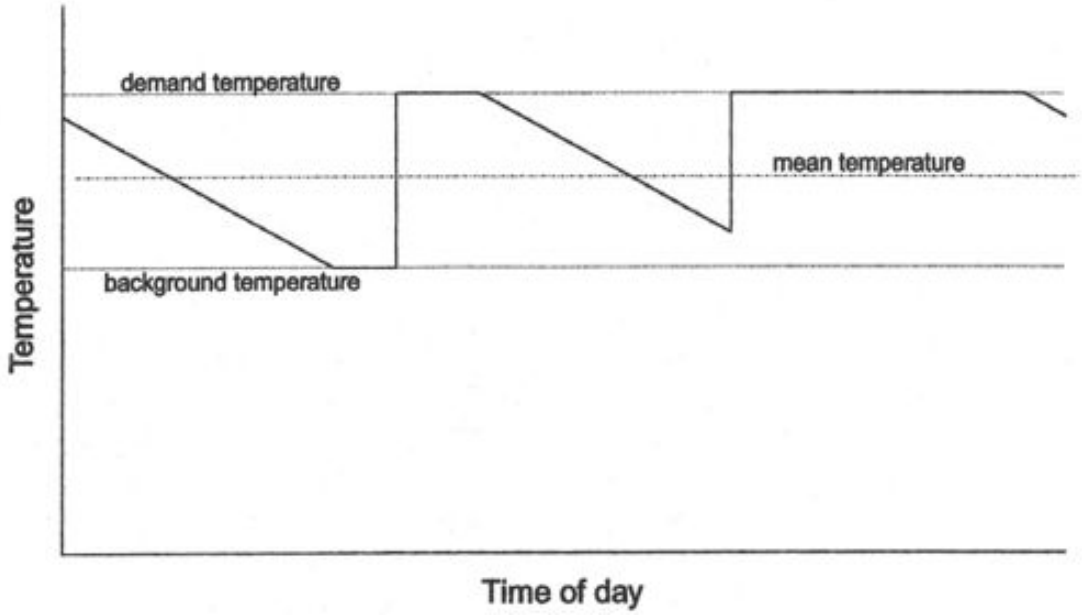



Figure 5: BREDEM temperature-time relationship for one zone. Reproduced from Figure 9.1 of Anderson et al. (1997).

Figure 5 is based on the following concepts. The 'demand temperature', which in this thesis will be termed the **modelled demand temperature**, is the temperature assumed to be desired by the occupants during hours in which the heating system is doing work. The dwelling is divided into two zones: zone 1 is the living area and zone 2 is the rest of the dwelling.

In SAP, the defaults used for the above variables are as follows. The zone 1 modelled demand temperature is 21°C[5]. The zone 2 modelled demand temperature is more complex.[6]

The SAP assumptions for 'heating hours', from hereon termed **modelled daily heated hours**, comprise of 9 hours on weekdays and 16 hours at weekends. Heating patterns such as this, in which the heating is on some hours and off others, will be referred to in this thesis as **transient heating**.

5 That is, unless there is a lack of temperature control, in which case the zone 1 demand temperature is effectively increased.

6 During heated hours in zone 2, it is usually assumed that zone 2 is desired to be cooler than zone 1. The zone 2 modelled demand temperature ($Td_2$) is a function of the zone 1 modelled demand temperature ($Td_1$), the desired temperature difference between the zones ($Td_{diff}$), the level of independence of the control system of zone 2 from zone 1 ($Tctl$), the heat loss coefficient of zone 2 ($H_2$) and the interzone heat loss coefficient ($H_3$) (Anderson et al. (1997)):

$$Td_2 = Td_1 - Td_{diff}\left[1 - \frac{H_3}{(H_3 + H_2)}\frac{1}{(1 + Tctl)}\right] \tag{13}$$

In both zone 1 and zone 2, the modelled demand temperature is instantly reached at the start of the heating period. Cooling down between heating periods is modelled as a linear decrease in temperature as a function of time, of which the gradient is $-\frac{H}{C}$; this is the first term of the Taylor expansion of Equation 9 introduced above and is thus a first order approximation. When the internal temperature of a zone drops to a threshold called the **background temperature**, designed to represent the minimum temperature resulting from incidental heat gains and the heat loss of the building, it does not fall any lower.

The next section will explain the implications of these modelling assumptions on the outcomes of retrofit.

### 2.3.3 *Modelled effect of retrofit on modelled demand temperature and heating timing*

In BREDEM, building fabric retrofit is represented by a change in one class of variable: the heat loss coefficients of the external building fabric elements. Figure 4 illustrates how this influences modelled M.I.T. directly without affecting the other variables in the diagram. In particular, neither the zone 1 modelled demand temperature nor the modelled daily heated hours change following fabric retrofit (the zone 2 modelled demand temperature, which is dependent on the zone 2 heat loss coefficient, slightly increases). BREDEM does allow the values of these variables to be altered, but the change in heat loss coefficient does not lead to their values changing automatically.

### 2.3.4 *Modelled effect of retrofit on mean internal temperature*

In this section, the modelling assumptions introduced above will be combined with a theoretical pre and post retrofit built form to show the resulting internal-external temperature relationship produced by this type of model, and how it changes following retrofit.

The assumptions used are as follows:

- Built form: whole-house heat loss coefficient of 600 W/K pre retrofit and 300 W/K post retrofit, constant internal gains of 1800 W, thermal mass of 10 MJ/K.
- Retrofit: represented by a change in heat loss coefficient as in Section 2.3.3.

- Heating assumptions: modelled M.I.T. is determined by the BREDEM temperature-time relationship as in Figure 5, with the modelled demand temperature and modelled daily heated hours set according to SAP normative assumptions as described in Section 2.3.2. Since this latter assumption is according to SAP and not BREDEM, this narrows the resulting internal-external temperature relationship to that which would be obtained in SAP as opposed to BREDEM.

Given three sets of assumptions introduced above: the BREDEM temperature-time relationship, the SAP normative heating timing/temperature assumptions and the way in which retrofit is represented in BREDEM, the modelled internal versus external temperature relationship shown in Figure 6.

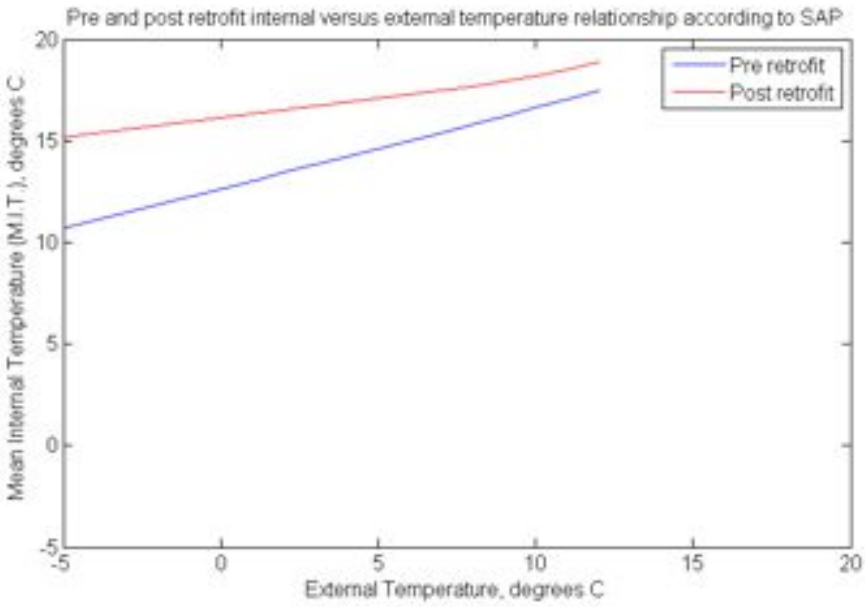



Figure 6: Modelled mean internal temperature versus external temperature, calculated in SAP.

## 2.4 POSSIBILITY SPACE AND MODEL PRESENTED TOGETHER

The final graph to be presented in this chapter is the superposition of the modelled M.I.T. versus external temperature relationship plotted above onto the possibility space introduced in Figure 3. This is shown in Figure 7.

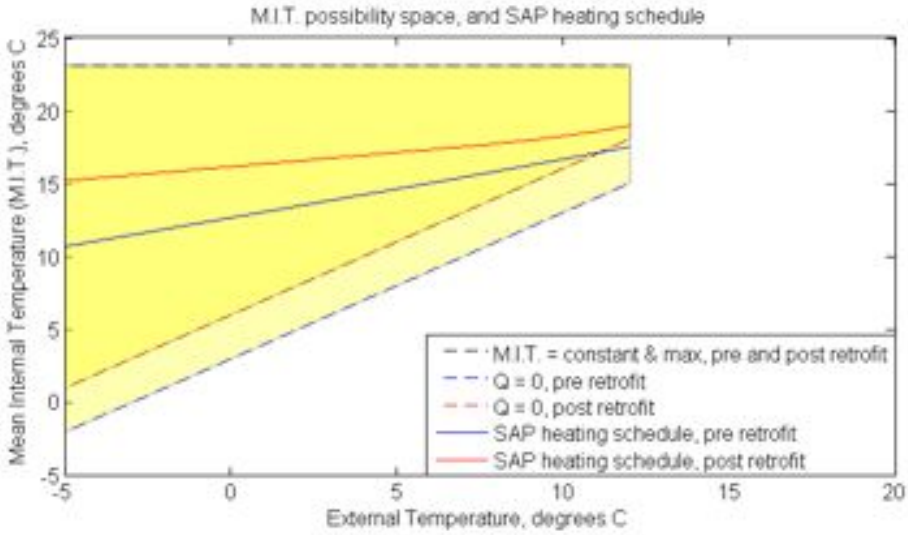



Figure 7: Bounded possibility space of M.I.T. versus external temperatures, including SAP predictions.

Four features of Figure 3 are pointed out below:

1. The internal-external temperature profile modelled in SAP is just one possible pair of scenarios in a large possibility space. There is a lot of space around it for lines with other gradients, intercepts and polynomial orders to be plotted. Much of the following chapter will be devoted to occupant heating behaviour and its influence on the internal-external temperature relationship.

2. If occupants do nothing differently after retrofit in terms of their heating timing and thermostat setting, then the mean internal temperature rises. This was also shown in Mavrogianni et al. (2011), and originates from unheated hours being warmer after retrofit due to the physical principles introduced above.

3. However, the size of the change in modelled mean internal temperature from retrofit with constant heating behaviour is small compared to the size of the entire space, indicating that behaviour change could *potentially* have a larger effect on M.I.T. *at this level of retrofit* than the effect of the retrofit itself (this statement will be further explored as to how true it is across all levels of retrofit in Chapter 4).

4. The SAP pre and post retrofit lines have different gradients, suggesting that in SAP there is more of a warming effect of retrofit at lower external temperatures than higher ones.

## 2.5 CONCLUSION

This chapter has introduced some simple physical equations describing M.I.T. and how it may be expected to change following retrofit. These equations are easily operationalised in models, but adapting their mathematical form or the values of their parameters to real world situations is much more difficult. One important aspect of this is occupant heating behaviour, which is the subject of the next chapter.

# 3

# LITERATURE REVIEW

## 3.1 INTRODUCTION

In the previous chapter it was shown that, under normative modelling assumptions of heating timing and temperature during heated hours, building fabric retrofit is expected to cause an increase in mean internal temperature. This chapter adds another layer into the study of retrofit: occupant behaviour. A literature review is undertaken, with the overall aim of describing the current state of knowledge on occupant heating behaviour, its relationship to retrofit, and the implications for energy use. The review is broken down into the following five stages:

- What is the purpose of space heating?
- What is known about heating behaviour?
- What is the relationship between heat loss coefficient of a dwelling and space heating behaviour?
- How does retrofit change occupants' behaviour, including heating behaviour?
- How does change in heating behaviour affect energy use for space heating?

## 3.2 what is the purpose of heating?

### 3.2.1 *Thermal comfort*

The main purpose of heating is usually considered to be achievement of thermal comfort. This is a vast topic, so will be narrowed down to just those aspects which are shown to relate to domestic heating behaviour.

Thermal comfort is defined by ASHRAE Standard 55-2004 as, *"the condition of mind that expresses satisfaction with the thermal environment"* (ASHRAE (2004)). There are two conventional models used to assess whether this condition of mind is likely to be achieved within a certain space: the steady state heat balance model (Fanger (1970)) and the adaptive model (de Dear and Brager (1998), Nicol and Humphreys (2002)). The models and the extent of their suitability to the domestic retrofit context are described below.

The steady state heat balance model is currently used in environmental design standards such as CIBSE (2006). It contains six variables, of which four are environmental - air temperature, mean radiant temperature, humidity (water vapour pressure in ambient air), relative air velocity (in reality including turbulence as clarified in Oseland and Humphreys (1994)) - and two concern the occupant (activity level and thermal resistance of clothing). All are validated empirically, but only under steady-state laboratory conditions. The premise underlying the model is that heat entering and being lost from the human body balance out, keeping the core temperature within the correct range.

A major limitation of this model is that the very nature of thermal comfort is not steady state: people react to discomfort by changing their thermal environment in some way, especially in a domestic context where people generally have control over this environment. Novel work is currently being carried out by Stephanie Gauthier of UCL Energy Institute on how people respond to cold-related thermal discomfort in homes. It is useful to summarise some of her work here as it begins to investigate the relative occurrence of responses which involve space heating energy use.

Gauthier used two different methodologies - self-reported and monitored - to elicit responses to thermal discomfort. In Gauthier (2011a) focus groups were used to elicit which responses were stated as most common amongst participants; this was triangulated with data from photographic, metabolic and infrared sensor data in Gauthier and Shipworth (2014a). It was shown that the two streams of data gave very different results.

The most common self-reported response to thermal discomfort in the winter was interaction with the heating system, followed by change of clothing level, then food and drink, blankets and change of location. In the sensor data, interaction with the heating system was a very infrequent response: change of location - both within a room and between rooms - emerged as the most common response.

This work raises some interesting questions about methodology of studies on home heating behaviour. Firstly, it appears that collecting self-reported data alone is not adequate. Secondly, the monitored result of infrequent interaction with the heating system may have come about since most of the participants controlled their heating by automatic means (Stephanie Gauthier 2014, Pers. Comm.). It is quite possible that very different results would have been obtained in a sample with different modes of heating control.

The other conventional thermal comfort model is known as the adaptive model. This is not a heat balance model; its approach is entirely different, consisting of an empirically determined relationship between external conditions and a band of internal temperatures within which occupants do not experience discomfort. This has been studied in detail in work environments such as offices, but there is currently no comprehensive adaptive model for dwellings as empirical data has not been collected on a large enough scale to reliably ascertain the band of appropriate internal temperatures. One recent development in this area is the publication of CIBSE TM52, whose subject is the definition and prediction of overheating in naturally ventilated buildings, taking external temperature into account.

One of the few studies in which thermal comfort data has been collected from occupants of dwellings is Hong et al. (2009). Self-reported thermal comfort (measured on a seven-point scale), clothing and activity levels and indoor temperatures were collected in the living room and main bedroom in low-income dwellings twice per day, before and after insulation and upgrade to the heating system (subject to the same caveats in the nature of the 'longitudinal' sample described in Section 1.9.2). As well as the increase in mean internal temperatures already described in Section 1.9.2, the authors also found an increase in the proportion of households feeling thermally 'comfortable' or warmer from 36.4% to 78.7%. An interesting further finding was a slight increase in the whole house neutral temperature - the temperature at which most residents feel thermal neutrality - from 18.9 °C to 19.1 °C. This was proposed to be largely related to reduced clothing level associated with greater energy efficiency.

However, like the steady state model the adaptive model is not perfectly suited to the context of domestic building fabric retrofit. For example, a temperature variable present

within the steady state model of thermal comfort - but missing from the adaptive model - is radiant temperature within a space. Radiant temperature would be expected to increase with thermal efficiency of the building fabric, since internal surfaces should be warmer. It is recommended by WHO (1988) that at or near comfort conditions, the mean radiant temperature should be no more than 3°C different from mean air temperature (this does not include situations in which occupants voluntarily change the radiant temperature, for example sitting in front of a fire; it refers primarily to radiation from surfaces). If this condition were not met prior to retrofit, but the surface temperatures increased after retrofit to bring radiant temperature closer to air temperature, then air temperature could be maintained at a lower level and still be perceived as comfortable by the occupants. This would lead to energy consumption being less than expected in well insulated dwellings, or decreasing further than expected following retrofit. To the author's knowledge there are no studies investigating the empirical relationship between building fabric efficiency, radiant temperature and resultant air temperature in dwellings.

In summary, neither the steady state model nor the adaptive model is entirely suitable for the prediction of comfort in a domestic retrofit context.

Although thermal comfort is a vast field, this brief exposition is sufficient for the purposes of this thesis. The review will now move on to another important reason to heat: human health.

### 3.2.2 *Heating for health*

There exist general recommendations, set by the World Health Organisation, concerning the domestic internal conditions which should be maintained in order to avoid certain health problems. These recommendations form the basis of environmental design guidance by institutions such as the Chartered Institute of Building Services Engineers (CIBSE) in the UK. Health guidance on domestic thermal conditions has to date mostly focussed on lower limits of ambient air temperature for some groups of the population (Ormandy and Ezratty (2012)). A report by WHO (1987) stated that no conclusion could be reached on the average indoor air temperature below which the health of the *general population* may be considered endangered, since there is no definite evidence for the a effect of cold itself on health for the whole population. There are however certain groups whose health can be affected by cold:

*"For certain groups, such as the sick, the handicapped, the very old and the very young, a minimum air temperature of 20°C is recommended."* (WHO (1987))

The minimum age threshold defining 'very old' is not specified but the report refers to studies on people aged over 65 years (Ormandy and Ezratty (2012)). For the rest of the population, the indirect effect of low temperature on health, through the intermediate variable of relative humidity, is considered important:

*"At air temperatures below 16°C, relative humidities of about 65% can be problematic for those with respiratory and arthritic diseases, or with allergic reactions to moulds, fungi, house dust-mites and allergens from domestic animals."* (WHO (1987))

In fact, different allergens are more likely to be present at different R.H. levels. House dustmites have been found to prefer conditions above 60% R.H. (Crowther et al. (2006)), whereas the critical level above which mould is likely to grow is 70% R.H. (Oreszczyn et al. (2006b)).

Over the lifetime of a given dwelling, it is likely that one or more sets of tenants who fit into one of the groups described above will reside there. It is therefore recommended that the heating system be capable of raising the internal temperature to 21°C in the living room and 18°C in the bedrooms, when the external temperature is 0°C (WHO (1987) and RIBA and IoH (1983)). This does not mean that these temperatures are necessary or recommended for everybody; purely that the combination of the heating system and building fabric should enable these temperatures to be achieved.

Despite the existence of these physiological and psychological temperature (and other thermal comfort) needs, not all spaces within a dwellling necessarily have to maintain a fixed temperature at all points in time in order for occupants to be satisfied. The review will now move on to the circumstances in which people need and want heat.

### 3.2.3 *Where and when do people want heat?*

What occupants actually want from their heating system has not historically been a well explored area. However, a recent study by DECC (2013b) used a qualitative methodology to investigate the functionality and services people want from their heating controls. Heating practices and heating control requirements were explored through diary self-reporting and in-home in-depth interviews of 43 households[1]; the results involved

1 The sample is not representative of the UK but is larger than those used in most qualitative studies.

several themes of relevance for this chapter. One such theme was people's comfort preferences in terms of space and time. The following two results, concerning space and time respectively, have been chosen as they are relevant to the findings later on in this thesis.

- In terms of *when* heating was desired, people wanted their home to be warm when they were in and also when they returned home. Whilst at home, participants' level of activity could influence heating use: sedentary activity may need more heating than physical activity such as cooking and cleaning, and is also likely to take place in the evening when there is a drop in outside temperature. People wanted their bedroom to be warm when getting into bed but not once they were in bed.

- In terms of *where* heating was desired, there was a distinction between occupants in larger dwellings, who perceived their home as a conglomeration of different spaces, and those in smaller dwellings, who perceived their home as a single space. In the former, radiators in rarely occupied rooms were nearly all turned off; in the latter all radiators were still on.

Understanding and then providing for occupants' needs and comfort preferences through heating systems requires a truly collaborative approach between the fields of social science, building physics and engineering. The framework in which to pursue this is starting to be developed (see Section 5.3.3). However, much of the terminology used is still phrased in engineering expressions or adopted from modelling language. 'Demand temperature', to be explored below, is one example of this.

### 3.2.4 *What is the meaning of 'demand temperature' in real dwellings?*

In Section 2.3.2, modelled demand temperature was introduced as one input to BREDEM-type models which influences modelled mean internal temperature and subsequently energy consumption. Since this thesis is concerned with the influences on mean internal temperature in real dwellings, it is useful to compare the interpretations of the term 'demand temperature' in modelling methodology with those in real dwellings.

The phrase 'demand temperature' originates from physics-based modelling and not real life; as such, it is a construct invented to facilitate modelling exercises. Its assumed real life equivalent, as stated in the previous chapter, is the temperature apparently desired by the occupants during hours in which the heating is switched on. The type of data

used to give a value for the model input varies according to what is available. The following quotation refers to the zone 1 *modelled demand temperature*:

*"Ideally this would be based on temperature measurements taken in the dwelling, in which case it would be the value normally achieved after the heating has been on for long enough to reach a relatively steady temperature. Where actual temperature measurements are not available $T_{d1}$ will usually be based on the thermostat setting. If the thermostat is in the living room, its setting would be the demand temperature. If it is outside the living room (e.g. hall), add 3°C to the thermostat setting to estimate the temperature achieved in the living room."* (BRE (2013a))

The above quotation demonstrates that, even within one modelling methodology, 'demand temperature' can be formed from different types of input: temperature measurements, thermostat setting, or thermostat setting plus a constant; all either during or after some time within the heating period. Across different studies, definitions and metrics vary even more widely as will be demonstrated shortly. This is important, as which definition is used leads to different hypotheses about whether 'demand temperature' can be expected to change following retrofit.

The term 'demand temperature' has also come to be used to refer to empirical findings from real dwellings. The most precise definition in the literature is that of Huebner (2013), who defines 'demand temperature' as the empirically determined highest air temperature during a heating period, only if that temperature is approximately stable for at least two consecutive measurements in a time series. In this thesis this construct will be given the name **stabilised demand temperature**.

This means that if the air temperature rises during a heating period and is still rising at the end of the heating period, i.e. if the maximum temperature during the heating period is at the final timestep, then there is no stabilised demand temperature for that heating period. This is because it is impossible to know which out of two phenomena occurred:

- The heating was switched off (by an occupant or the timer) at the temperature at which it would have stabilised (the stabilised demand temperature);
- The heating was switched off (by an occupant or the timer) before the temperature at which it would have stabilised (hence the achieved temperature is lower than the stabilised demand temperature).

In this way, the stabilised demand temperature is a subset of the highest achieved temperatures, so could be re-expressed as the highest achieved stable temperature during a monitoring period.

The authors used this definition with a nationally representative dataset containing time series of internal temperatures every forty five minutes from the UK CARB study (to be formally introduced in Section 3.3.3). Three main findings relevant to this thesis will be highlighted here. Firstly, the temperature during the heating period did not always stabilise: on a number of occasions at the end of the heating period it was still rising. The fraction of heating periods in which this occurred was not reported, although it was reported that this did not depend on the stabilised demand temperature. This finding implies that, in some dwellings, either the length of the heating period, or the inefficiency of the dwelling fabric or the heating system, was too low to allow the temperature to stabilise before the heating was switched off again. Secondly, the mean temperature during the heating period was found to be approximately 1°C lower than the stabilised demand temperature, although this could be partly as a result of the temperature not reaching its maximum, as described above. Thirdly, the mean stabilised demand temperature was found to be 20.6°C; close to but statistically significantly lower than the assumed 21°C in SAP, and with considerable variation between dwellings.

To summarise these findings, differences were identified between real-world temperature evolution during the heating period, and its representation in SAP. Modelled demand temperature and stabilised demand temperature are different concepts. Furthermore, it will be argued later on in Section 7.9 using the empirical data collected for this thesis that a third definition of 'demand temperature', consisting of the temperature achieved during the heating period, is necessary to describe heating periods in poorly insulated homes.

## 3.3 WHAT IS KNOWN ABOUT OCCUPANT HEATING BEHAVIOUR?

### 3.3.1 *Introduction to heating behaviour*

Just as in Chapter 1 two different ways of thinking about 'rebound' were presented - microeconomic and quasi-experimental - there exist different lenses through which household energy behaviour can be studied and understood. This section will mostly focus on the study of behaviour through technical measurements such as heating timing, which allows quantification of behaviour but not understanding of why it comes about. This thesis is concerned to a large extent with why people might change their behaviour following retrofit, yet is not situated within a purely social science framework. Instead of devoting a large section of the literature review to a thorough exposition of different

theories of behaviour, a shorter section follows exploring what factors might underlie behaviour using some concepts from practice theory. The latter is just one of the aforementioned lenses through which energy-related behaviour can be understood (others include psychological theory, economic theory and other aspects of social theory). The reason for selecting practice theory is to illustrate that energy-related behaviour is not always conscious, is not always determined by the individual alone and is not always viewed as related to energy.

Practices can be defined as "*coordinated entities of sayings and doings that are held together by different elements*" (Gram-hanssen (2011)). Although authors are not always in agreement about what the complete set of elements consists of, Gram-hanssen (2011) summarises four key practice theorists' interpretations (Schatzki, Reckwitz, Warde and Shove/Pantzar) into the following categories:

1. Know-how and embodied habits (the body knowing how to act);
2. Institutionalized knowledge and explicit rules;
3. Engagements (purposes, beliefs and emotions);
4. Technologies.

An example of an energy-related practice is that of taking a shower. The reason a person takes a shower might be because he/she wants to feel clean - an example of the 'engagements' type of element. He or she might carry out a certain set of actions - a routine - in the shower, without thinking about it. These actions can be classed as embodied habits. However, the duration of the shower and the set of actions undertaken might have been influenced by a rule or some guidance imposed on the person at some point in the past - for example, they might have been instructed not to take too long. It could even be the case that the fact he/she showers instead of takinf a bath might be due to a widely-held belief that this uses less water. However, it can also be argued that showering behaviour is at least partially determined by the technology (the shower) itself. For example, the the amount of water used could well be influenced by the power of the shower; attaining a comfortable temperature might involve increasing the flow rate, etc. In this way, the practice arises from a combination of the individual's preferences and beliefs, his or her physiology and memory, the societal norms and structures in place, and the installed technology.

The lens of practice theory is helpful for understanding where certain behaviours might come from. However, this thesis will define 'heating behaviour' itself in terms of a

set of variables which can be observed and measured. This may seem a very different approach to practice theory; the definition and its justification are given below.

### 3.3.2 *Definition of heating behaviour in this thesis*

From hereon the phrase **heating behaviour** will be used as an umbrella term for the following set of variables:

- **Heating schedule**: the times during the day at which the heating is on.
- **Setpoint temperature**: the temperature setting of the **thermostat** (defined in this thesis as the room thermostat).
- Which rooms are heated.
- Which heat sources are used.
- Which ventilation sources are used.

The reason for defining heating behaviour in this strict scientific way is to facilitate measurement and modelling later on - that is, so that heating behaviour variables can be constructed and, ultimately, change after retrofit demonstrated. However, it is unlikely that occupants actually think about behaviour in terms of a set of variables such as those outlined above. For example, an occupant who likes to maintain a certain comfort temperature during the heating period may find that after building fabric retrofit his home warms up faster and cools down more slowly, and therefore that he can turn the heating on later and off sooner. According to the definition of heating behaviour above, this would constitute a change in behaviour following retrofit, whereas the occupant might feel that his 'behaviour' had not changed, as he is still acting to achieve the same outcome.

Therefore, despite not encapsulating all that occupants do when describing 'behaviour', this working definition will be used. Current knowledge on each of the variables within the definition is set out below.

### 3.3.3 *Heating schedule and setpoint temperature*

This section will describe national data on heating schedules and setpoint temperatures. The purpose is threefold: to introduce the methodologies used in the main studies; to

document which variables have been investigated and which have not; and to begin to explore the diversity across the population.

There are two recent nationally representative studies of heating patterns: CARB-HES (Carbon Reduction in Buildings Home Energy Survey) and the Energy Follow Up Survey to the 2011 English Housing Survey. For brevity, they will hereinafter be termed CARB and EFUS respectively. Using these studies, information can be acquired concerning monitored and self-reported heating use, and the relationship between the two. At the time of writing, the CARB data has been used by several research institutions whilst only BRE have carried out analysis on the EFUS data.

The study methodologies were as follows. The CARB data was collected through a nationally representative study of 427 homes, using face-to-face structured interviews and 45-minutely temperature data from the living room and main bedroom, through the period July 2007 to February 2008. The results presented here are from dwellings whose main heating source was gas central heating. Meanwhile, the EFUS monitored temperatures in up to three rooms of 823 homes over one year (2011), and compared it to interview data from 2,616 homes.

#### 3.3.3.1 *Heating schedule*

Heating patterns are presented in Shipworth et al. (2010) and BRE (2013c) using CARB and EFUS data respectively. In order to discern heating schedule, both studies used air temperature time series data. The CARB study used an algorithm to pick out the hours per day in which the temperature in winter was stable or rising. By contrast, in the EFUS study, visual inspection of the air temperature time series was deemed more reliable.

Some summary findings from BRE (2013c) include average yearly heating period duration (5.7 months), of which the modal starting month is October. During the three-month period Nov-Dec-Jan, half of households have the heating on twice per day and 40% once per day. These two categories of household can be separately investigated, in terms of number of hours of heating during each period. Detailed findings will not be presented here; the important point is that previously unknown variables such as number of heating periods per day and average length of heating period were obtained. A further finding concerning this particular three-month period was that bedroom temperatures are only 0.6°C lower than living room temperatures (BRE (2013d)).

As was acknowledged in BRE (2013c), occupant-reported data on heating patterns is difficult to interpret: one reason being that households do not exhibit the same heating behaviour across the whole heating season (for example, in the monitored data, only 37% exhibited the same daily hours of heating in Nov, Dec and Jan). Heating behaviour is clearly a dynamic phenomenon with respect to time of year. There was no difference in daily hours of heating use between weekdays and weekend days which fell outside the bounds of instrument uncertainty. Thus, seasonal variation was concluded to be greater than variation between weekdays and weekend days. Although the exact reason for this result is unknown, it could mean that external temperature is a bigger factor of heating use than differing occupant heating behaviour patterns on different types of day.

Shipworth et al. (2010) did not report number of heating periods per day (further work with the same dataset in Huebner et al. (2013), discussed later on, did) but did report 'estimated heated hours per day', with a sample mean of 8.3 hours. 'Estimation' in the CARB study refers to examination of temperature data, which will here will be referred to as 'physical estimation' to differentiate it from methods involving occupant-reported information. Again, little difference was found between weekdays and weekend days. This study also attempted to correlate physically estimated heated hours with other variables, such as level of certain energy efficiency measures and built form; some statistically significant correlations were found.

Following Shipworth et al. (2010), further work on heating patterns has been and is still being carried out on the CARB dataset. Huebner et al. (2013) carried out cluster analysis on daily temperature profiles (internal temperature over 24 hours) and found that four distinct clusters emerged. Upon further investigation, these different temperature profiles were associated with different heating timing across the day: Huebner et al. showed this by plotting probability that the heating is on during each monitored timestep (45 minutes) against time of day. This is reproduced in Figure 8, in which 'Cluster 1' etc refers to grouping by internal temperature cluster, and each plot represents the inferred heating timing for the set of dwellings in that group. For example, the households in Cluster 3 use a two-period daily heating pattern, whereas those in Cluster 2 are more likely to have the heating on continuously.

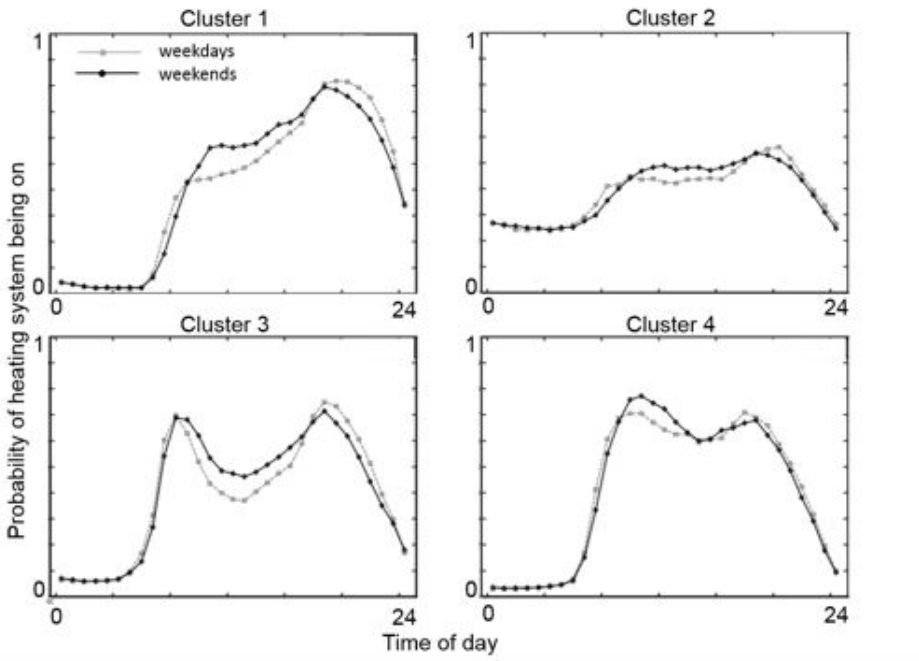



Figure 8: Probability the heating is on, for each of four clusters of internal temperatures. From Huebner et al. (2013).

#### 3.3.3.2 *Setpoint temperatures*

Shipworth et al. (2010) estimated thermostat settings from living room temperature data by assuming they were equal to the highest temperature achieved during a winter day. The authors found a mean of 21.1°C with a standard deviation (2.5°C). This method is, as yet, unvalidated; the authors note that in some circumstances it would overestimate the thermostat setting. This author believes the opposite: in some dwellings the maximum temperature achieved is likely to be below the thermostat setting. Indeed, as noted in Section 3.2.4 the degree of stabilisation of temperature was variable. Shipworth et al. also found no correlation between physical estimated and occupant-reported thermostat settings, a result which could impact the validity of other studies to be reviewed in this chapter.

The EFUS study did not use physical data to estimate thermostat settings, instead opting for occupant-reported settings. This may be an adequate method for estimating average thermostat setting *across the stock* (the authors of BRE (2013c) refer to Shipworth et al. (2010) in which there was only 1°C of difference across the stock between 'estimated' and occupant-reported settings). However, on a per-dwelling level, the above result from Shipworth et al. (2010) showing that occupant-reported thermostat setting are not

correlated to physical estimated ones may invalidate any per-dwelling analysis of the EFUS data involving thermostat setting as one of the variables. Furthermore, in general regarding the EFUS analysis so far, there has been no dwelling-by-dwelling comparison of monitored and reported variables as was performed in Shipworth et al. (2010).

#### 3.3.3.3 *Resulting mean internal temperatures*

Although the topic of this section of the review is behaviour, and mean internal temperature is a resultant variable as opposed to a behaviour, it is useful at this point to discuss the observed M.I.T. across the UK dwelling stock as it is generated from the CARB dataset and analysed by some of the same authors as above.

Differences in heating behaviours, heating systems and thermal characteristics of dwellings compound to produce a large amount of diversity in mean internal temperatures. Kelly et al. (2013) present a binned scatter plot showing all of the mean internal temperature data (by dwelling and by day) within the CARB dataset, reproduced in Figure 9 with a $y = x$ line added by the author of this thesis:

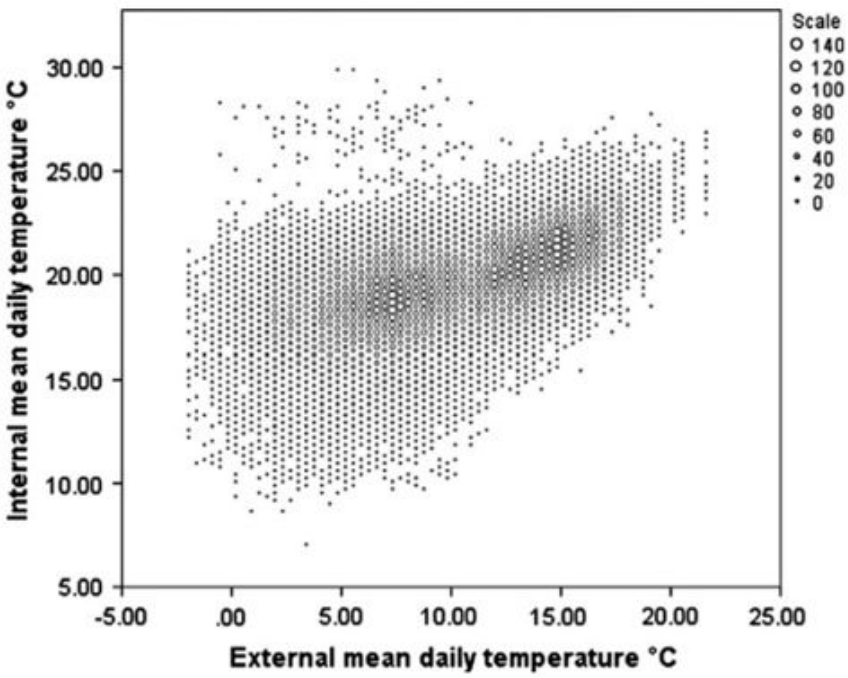



Figure 9: Internal versus external temperatures in the CARB dataset, from Kelly et al. (2013).

Figure 9 in fact resembles the possibility space of M.I.T. versus external temperature created in Figure 3 in the previous chapter. It does not show quite the same information,

as Figure 9 displays hundreds of dwellings each with different thermal characteristics, whereas Figure 3 was created using one value of thermal mass and two values of the heat loss coefficient. However, a qualitative comparison of the two figures highlights the diversity of internal temperatures in UK dwellings.

This variation in M.I.T. was examined in two ways in Huebner et al. (2013) and Kelly et al. (2013). In the former study the authors used a clustering method called regression tree analysis, to incorporate some known independent variables from the CARB dataset. These were sociodemographic variables, namely, age of household and household type. Temperature profiles fell into eight clusters based on these sociodemographic variables. This is a useful piece of analysis as Huebner et al. were able to use projections of future household demographics to predict changes in internal temperatures . In Kelly et al. (2013), a panel model was used to explain 45% of the variance in mean internal temperatures between dwellings by variables collected within the CARB study. Not all of the 43 input variables will be discussed here; results relevant to this thesis include the presence of children being associated with higher internal temperatures, and the presence of a thermostat or thermostatic radiator valves with lower internal temperatures (although the presence of a timer did not make a difference).

#### 3.3.3.4 *Summary*

To summarise the work carried out to date using the CARB and EFUS datasets, the following knowledge on heating use has been obtained: on a national level (albeit using unvalidated methods):

- The times during the day at which heating is used (also how many times per day and for how long each period lasts);
- The smaller than previously assumes difference between heating schedules of weekends and weekdays;
- Seasonal variation within heating schedules.
- It is becoming possible to attribute certain types of heating pattern to households with particular dwelling types and sociodemographics.

All of this has exposed large amounts of variation in the data, much of which remains unexplained, showing that the possibly large number of variables causing this variation have not yet been fully identified. A further unknown is actual setpoint temperatures or the degree to which internal temperatures reach them. Thermostats and other heating controls will be further discussed in the next section.

### 3.3.4 *Heating controls*

There are four possible interaction points with a basic gas central heating system: **thermostat** (shorthand for **room thermostat** in this thesis), **programmer** (which can be operated manually or through a **timer**), radiator valves (either **manual radiator valves** or **thermostatic radiator valves** (T.R.V.s)) on individual radiators and temperature controls on the boiler. To date, the only nationally representative study recording the presence of these heating controls in dwellings is the CARB study, introduced above. Kelly et al. (2013) showed from the CARB data that the presence of a thermostat or T.R.V.s is associated with slightly lower mean internal temperatures. However, the authors argued that it is not so much the presence of a certain control mechanism but how the occupants interact with it which matters.

DECC (2013b), introduced in Section 3.2.3, explored not only which controls were present but also whether the occupants thought they were useful. For example, the majority of participants used a timer to activate the heating, whereas participants saw T.R.V.s as an inconvenient means of controlling the heating and were unsure how the latter brought about energy savings[2]. More widely, there was a general lack of clarity on the cost implications of participants' heating behaviour and, hereby, where savings could be made.

Meier (2012) reports that many researchers have discovered, often *"as a by-product of other studies"*, that people often do not use heating controls in the way they were designed. The significance of this can be illustrated in the following 'paradox' concerning one part of a heating system, termed the **programmable thermostat** (P.T.), which is an integrated programmer and thermostat:

*"The P.T.'s full technical energy savings potential is unlikely to occur and sometimes will result in increased energy consumption. At the same time, P.T.s are acquiring new functions and responsibilities, include time-of-use response, network connections, and humidity and ventilation controls. We are concerned that these features will be incorporated before the existing ones have been fully integrated and consumers can successfully operate them".* (Meier (2012))

Meier (2012) gathered evidence for usability problems by combining a literature review with the results of four usability studies. His review was carried out in the USA where some brands differ from those in the UK, as do domestic HVAC systems (not to mention cultural factors). However, some of it was based on British research, e.g. Rathouse and

2 Unfortunately there was no significant exploration of occupants' interaction with thermostats in this study.

Young (2004). Given that the resulting list of usability problems is very long, it will not be reproduced here - the reader is referred to Table 1 in Meier (2012). However it can be summarised and backed up with other studies as follows: there is a general agreement in the literature that people's mental models of their heating systems are not the same as the physical reality (see also Revell and Stanton (2014)) in terms of control logic. This is one of the reasons for usability problems (see also Peffer et al. (2011)), and also causes misconceptions about the impact of controls on energy consumption.

Mental models of heating systems is a topic which will prove important later on in the thesis so is expanded upon here. Kempton (1986) categorised theories of home heating control inferred from analysis of a mixed-methodology dataset (interview data and automated recording of thermostat settings) into two general types of logic: 'valve theory' and 'feedback theory'. Valve theory refers to the logic that since in general in household devices, turning up a knob/dial/tap increases the rate of flow of the desired substance, turning up the thermostat will result in heat being delivered more quickly into a space. Feedback theory refers to a self-regulating device which uses room temperature as the criterion for whether to be on or off. Kempton makes the point that although several examples of feedback theory may be present in a typical house (e.g. there is temperature regulation in the refrigerator), the thermostat is the only self-regulating device whose operation is visible. Thus our practical direct experience of valve controlled devices is greater than that of feedback controlled devices, and as such occupants often think the thermostat is a valve.

### 3.3.5 *Secondary heating*

In addition to the main heating system, which in the UK is usually gas central heating, it is common for households to possess and perhaps use additional systems known as secondary heating systems. Although any secondary systems in a dwelling are likely to be smaller in terms of peak output power than the main heating system, secondary heating systems are important as their efficiency, fuel cost and $CO_2$ emissions are often radically different from those of primary systems.

Little is known about the proportional contribution of secondary heating systems to a dwelling's space heating energy use and $CO_2$ emissions. In SAP it is assumed that secondary heating provides for 10% of space heating demand; this is not based on empirical data but on estimates of likely usage (Brian Anderson 2013, pers. comm.). Monitored data on secondary heating use is sparse: one reason is that it is difficult to

measure. Some types of fuel are unmetered: wood and coal being examples of these. Furthermore, even where secondary heating systems run on metered fuels (gas and electricity), sub-metering the systems is often difficult.

This difficulty was acknowledged in the Energy Saving Trust's condensing boiler field trials reported in DECC (2009), in which monitoring of secondary heating was carried out in 47 dwellings to accompany monitoring of the condensing boilers which were the main heat source in these dwellings. Undertaking this monitoring was relatively straightforward for fixed electric fires, to which electric meters could be connected. However, gas fires presented more of a problem as gas flow meters are much bulkier. Instead of using these, temperature sensors were placed on pipes and heat flow was inferred by making assumptions about the power output of each fire.

The average proportion of space heating provided by secondary heating was then calculated as 4%. However, there is considerable uncertainty around this figure. The error on the denominator of the proportion - that is, the total space heating energy use - was stated as 2%. The error on the set of assumptions converting temperature to heat flow was not given. When these two sources of error are compounded, it is likely that the total error would be of the same order of magnitude as the quantity of interest.

The authors noted the difference between their result and the 10% contribution assumed in SAP, whilst suggesting that further more comprehensive monitoring of secondary and whole house energy consumption should be undertaken.

In contrast to DECC (2009), a self-report methodology was used in BRE (2013e) to study secondary heating use. Occupants were asked questions around which sources they used and for how many hours per day. Although the resulting data is self-reported and does not contain variables such as the power of each heat source which are needed to calculate energy consumption, it is the largest dataset currently available on secondary heating use. Therefore, some results from this study will now be presented.

The authors of BRE (2013e) defined two types of secondary heating: **alternative**, in which secondary heating is used in a room instead of primary heating, and **supplementary**, in which secondary heating is used in a room in addition to primary heating. Summary statistics will be presented here for each type to demostrate the type of results obtained. It was found that alternative heating was used by 17% of households, normally in just one room, for an average of 2.5 hours a day, and that alternative heating was predominantly electric-based. Supplementary heating was used by 48% of households, of which 79% stated it was used in one room only. Where supplementary heating

was used, it was electric-based in 46% of households and gas-based in 41%. The EFUS also collected interview responses on why rooms are not heated, frequency and schedule of use of alternative and supplementary heating and purpose of use. There is no validation of the self-reported data with monitored data in this study.

In summary, the evidence base on secondary heating is still far from complete, partly because some fuels are not conducive to metering and partly because some systems are difficult to sub-meter. Furthermore, even less is known about use of non-gas/electric heat sources and unconventional uses such as patio or conservatory heating. However, it is possible to form a limited hypothesis as to how building fabric retrofit might influence secondary heating use, namely, that the balance between use of primary and secondary systems might change. This would affect the $CO_2$ intensity of the delivered heat and as such could be important.

### 3.3.6 *Ventilation behaviour*

Occupant controlled ventilation consists of window opening, background ventilation from trickle vents, and, in some dwellings, mechanical systems such as extract fans or whole-house mechanical ventilation and heat recovery (MVHR). This is to be differentiated from infiltration, which is involuntary air exchange through unsealed parts of the building fabric. Here, current knowledge on the factors influencing window opening will be summarised. The topic is not trivial: in the words of Fabi et al. (2012), *"what seems to be a simple task, to open or close windows, is in reality a task that is influenced by many factors, which interact in complex ways".*

There are to date no studies specifically concerning change in ventilation behaviour following retrofit, but it is potentially an important topic for two main reasons. The first is occupant health: the link between ventilation in dwellings and health is demonstrated in Engvall et al. (2005) and guidelines for minimum rates of fresh air in certain spaces are are given in CIBSE (2001) and in the Building Regulations. There is concern that sealing buildings better through building fabric retrofit could result in the unintended consequence of poor indoor air quality and associated health risks (Davies and Oreszczyn (2012)). The other important aspect of ventilation behaviour pre and post retrofit is the consequence for energy consumption. The heat loss of a dwelling is made up of fabric component and a ventilation component; as such ventilation directly influences building energy use and so potential change in occupant controlled ventilation as a result of retrofit would also have a direct effect on energy consumption.

Windows are the most well studied of ventilation systems. The most comprehensive study on occupant motivations to open and close windows was carried out by the International Energy Agency in 1988 (Dubrul (1988)), summarised in Fox (2008). This took place in a variety of countries and it is acknowledged that the results vary between countries due to factors such as weather, construction materials and lifestyle/cultural factors. They found that the provision of fresh air and elimination of odours and condensation were given as reasons to open windows, whilst saving energy, noise reduction, privacy, safety, sealing the building against adverse weather conditions and draughts and maintenance of a preferred indoor temperature were given as reasons to close windows.

Studies disagree on which of the above factors dominate occupant window opening and closing behaviour (Fabi et al. (2012)). One place in which complexity is introduced is that the primary drivers may be different depending on whether windows are being opened or closed. For example, Anderson (2011) found that in Denmark, the $CO_2$ concentration was the most important driver for opening of windows, while the most dominant driver for closing of windows was the outdoor temperature. In the UK, it could be hypothesised that moisture levels play a significant role in window opening, due to the higher external moisture levels and milder temperatures.

The relevance of research on window opening to this thesis lies in the question of which of the above variables may change as a result of building fabric retrofit. Of the window opening variables introduced in this section, those most likely to be affected by fabric retrofit are indoor temperature and indoor pollutants. The former may be expected to increase following retrofit, although it is not clear whether this leads to increased window opening. A further relevant variable is airtightness, which is expected to change following fabric retrofit. This may have an indirect relationship with window opening (Grey and Raw (1990)), in that the occupants' *perception* of how airtight their dwelling is may influence the extent to which they open the windows for fresh air.

## 3.4 how does building fabric efficiency affect heating behaviour?

Since building fabric efficiency can be considered as the driving or independent variable in the study of retrofit, it will be helpful to use the next part of the literature review to examine what is known about domestic energy use and occupant heating behaviour as functions of fabric efficiency. The discussion particularly focusses on dwellings with low thermal efficiencies, as might be expected in pre-retrofit dwellings, and the consequences for energy use when such dwellings undergo fabric retrofit.

In this section, the concept of **prebound** will be introduced. This term was first used in Sunikka-Blank and Galvin (2012) and refers to the relationship between thermal inefficiency of a dwelling pre-retrofit and the inhabiting household's actual space heating energy use lying below the normative modelled value. These authors reported that households in poorly insulated dwellings use less energy than predicted using such normative assumptions. The evidence they provide to form their argument will now be critically reviewed to provide a clearer picture of the nature of prebound.

Figure 10 from Sunikka-Blank and Galvin (2012) shows monitored heating energy use in Germany on the y-axis against modelled heating use on the x-axis for a sample (exact number unknown) of dwellings. The left hand subplot contains data from detached houses; the right hand one represents multi-household dwellings. In each subplot, a dashed line is plotted through $y = x$, and a solid line of best fit is plotted through the scattered data points.

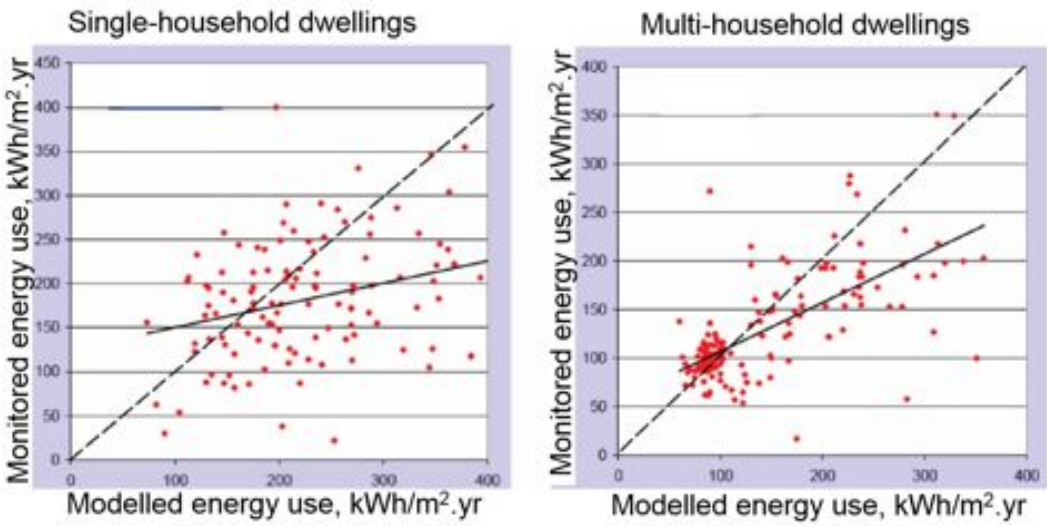



Figure 10: Monitored versus modelled space heating energy use, from Sunikka-Blank and Galvin (2012).

Considering, for example, the left hand subplot of Figure 10, it can be seen that at higher x-values (that is, modelled energy use), most of the points fall to the right of the $y = x$ line. In other words, actual energy use is less than modelled energy use. This is evidence of the existence of prebound. However, concerning the mathematical relationship between monitored and modelled energy use, the solid straight line plotted through the data points is not necessarily correct. The scatter is so large that the actual relationship may not even be linear. Thus, Figure 10 provides evidence that prebound exists,

but does not yield not the form of the relationship between monitored and modelled energy use. Furthermore, the authors acknowledge that the reason for the proposed relationship cannot be known from this dataset.

Therefore, two pieces of evidence discussing the existence and nature of prebound in the UK are now presented in order to supplement the evidence provided by Sunikka-Blank and Galvin (2012).

The first piece of evidence requires the reframing of the term 'prebound' into **underspend**. These are almost equivalent concepts - the only difference being that prebound refers to a dwelling pre-retrofit whereas underspend can be used with reference to any dwelling and its associated household. Underspend was first defined in the 1991 English House Condition Survey Energy Report (DoE (1991)): a household is deemed as underspending if their actual fuel expenditure is less than a normative modelled estimate of what it should be in order to maintain certain temperature conditions[3]. The degree of underspend is then expressed as a ratio of actual fuel expenditure to modelled fuel expenditure. This ratio is termed **fuel spend ratio**, and is shown in Equation 14:

$$\text{fuel spend ratio} = \frac{\text{actual expenditure on fuel}}{\text{normative modelled expenditure on fuel}} \tag{14}$$

For the purposes of this thesis, it is not especially relevant to have a discussion around the number of households deemed as underspending, since the denominator of the fuel spend ratio is based on a set of standard and/or questionable assumptions about what households 'need', and the numerator is also not primary data (often derived from other types of data). However, if there are a large number of dwellings for which data is collected, modelling is carried out using a standard technique, and additional variables characterising energy efficiency are also known for each household, then useful insight can be obtained by comparing dwellings' fuel spend ratio as a function of dwelling efficiency. This will now be discussed.

In the UK, both the 2001 and the 2011 EFUS collected data which allowed monitored and modelled energy use to be compared. BRE (2013b) calculated *fuel spend ratio* using the 2011 data. A surprising result was the apparent lack of relationship between income and *fuel spend ratio,* as shown in Figure 11:

3 As per the standard SAP assumptions: demand temperature of 21°C in the living area and 18°C in the rest of the dwelling, for 9 hours per day on weekdays and 16 hours per day on weekend days.

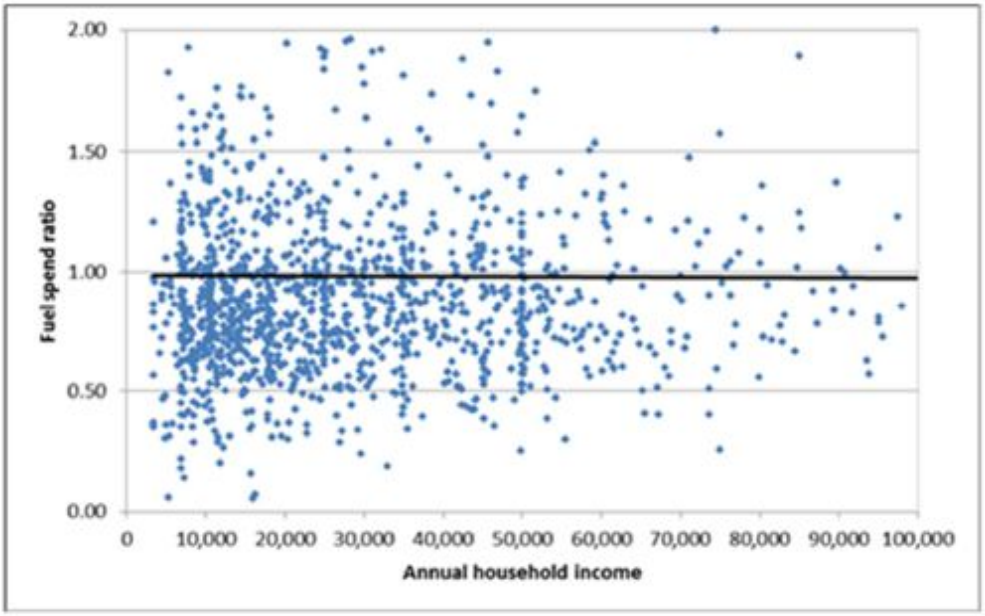



Figure 11: Fuel spend ratio versus household income, from BRE (2013b).

If Figure 11 is correct, this has a fairly important implication for this thesis, which was mentioned in Section 5.1.2 and will be restated here. At the start of this PhD, it had been assumed by the author that in social housing, the chosen sector upon which to focus this research, low income necessarily leads to occupants' demand for space heating not being saturated. However, this recent EFUS analysis suggests that it is not low income which is causing underheating. Since this is a fairly counter-intuitive result, further research is needed to be able to validate it using other datasets.

A further result from the same study as that SAP rating of a dwelling is associated with fuel spend ratio. This is shown in Figure 12:

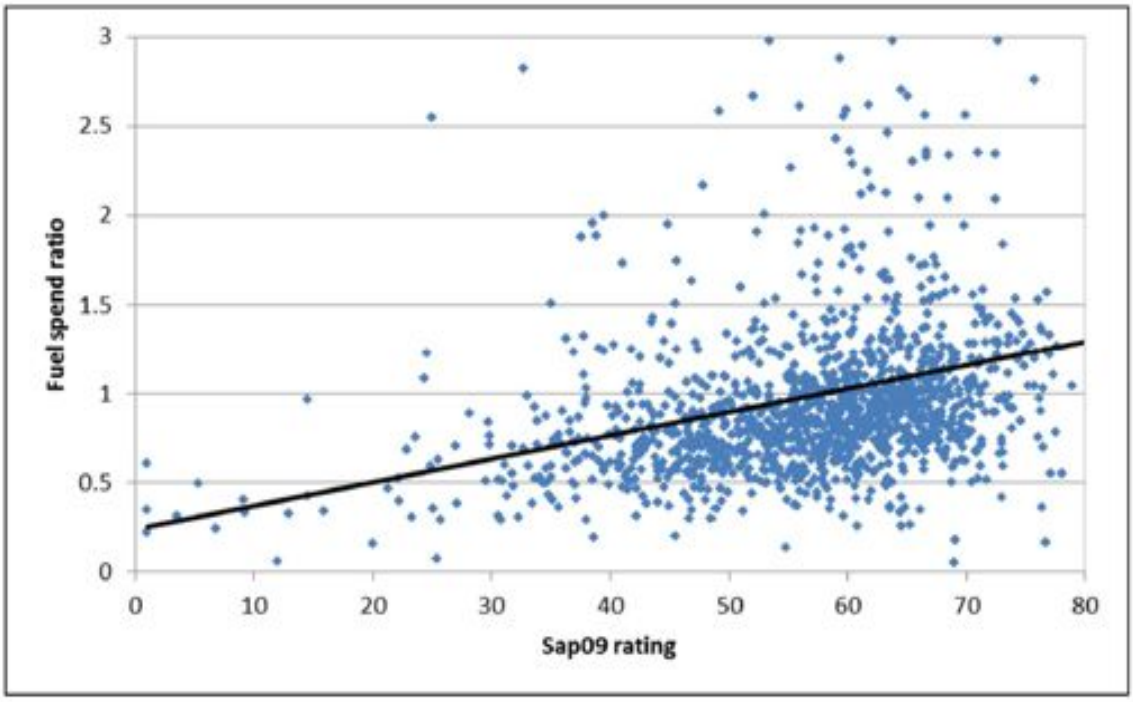



Figure 12: Fuel spend ratio versus SAP rating, from BRE (2013b).

It should be noted that not only does Figure 12 it is difficult to interpret for multiple reasons. Firstly, its x-axis is SAP rating. As explained in Section 2.3.1, SAP rating is an arbitrary scale constructed not from physical reality but a logarithmic transformation of modelled energy use. Heat loss coefficient or modelled space heating energy use would be a more straightforward variable to plot on the x axis. A further complication is the y axis being constructed from not just heating energy but total fuel consumption - that is, including electricity. This inclusion of more than one energy end use may explain some of the high degree of scatter of the data.

BRE (2013b) also provides some evidence concerning the mechanism by which the heating component of SAP rating influences fuel spend ratio. It was found that fewer daily heating hours and lower 'demand temperature' (it is not clear what this term refers to) were present in households who underspent. Lower 'mean internal temperature' was also found; this is likely to be a function of the lower 'demand temperature' and daily heating hours as well as of the heat loss of the building fabric. Since this was a quantitative survey, the reasons why these physical monitoring findings were found are not known. That is, there is no indication as to whether, for example, occupants expected to spend the same amount of money on energy regardless of their dwelling efficiency, whether they did or did not feel warm enough, or what factors in general brought about

different heating behaviour in dwellings of different efficiency, given that it was argued that income was not the reason.

The second piece of evidence to be presented concerning prebound/underspend in the UK uses the 2001 EFUS data. BRE (2005) plotted monitored energy consumption (y-axis) across different SAP bands, with the effect of floor area separated out through the use of clusters, to yield Figure 13:

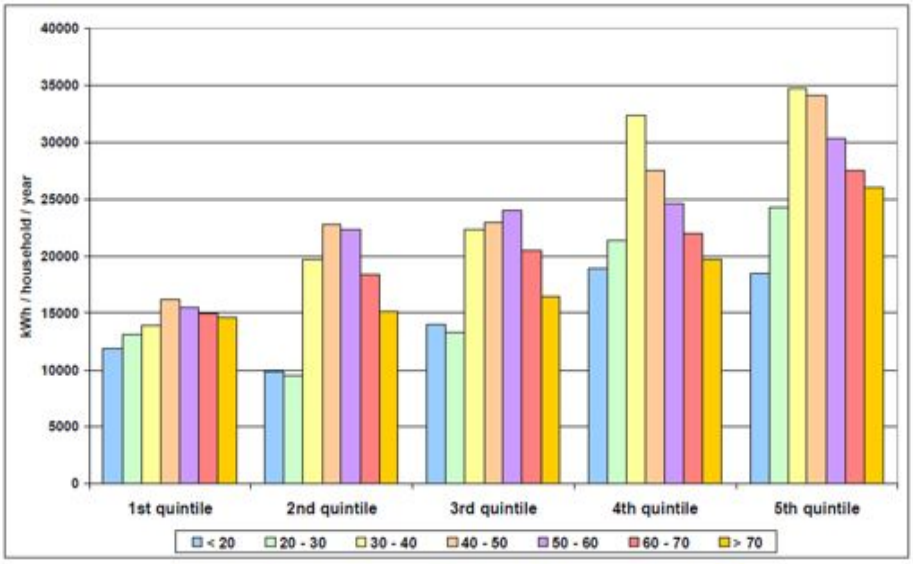



Figure 13: The relationship between SAP rating and actual energy use, for each floor area quintile (smallest to largest), from BRE (2005).

The same caution should be applied in interpreting Figure 13 as Figure 12, since firstly the SAP rating is not proportional to the actual efficiency of a building, and secondly the y-axis again includes electricity use and thus some of the vertical variation could perhaps be explained by this. The following interpretation is a hypothesis to explain the shape of Figure 13. It is not given by the authors of BRE (2005), and there could be other explanations to that presented below.

Two features of Figure 13 are useful to point out. The first feature involves consideration of one cluster of bars (representing one floor area quintile). Starting from the left hand side of the cluster and moving to the right towards the middle of the cluster, actual energy consumption increases with SAP rating - that is, with dwelling efficiency. This appears to be evidence of prebound in its strict definition of pre-retrofit, since these dwellings are at the lower end of the SAP scale so are less likely to have undergone retrofit. The units on Figure 13 are slightly different from those used to measure fuel spend ratio or prebound in that the y-axis is actual energy use, not the ratio of actual to

modelled. However, if actual energy use increases whilst SAP rating increases, as is the case in the part of the cluster being discussed, then the ratio of monitored to modelled energy use will increase, and thus prebound is present in this data.

Secondly, still considering one cluster of bars and this time starting from the middle and moving to the right, energy use is at its highest in the middle, then decreases. In other words, this time, increasing dwelling efficiency has the opposite effect. There is another force at work, taking over from prebound as the driving force on the direction of change of energy use. It is proposed here that as efficiency increases from mid-range to efficient dwellings, energy use is constrained by some physical limits: there is a point at which, whatever comfort level the occupants demand, as the dwelling becomes more efficient less energy is required to satisfy this demand. In this particular half of the cluster of bars, the ratio of monitored to modelled energy use cannot be discerned. However, given that useful insight has been gained by observing actual energy use as SAP rating increases, it is possibly more interesting to frame the discussion in terms of absolute energy use as opposed to the ratio of actual to modelled.

To summarise the above two paragraphs, upon traversing the stock from inefficient to efficient dwellings, energy use firstly increases, then it peaks, then it falls. This pattern occurs in all the clusters; that is, all categories of floor area. The increase is *perhaps* due to the 'prebound' phenomenon as described in Sunikka-Blank and Galvin (2012), and the decrease is *perhaps* due to physical constraints on possible energy demand. However, there could be other explanations for the observed trend, for example lower-SAP dwellings being heated electrically, which costs more and may reduce heating use, or lower-SAP dwellings performing better than expected due to solid wall heat losses being lower than the SAP rating suggests.

The above hypothesis is qualitative only; Chapter 4 will use modelling to show how increasing the thermal efficiency of a dwelling can allow energy use to increase at first and then forces it down later.

A summary of the two pieces of evidence concerning prebound in the UK is as follows. There is some evidence that regardless of how well-off households are or the size of their dwelling, they are unlikely to heat it as much as is predicted in normative models if the property has poor thermal characteristics. As dwelling efficiency increases from poor to mid-range, not only does degree of underspend become less, energy use actually increases. However, as dwelling efficiency increases from mid-range to efficient, energy use decreases. This was proposed here to be due to saturation of demand, which occurs at a lower energy use as dwelling efficiency increases.

Next, the possible implications of the above discussion for the consequences of retrofit are examined.

### 3.4.1 *What do cross-sectional results show about the possible effects of retrofit?*

It is stated in BRE (2013b) and Sunikka-Blank and Galvin (2012) that one of the possible consequences of underheating resulting from poor energy efficiency of a dwelling is that, when retrofit is carried out, there is potential for level of underheating to decrease, and thus the full extent of normative modelled energy savings not to be realised.

This hypothesis is based on a trend observed in **cross-sectional** data (across the stock, at one point in time) being extrapolated to predict a **longitudinal** phenomenon (one dwelling, through time). In BRE (2013b), this extrapolation is acknowledged. In Sunikka-Blank and Galvin (2012), there is no mention of the uncertainties introduced upon making such an assumption. Furthermore, recommendations to the German government concerning retrofit were made on the basis of the theory. The nature of these recommendations, and a counter-argument resulting from the author's own work in this thesis, will be discussed in Chapter 4.

The question then arises of whether it is possible to justify the aforementioned extrapolation - in other words to what extent cross-sectional data can predict the outcome of a longitudinal intervention. This issue is not often addressed in the field of energy and buildings but will be explored here.

One possible argument for the extrapolation is that longitudinal change, given enough time, may tend towards cross-sectional change (the latter referring to difference across the stock). This is because at some point after retrofit, the occupants of a dwelling will move out and new ones move in. In this way, a sample taken from a longitudinal study in which different people live in 'different' dwellings (where the difference is made by retrofit) could in some cases be argued to be similar to a cross-sectional sample containing different people living in genuinely different dwellings. The counter-argument to this is that the two types of change, across time and across the stock at one point in time, are still different: in cross-sectional data, there are factors which influence which type of dwelling people live in, such as income, which are likely to be more homogeneous in longitudinal data. Thus, using one type of change to predict the other may introduce extraneous variables.

### 3.4.2 *Summary of above discussion*

The above discussion can be summarised as follows. Firstly, it is not yet fully known whether level of underheating pre-retrofit (prebound) is related to shortfall in predicted energy savings after retrofit. However, there is evidence to suggest that that level of underheating decreases with SAP rating of a dwelling, and that absolute energy use increases with SAP rating up to a point - and then decreases again. Applying this cross-sectional result to a retrofit situation may or may not be justified. As such, the next section is about longitudinal evidence for change in heating behaviour following retrofit.

## 3.5 HOW DOES OCCUPANT HEATING BEHAVIOUR CHANGE FOLLOWING RETROFIT?

No empirical studies have focussed on measuring or specifically identifying changes in heating behaviour following fabric retrofit, but some findings have emerged as a by-product of studies concerned with how people's lives might improve through an increase in the thermal performance of their home. It should be emphasised here that it is necessary to distinguish between the type of retrofit works applied to a dwelling when proposing a causal relationship between the intervention and a certain outcome. For example, installation of central heating is a different reason for rooms increasing in temperature after retrofit to insulating the building fabric.

### 3.5.1 *Through change in use of space?*

Factors related to cold have been qualitatively shown to constrain occupants to staying in only one room of their dwelling. These factors include inability to afford sufficient heating, especially in inefficient buildings, and necessity of maintaining a high internal temperature due to occupants' old age. Two such studies are Age Concern (2006) and CSE (2010) which both used open-ended interviews as their method and found similar phenomena of people heating one room and staying within it. It is not clear exactly what type of heating system these homes had in place.

It is then reasonable to postulate that certain types of retrofit might allow expansion of people's use of space in their dwelling, by a causal mechanism of previously unused

rooms becoming warm enough for occupation. For example, the following effects have been documented in Gilbertson et al. (2006):

- There is qualitative evidence that if the retrofit involves installation of central heating, then people heat and use more rooms afterwards. An example of how this can come about is a case of an occupant who had felt 'trapped' in the living room in the evening as it was too cold to move from one room to another. Central heating had the effect of making the other rooms warmer: for example the occupant felt free to come and go to the kitchen during the evenings, and was thus able to cook evening meals in more comfort.

- The above documents a single case, but the same study found that a third of the 49 households interviewed reported using more of their rooms post-intervention (it is not clear which retrofit measures these respondents received as the responses were not broken down by intervention - central heating, cavity wall/loft insulation and draught proofing were some measures mentioned in the study). The authors attributed this to improved warmth and control of heating.

- There is a small amount of qualitative evidence that when the retrofit involves efficiency improvements to the pre-existing central heating system, people then use more rooms. One example is radiator replacement leading a room becoming warm enough to use: in this case a bedroom became useful for hobbies during the day. The other example is where replacement of an inefficient boiler with a new combi system led to the use of the whole house being increased, although the exact mechanism by which this occurred is not stated. There is no evidence given as to whether improvements to the existing heating system lead to occupants *heating* more rooms than previously.

There is no specific study documenting change in number of rooms used and/or heated when the retrofit is of the building fabric only. Section 2.2.2.3 in the previous chapter considered in detail the potential effects on temperature in space and time when building fabric is improved thermally; a decrease in inter-room temperature gradient could, in theory, cause previously unused rooms to become occupied.

In general, the extent to which occupant use of space is coupled with use of heating is unknown. Analysis of the 2011 EFUS data in BRE (2013e) showed that 26% of households have one or more rooms which are connected to the main heating system but in which the heating has been switched off. It is not known why the heating is turned off in these rooms, although Section 3.2.3 gave qualitative evidence from DECC (2013b)

suggesting that, in larger dwellings, radiators are generally turned off in rarely occupied rooms. It is not possible to discern from the literature whether building fabric retrofit might change occupant use of space and use of heating.

Having highlighted some indications from several qualitative empirical studies that occupants may increase their temperature demand following retrofit, a key study using a very different methodology - modelling - will now be used to present a contrasting argument.

### 3.5.2 *No change in behaviour?*

Deurinck et al. (2012) argued that observed increase in M.I.T. following building fabric retrofit is likely to be mostly due to the increased efficiency of the building fabric and therefore not due to change in occupant heating behaviour. This argument was made by comparing monitored data with model results on temperature increase following retrofit, the latter assuming constant occupant heating behaviour. They found the monitored data and model results to be similar and concluded that occupant heating behaviour is indeed constant. Their model and monitored data are described below.

The modelling exercise undertaken by Deurinck et al. (2012) was essentially a more detailed version of that undertaken by the author of this thesis in Section 2.3.4. The authors used a dynamic model, TRNSYS (Transient System Simulation Tool), instead of BREDEM, to obtain the temperature profile in every room at two different values of the heat loss coefficient, representing the dwelling fabric before and after insulation.

Their model predicted that decreasing the U-value of the external walls from 2.00 $\frac{W}{m^2K}$ to 0.29 $\frac{W}{m^2K}$ would lead to a 1°C rise in whole-house mean internal temperature at a standard external temperature of 5°C. This was compared to empirically observed temperature increases after retrofit, from some studies already introduced in this thesis (Martin and Watson (2006), Oreszczyn et al. (2006a) which was part of the same project as Hong (2011), Henderson et al. (2003) and Dinan and Trumble (1989)). The latter ranged from 0.3°C to 2.8°C. The model prediction and empirically observed results were argued by Deurinck et al. to be of the same order of magnitude, from which it was suggested that real-world temperature increase is likely to be mostly natural temperature increase as introduced in Section 2.2.2. However, according to this argument, if the observed M.I.T. increase is at the top of the observed range - that is, 2.8°C - then only $\frac{1}{3}$ of this would then be natural temperature increase, and the remaining 2/3 could be due to change in occupant behaviour.

Having explained the method and the results, two of the premises behind the study are useful to draw out here. The former is acknowledged by the authors; the latter is not.

The first premise is illustrated by the use of the word 'heating patterns' in the following quotation:

*"Even if the inhabitants do not change their heating patterns after retrofit, a temperature rise will still occur."*

'Heating patterns' here refers to temperature during and duration of heated hours. The authors claim that using monte-carlo sampling of heating schedules represents a large diversity of heating patterns, but in reality they are all constrained to fixed temperatures during heated hours, which is a particular type of heating pattern involving the immediate attaining of setpoint temperatures during heated hours. This excludes all types of heating behaviour which do not rely on setpoint temperatures, and as the authors themselves acknowledge, real-world heating systems do not immediately (if at all) achieve the setpoint temperature. The main point to make here is that the field of building physics sometimes tries to make general statements about occupant behaviour which do not encompass the full range of potential realistic behaviour. This is in fact exactly the same point made in Section 3.3.2 regarding the working definition of 'heating behaviour' adopted by the author of this thesis, which again does not encapsulate all of behaviour, nor how occupants think about 'behaviour'.

A second premise upon which the argument of Deurinck et al. (2012) rests is that of comparison of model results and observed data to make a statement about the latter. It was already argued in Chapter 1 that comparison of these two types of knowledge is problematic as they are formed from different assumptions, each with associated uncertainties. Therefore, although this is a useful study in terms of its concept, its validity has not been properly argued by its authors.

If the argument in Deurinck et al. (2012) is taken to be true; that is, if most empirically observed increase in M.I.T. is due to natural temperature increase and not the occupants turning up the heating, this would have the following implication for the outcomes of building fabric retrofit: the only ways in which the mean internal temperature would be kept constant following retrofit are if the occupants turned the heating *down*, or increased their level of window opening. Both options require the occupants to intervene in some way.

### 3.5.3 *A potential method of observing change in heating behaviour following retrofit*

The review will now briefly turn from evaluating outcomes of studies to introducing a useful method for observing behaviour. Martin and Watson (2006) devised a simple, cheap and effective way of monitoring heating timing which could be used to observe change following retrofit. A temperature logger was placed on the central heating flow pipe leading to the radiator circuit of each of 88 case study dwellings before and after installation of cavity wall insulation. The signal obtained from these loggers gave a very clear indication of when the heating system was on, compared to using air temperature data as in the CARB and EFUS studies above. The authors published the algorithm they used to turn temperature data into a binary state variable ('on' or 'off'). They used the resultant state variable to make some comparisons of heating timings - for example difference between heating periods on weekdays and weekends - but did not report whether heating timing changed following retrofit. However, their method and algorithm will be drawn from later in this thesis for exactly this purpose.

## 3.6 how does occupant behaviour affect energy use?

If it were found that following fabric retrofit occupants turned up their heating settings in some way, the question can then be asked of the extent to which this would impact on energy consumption. Perhaps the extra heating would cancel out the reduction in heat loss, or perhaps it would be negligible compared to the energy saved by the physical intervention. The relative influences of occupant rebound and change in building fabric heat loss on energy use have not yet been empirically investigated.

However, the problem can be addressed from a slightly different point of view: whether it is possible to attribute observed variation in a dataset of domestic energy use to variation in occupant behaviour and variation in building fabric characteristics separately. This is sometimes concisely phrased as, *'Is it the people or the building?'* Reviewing the literature on this below highlights a significant knowledge gap which will be addressed in the next chapter.

The question of attribution is by no means new; the relative effects of occupants and buildings on dwelling energy use were first researched in the 1970s. In this early research, Ordinary Least Squares regression analysis was carried out by multiple authors (Fox (1973), Mayer and Robinson (1975) and Sonderegger (1977)) to obtain coefficients

representing the importance of building design features (such as number of bedrooms) on total energy use. They did this by calculating the variance in total energy use explained by building characteristics. For example, the conclusion of Sonderegger's study was that features of the building design accounted for 54% of the variance in energy use.

Sonderegger (1977) then took this further by designing an experiment to attempt to explain the other 46% of variance in energy use. He compared two groups of dwellings over two winters: those whose residents changed between the winters, termed 'movers' (N = 52), and those whose occupants remained the same, termed 'stayers' (N = 153). He then used the difference in variance between these three groups to form conclusions concerning the origin of the aforementioned 46%, for which design features of the building were not the explanation. These conclusions were as follows: 71% of this variance was attributed to occupant behaviour, and the remainder to features of the building which did not concern design (for example, flaws in construction). Sonderegger then went even further and attempted to differentiate between different types of change in behaviour: behaviour of one household evolving over time, and a new household moving in. Both of these factors are also very important to the long-term study of the effects of retrofit, and will be returned to in Chapter 4.

Since then, others have attempted to answer the attribution question using a variety of non-experimental techniques. Lutzenhiser and Bender (2008) carried out multivariate regression analysis using a dataset containing domestic energy use of 1627 dwellings, concluding that so-called 'social' variables (e.g. household income, ethnicity) explained 36% of variance in energy use, 'building characteristics' (e.g building age, number of rooms) 9% and 'environment' (e.g. climate zone) 17%. The remaining 39% was attributed to the *"undifferentiable effect of people, environment and buildings"*. Mathematically, the latter term represents the fact that the model does not contain all the explanatory factors.

A phenomenon not treated by any of the above analyses is covariance: the interaction between input variables. There are some phenomena which, by their very nature, are a function of both occupant behaviour and buildings. An example concerning the outcomes of retrofit is as follows: one can imagine an occupant who keeps their thermostat at 30°C, and whose dwelling is inefficient and thus unable to achieve this temperature. As the heat loss coefficient of a dwelling is reduced, the temperature will rise; this temperature rise is because of both the occupant's decision to set the thermostat so high and the thermal characteristics of the dwelling fabric. Capturing these interactions is not trivial and requires different types of analysis to linear regression: Kelly (2011) used

structural equation modelling for this purpose, although his aim was not to explain variation but to predict energy use; Steemers and Yun (2009) used path analysis.

The above studies have an important feature in common: the way in which they describe variation in energy use. It is always stated in terms of percentage (or proportional) variation compared to the mean energy use. Absolute, as opposed to proportional variation, is not stated. This means that it is not clear how much a given proportional variation matters in energy terms. For example, if the proportional variation in energy use is 50% and the mean is 1,000 kWh per year, then the range would be 500-1500 kWh per year. If, however, the same proportional variation is present around a mean of 30,000 kWh per year, then the range is 15,000-45,000 kWh per year. In the context of the latter range, the smaller range is practically insignificant. This topic of the absolute energy consequences of variation is very important to the discussion in Chapter 4 which concerns variation in post-retrofit energy consumption and how predictable the savings might be.

Finally, a certain belief about the relative roles of the building fabric and occupants can be found in the literature. It is expressed in Palmer and Cooper (2013) as follows:

*"...as homes become more energy efficient, the behaviour of their occupants can play an increasingly important role in their energy consumption".*

This particular quotation cites Guerra-Santin and Itard (2010), who claim something to the same effect without explaining why this would be the case. One explanation again involves the *proportional* impact of occupants opening windows in efficient dwellings as opposed to inefficient ones (Ian Cooper 2014, Pers. Comm.), even though the absolute energy use would increase by the same amount in each case. Another explanation might be that, as the heat loss coefficients of dwellings across the stock become *more similar*, variation in energy use due to variation in building fabric characteristics becomes smaller.

The next chapter will challenge the statement that as homes become more efficient, occupant behaviour becomes more important to energy consumption; in fact, it will argue the opposite.

## 3.7 SUMMARY

This literature review set out to describe the current state of knowledge on how and why people heat their homes, whether this is influenced by the thermal efficiency of their

dwelling, whether building fabric retrofit is likely to change their heating behaviour and if so the extent to which this might impact their energy use.

It was not possible to answer the final question from the literature. However, in the next chapter a modelling exercise using the theory introduced in Chapter 2 and the literature in this chapter will address the theoretical relationship between post-retrofit behaviour change and energy use. This will complete the context within which to carry out the empirical study which forms the core of this thesis.

# 4

# EXPLORATORY MODELLING

## 4.1 INTRODUCTION

A question introduced in the previous chapter was how much occupant heating behaviour, and possible changes in it following retrofit, affect energy use. This chapter will argue that the answer is a function of the the thermal efficiency of the building fabric, and that the lower the post retrofit heat loss the more predictable the energy savings.

'Space heating energy use' will hereinafter be termed **S.H.E.U.**, and refers specifically to the heating energy delivered into the internal spaces, i.e. excluding the boiler efficiency.

This chapter maps out a possibility space of S.H.E.U. based on building fabric efficiency and heating behaviour. The concept of a possibility space was introduced in Chapter 2 as a means of displaying every possible outcome given realistic ranges of values of a set of input variables. In Chapter 2, a possibility space of M.I.T. given a range of external temperature was mapped out, to show that the BREDEM assumed relationship between M.I.T. and external temperature is only one of many possibilities. In this chapter, the shape of the possibility space of S.H.E.U. will be examined to visualise how sensitive energy use is to behaviour at different levels of building fabric retrofit. This will be linked back to some of the arguments in the literature in the previous chapter. Just as in Chapter 2, the premise of the possibility space is that energy use is bounded by limits created by physics and physiology.

## 4.2 INDICATION OF THE RELATIONSHIP BETWEEN ENERGY USE, BEHAVIOUR AND HEAT LOSS

Despite being very simple, the steady state heat balance equation introduced in Chapter 2 contains an interesting feature concerning the possible effect of occupant behaviour on energy use. The equation is reproduced in Equation 15:

$$Q + G = H(T_{in} - T_{ex}) \tag{15}$$

Equation 15 can be rearranged as Equation 16:

$$Q = (T_{in} - T_{ex}).H - G \tag{16}$$

If $G$ and $T_{ex}$ are held constant, then Equation 16 has the mathematical form $y = m.x + c$, where $x$, or $H$, represents the physical characteristics of the dwelling and the gradient $m$, or $T_{in}$, crudely represents occupant behaviour - that is, encompassing the set of behaviours which lead to a certain $T_{in}$. In reality, physical and occupant influences cannot be separated from each other as they have been in Equation 16: for example in the previous chapter evidence from EFUS was presented suggesting that $H$ influences $T_{in}$. However, for the purposes of this exercise they will be kept separate.

This mathematical form means that the steepness of $Q$ as a function of $H$ changes with $T_{in}$. Plotting $Q$ against a range of values (for now arbitrary) of $H$ at the highest and lowest likely values of $T_{in}$ under some standard assumptions[1] shows the difference in gradient between the high and low assumption for $T_{in}$; filling in the area between the lines gives the shape of the possibility space of $Q$ against $H$ as in Figure 14:

1 External temperature = 5°C. Internal gains = 900 W/K, calculated using SAP. Highest internal temperature taken from Kavgic et al. (2012). Lowest internal temperature taken from Figure 3, the possibility space introduced in Chapter 2.

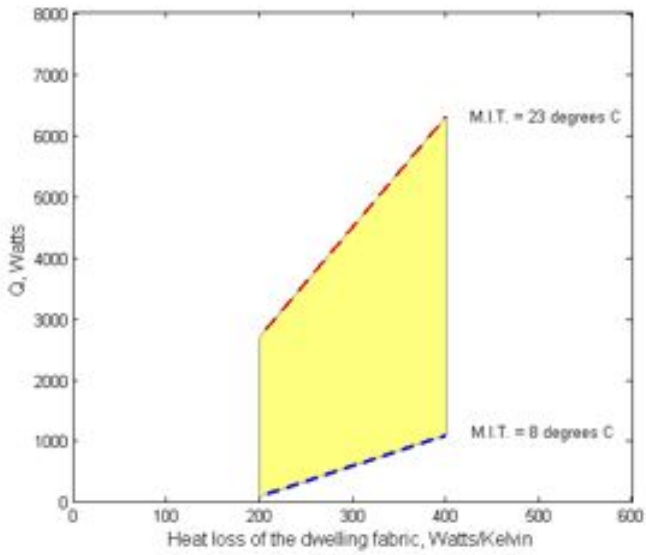



Figure 14: Theoretical relationship between space heating energy use and fabric heat loss.

The shape of Figure 14 is shorter at the left hand side than the right. This indicates that the internal temperature that is maintained makes more of a difference to energy use in higher heat loss dwellings than in lower heat loss dwellings. Otherwise stated, behaviour matters more in leaky dwellings than in efficient ones.

The above statement about the relative importance of behaviour given different dwelling efficiencies was observable simply from the steady state heat balance equation. However, it is potentially quite important. Since dwellings do not operate in steady state, and since M.I.T. does not give much information about actual behaviour, the possibility space will now be created in a less idealised form using a dynamic model which allows behaviour to be modelled in more detail than simply as M.I.T. and physical processes of heat transfer to be more accurately represented.

## 4.3 MORE ADVANCED MODEL

### 4.3.1 *Making the possibility space from behaviours*

The possibility space was created using the dynamic building simulation tool EnergyPlus. Simulations were run to calculate values of S.H.E.U. for a particular dwelling over a full feasible range of fabric efficiency and a full feasible range of occupant behaviour.

The methods of determining the inputs will be described, followed by the modelling process.

The input variables of interest were as follows: one physical variable, level of fabric efficiency, and three heating behavioural variables: number of rooms heated, setpoint temperature and number of heated hours per day. Please note that out of the five heating behavioural variables introduced in the previous chapter, window opening and use of secondary heating were excluded from the set of behavioural variables in this modelling exercise to limit the number of independent variables to 4. It should be mentioned that these exclusions do affect the analysis to come, since for example window opening is one factor influencing the heat loss coefficient; in this way, level of fabric efficiency is not a purely physical variable as assumed in this analysis.

Although these heating behavioural variables are unlikely to represent the manner in which occupants think about heating, they represent the physical limits of heating use, in that for example an occupant cannot heat more rooms than are present in the dwelling, he/she cannot use heating for more than 24 hours per day, and he/she will start to feel uncomfortable if the setpoint temperature is above a certain value. This latter variable, setpoint temperature, does not have a physical limit in the same way that heating schedule and number of heated spaces do. It could be pointed out that some occupants keep their thermostats higher than the selected limit of 23°C, but this limit was chosen since it has been shown in Kavgic et al. (2012) to be the average highest demand temperature of occupants whose fuel bills are not dependent on their usage.

The physical variable, level of fabric efficiency, also has physical limits: these are wide-ranging (put simply, from extremely leaky to extremely well-insulated), but finite.

Since it was not so much the exact values of resultant S.H.E.U. which were of interest but the shape of the space they all fell within, only three values of each variable were used: an upper, mid and lower bound. The inputs and sources are shown in Table 4; some of them draw upon other researchers' work presented in Chapter 3. Concerning the physical variable of level of efficiency, the heat loss coefficient was used. This was obtained not from data but from choosing combinations of building elements typical of low, medium and high efficiency dwellings from the EnergyPlus materials database and calculating their combined heat loss coefficient in SAP.

| | Setpoint temperature, degrees C | Number of rooms heated | Daily heating schedule | Heat loss coefficient |
|---|---|---|---|---|
| Scenario 1: low | 16 | Living room only | 07:00-08:00, 19:00-20:00 | 71 W/K: significant insulation and very efficient glazing. |
| Scenario 2: medium | 20 | Living room, kitchen, bedrooms. | 07:00-09:00, 17:00-23:00 | 437 W/K: medium insulation and glazing scenario |
| Scenario 3: high | 23 | All rooms. | 00:00-24:00 | 634 W/K: very poorly-insulated and glazed. |
| Source | Kavgic et al. (2012) | Realistic minimum (whilst still heating) to maximum possible. | Maximum possible; minimum assuming 2 heating periods as is typical in the UK. Middle one is 8 hours (based on Shipworth et al, 2010) | Using Energy Plus materials database to create custom-made building elements |

Table 4: Inputs to the model.

To eliminate variation caused by variables extraneous to those of interest, all other inputs to the model were kept constant. This means that only one built form was modelled: a semi-detached three-bedroomed house. There is no such thing as an 'average' house but semi-detached houses represent just under a third of the UK dwelling stock (Palmer and Cooper (2013)) so this was deemed an appropriate archetype.

Given that there were then only 4 independent variables, and 3 values of each, all possible combinations could be easily modelled to obtain $3^4$ results, that is, 81 values of energy use. This was carried out using parametric simulations in Energy Plus. The interface of choice was 'EP Generator', developed by Phill Biddulph of UCL Energy Institute. The timescale used was 3 winter months: December, January and February, representing the coldest time of year. The external weather file used was a CIBSE Test Reference Year for Heathrow, United Kingdom.

### 4.3.2 *Displaying the space*

Once the results of the model had been obtained, the possibility space by which they were all bounded was visualised in two ways. To be able to separately show the effect

of each of the four independent variables on the dependent variable of energy use necessitated displaying the entire model space of 81 outcomes. This will be shown, so that the reader can observe the separate effect of each independent variable, but as the full model space is complicated, the discussion around its implications will be based on a simplified two dimensional version resembling the other possibility spaces created so far in this thesis.

The first visualisation technique, showing all four independent variables and one dependent one, will be introduced gradually. That is, S.H.E.U. as a function of only two independent variables, number of daily heated hours and number of rooms heated, will first be shown to familiarise the reader with the type of relationship created. Figure 15 shows the dependent variable, S.H.E.U., varying with the two behavioural variables. A surface is created which slopes upwards. The partial derivative of energy use with respect to each independent variable is positive, so as both of the latter are increased, the dependent variable increases. Please note that the colours on the surface have no meaning.

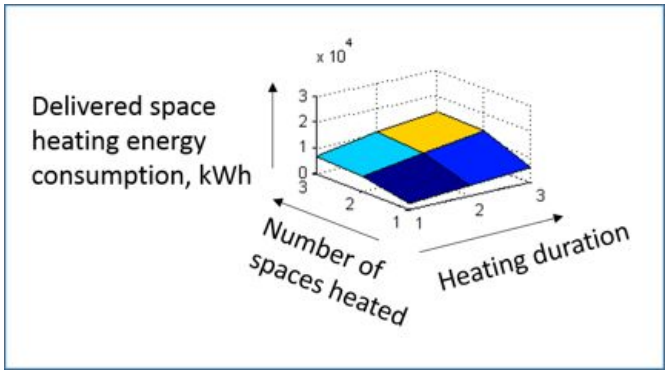



Figure 15: A part of the model space.

Now that the non-linear nature of the dependent variable has been introduced, it is time to introduce one more dependent variable representing behaviour: that of thermostat setpoint temperature. This third behavioural variable interacts with the previous two to create the value of the dependent variable. Since this cannot be added to an already three dimensional graph, the visualisation technique used will be to plot Figure 15 three times, one at each value of the new variable of setpoint temperature. This is shown in Figure 16.

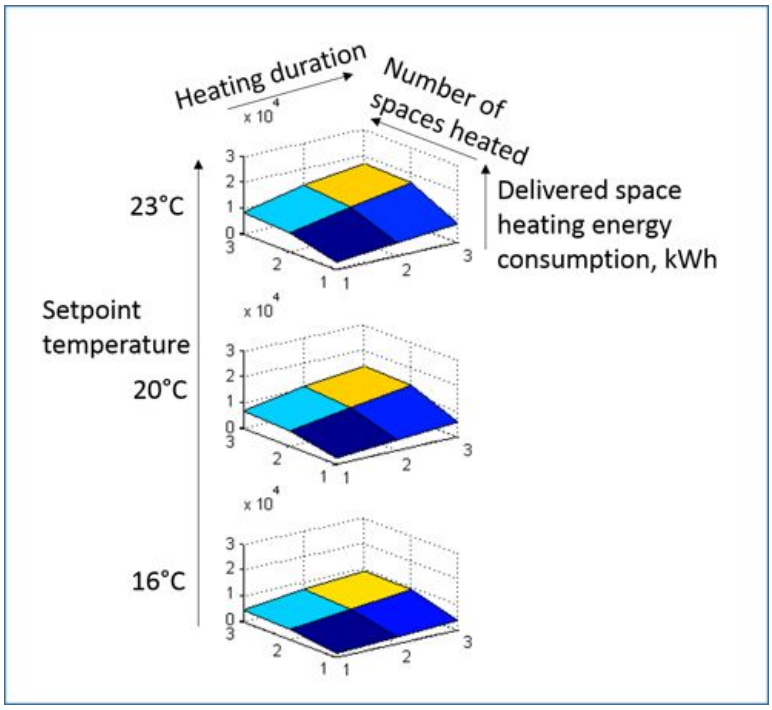



Figure 16: A larger part of the model space.

It can be seen from Figure 16 that the more one independent variable is increased (for example, setpoint temperature), the more S.H.E.U. becomes sensitive to the other independent variables (i.e. the steeper the surface becomes). This interaction between independent variables is not only interesting in itself but is also relevant later on in this thesis, as the three behavioural variables used as the independent variables here are all investigated empirically.

Now that three behavioural variables have been put into the model, it is time to introduce the final variable, which is a physical one: heat loss coefficient. The means of visualising the impact of this additional variable is to plot Figure 16 three times at different values of the heat loss coefficient, and display the results as three columns. This is shown in Figure 17:

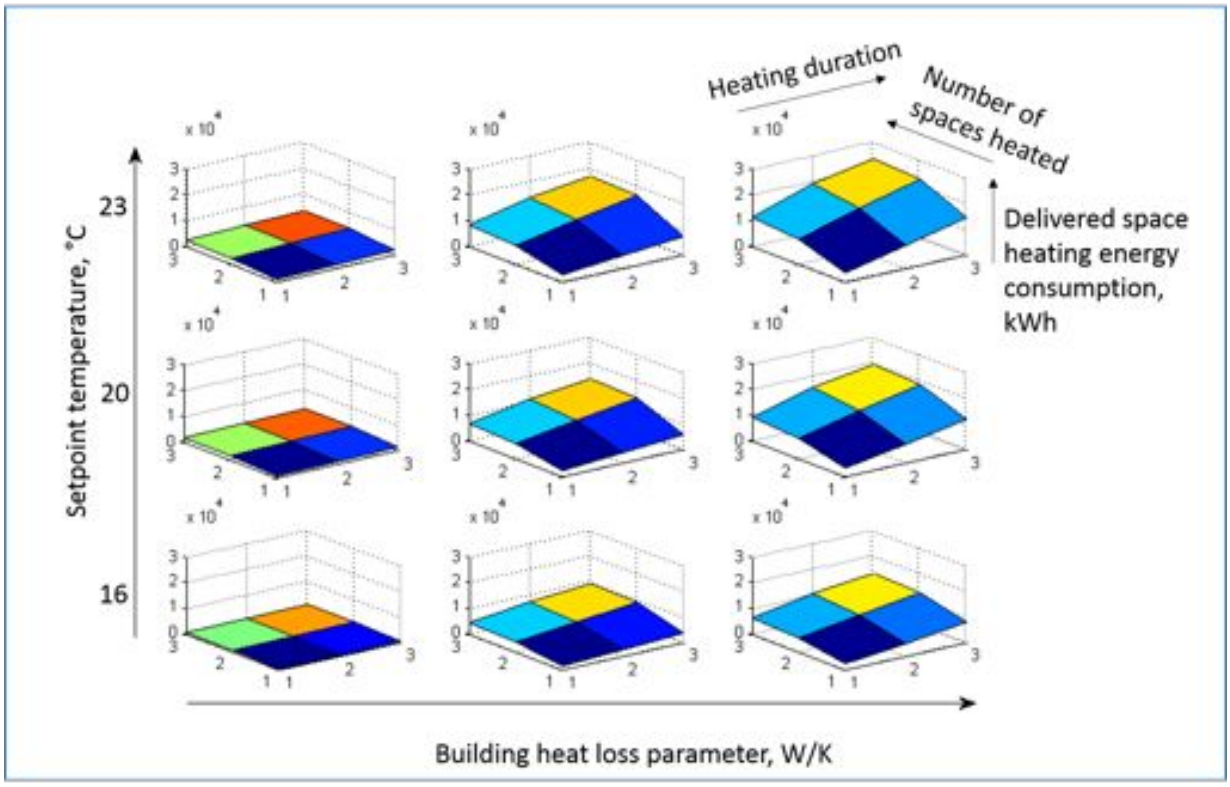



Figure 17: The entire model space.

Figure 17 shows once again that as the latest variable to be introduced to the model (heat loss coefficient) is varied, the effect of the other independent variables (the behavioural variables) upon each other is greater. That is, the steepness of the resulting surface varies with heat loss coefficient. In other words, S.H.E.U. is more sensitive to behaviour in inefficient dwellings than in efficient ones.

Now, Figure 17 is difficult to interpret due to its multiple dimensions, so the three behavioural variables will now be grouped together into 'low', 'medium' and 'high' heating behaviour scenarios, from reading across the first, second and third rows of Table 4 respectively. For example, the 'low' scenario represents a household heating for two hours per day, in only one room, at 16°C, whereas the 'high' scenario is a household heating 24 hours a day, all rooms, to 23°C. Then, energy use is plotted against heat loss parameter in two-dimensional space, which yields lines instead of multidimensional surfaces. Three lines are plotted, representing energy use versus heat loss paramter at low, medium and high heating behaviour scenarios (the effect of considering different behaviour scenarios changes the gradient of the line of energy use against heat loss parameter). The area bounded by the lines represents the possibility space.

Thus, Figure 17 is transformed into Figure 18, which is easier to understand. This time, the vertical axis is shown as average heating system power over the winter in kW, instead of energy use, for potentially easier interpretation due to the smaller numbers.

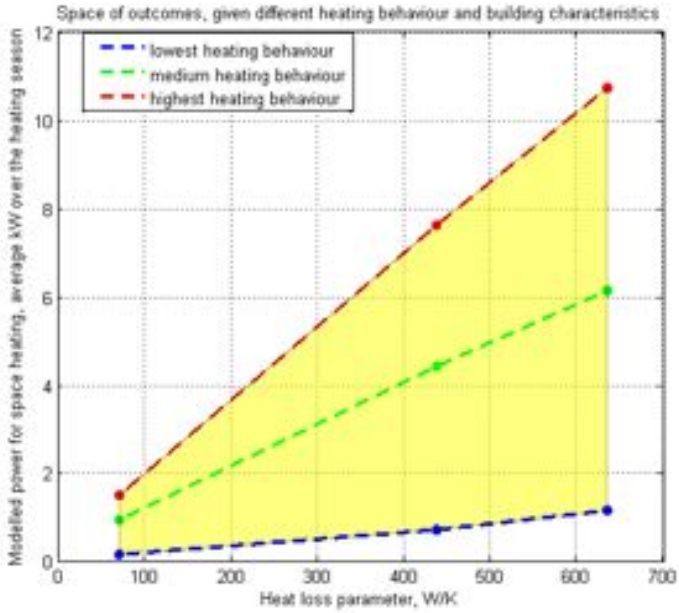



Figure 18: The model space as a possible area of outcomes.

### 4.3.3 *Using the space as a basis for discussion*

Now that a bounded space has been defined in Figure 18, it can be used to visualise some phenomena introduced earlier on. Firstly, building fabric retrofit is represented by a movement across the space from right to left, since this equates to reducing the heat loss coefficient. The trajectory, as well as going left, can go up or down at the same time, representing occupant behaviour.

The first way in which the space will be used is to show how a retrofit is normally modelled in SAP or other similar tools which assume a fixed normative behaviour. Figure 19 shows a theoretical fabric retrofit. If a line of constant heating behaviour (essentially a contour line) is followed, the heat loss coefficient is reduced without a change in occupant behaviour. The post retrofit value of S.H.E.U. is lower than the starting value.

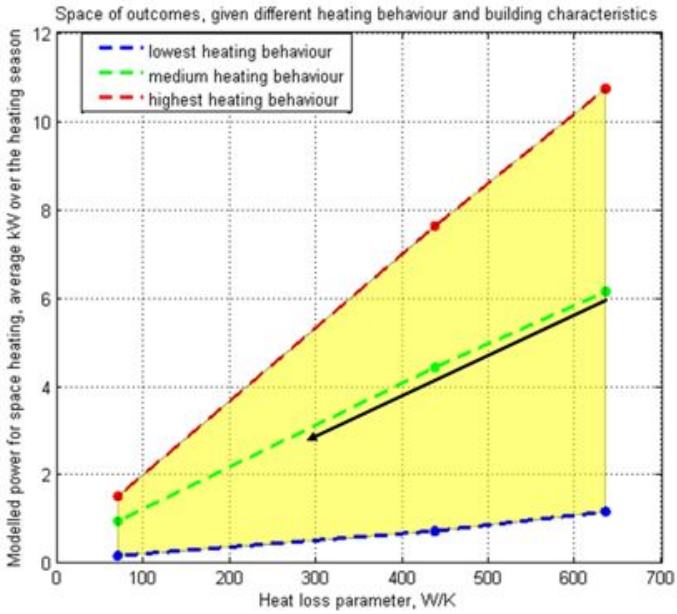



Figure 19: The model space showing how retrofit is modelled in SAP.

However, Figure 19 represents just one possible trajectory through the possibility space. In Chapter 3 the phenomenon of underheating was introduced. Evidence was given that in dwellings with a low SAP rating, the ratio of actual to modelled fuel expenditure is lower than in more efficient dwellings. This would correspond to a starting point on the possibility space on the right and some distance underneath the green (normative) line.

If one were then to try to plot an arrow representing retrofit of an underheated dwelling on the possibility space, it is not clear what trajectory this arrow would take as the building became more efficient. Cross-sectional evidence given in the previous chapter suggests that the ratio of monitored to modelled energy use would increase with efficiency, and then exceed 1 at high dwelling efficiency, but it is not known whether this applies longitudinally - see Section 3.4.1. Even if this were the case in a retrofit context, then the shape of the arrow (curve, straight line of some gradient) would be unknown. For example, if the shape in BRE (2005) (Section 3.4) were followed, the left hand subplot of Figure 20 might be obtained[2], whereas others might argue that a straight line may be more suitable, as in the right hand subplot of Figure 20. The arrows in either subplot follow different paths through the space but finish at around the same point.

2 Please note that in this chapter the x-axis is heat loss coefficient, which is not proportional to SAP rating used as the x-axis in BRE (2005).

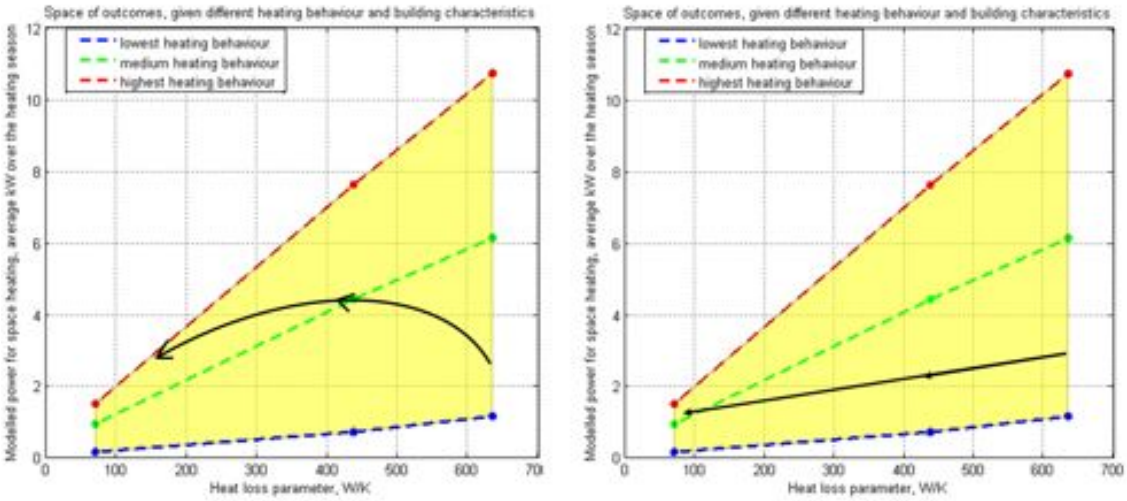



Figure 20: The model space with two underheating scenarios.

The importance of the shape of the arrow therefore depends on the level of retrofit - here, how far across the space to the left the dwelling lies post retrofit. If the retrofit took the dwelling halfway across the space ('shallow retrofit'), the curved trajectory in Figure 20 would leave the dwelling at a point where the energy use is higher after retrofit than before. This would not be the case for the straight arrow scenario. If the retrofit took the dwelling all the way to the left of the space ('deep retrofit'), the energy use at the end of both trajectories would be similar.

Next, since this is an exploratory exercise, instead of speculating the trajectory of a typical UK dwelling at different levels of retrofit, it is perhaps more useful to use the possibility space to visualise the set of outcomes which *could* occur. In Figure 21, possible outcomes are plotted for two different levels of retrofit: shallow and deep.

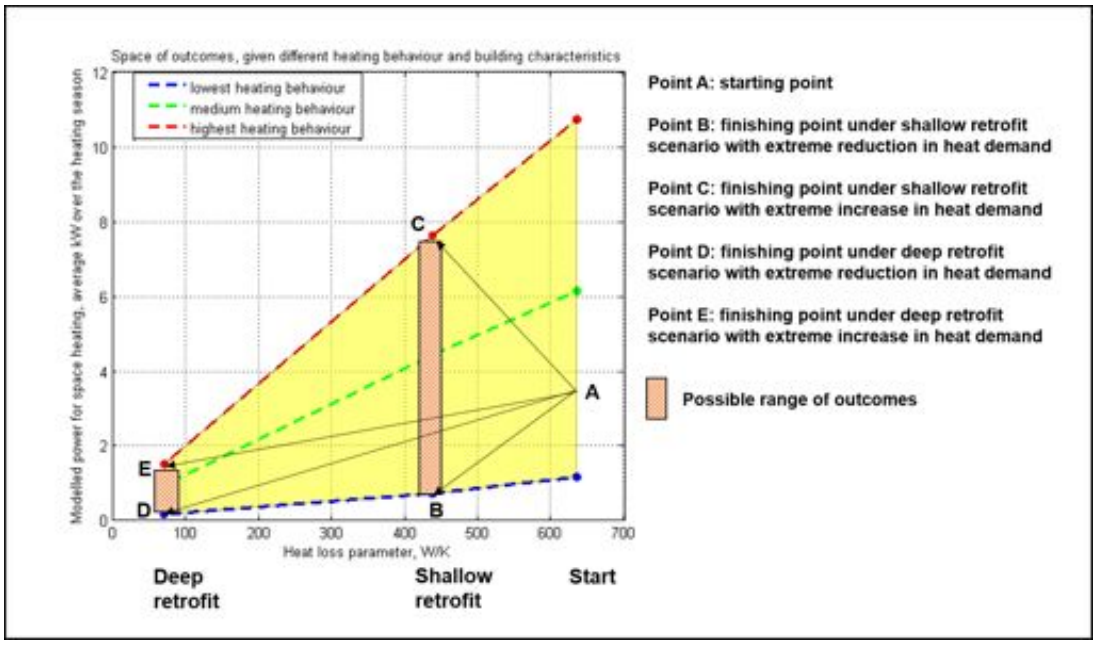



Figure 21: The model space with possible outcomes of deep and shallow retrofit.

If shallow retrofit is carried out to a dwelling starting at the right hand side of the space, there is a large possible range of outcomes. The path leading to the lowest possible S.H.E.U. is shown by arrow [A $\rightarrow$ B]. This represents occupants drastically reducing their demand for heat. Conversely, the path leading to the highest possible S.H.E.U. is shown by arrow [A $\rightarrow$ C], representing occupants increasing their comfort as much as is deemed possible within the bounded space. Between points B and C is a large range of possible S.H.E.U. - most of which lies above the original height of point A. In other words, in most possible outcomes of shallow retrofit, energy use is allowed to increase following retrofit.

This can be contrasted to the allowed outcomes of deep retrofit. Arrows [A $\rightarrow$ D] and [A $\rightarrow$ E] mark the two extremes of occupant behaviour: decreasing and increasing temperature demand in space and time to the permittted limits. Between points D and E is a small range of possible S.H.E.U. Not only is S.H.E.U. less sensitive to occupant behaviour under a deep retrofit scenario than a shallow one, it can also be seen that all points in the range of outcomes of deep retrofit are lower than point A. Therefore, energy use is guaranteed to decrease after deep retrofit, regardless of the behaviour of the occupants.

To summarise the above, if the retrofit is shallow, there is potential for energy use to drastically increase; if it is deep, there is no longer potential for energy use to increase.

The question could be raised of whether the significant increases in temperature demand represented by arrows [A → C] and [A → E] are likely to occur in reality. Some would argue that the trajectory represented by [A -> C] is unlikely: backfire (see Section 1.9) due to building fabric retrofit alone is not evidenced in the literature. Furthermore, there could be assumed to be a (possibly financial) reason for occupants not wishing to increase their energy expenditure following retrofit since the household was underheating before the retrofit. However, it could also be argued that arrow [A→ C] could be brought about as a result of changes in lifestyle of a household: for example, age, financial circumstances and the addition of a baby to a household. Decrease in fuel price could also allow comfort standards to increase without a corresponding increase in fuel expenditure.

Further to the above, it is normal for one dwelling to be inhabited by several households during its lifetime. A number of years on from the retrofit, it is likely that the occupants will have changed. The heating behaviour of the new occupants is independent of that of the old tenants, so in theory, they could have much higher comfort preferences, and thus the model space would seem to allow for the energy use of any subsequent set of occupants to be far above that of the original occupants unless the retrofit is deep. There is nothing to stop new tenants reaching the highest line of heating behaviour, as shown in Figure 21. Given the longevity of a dwelling's existence compared to the duration of a typical tenancy, perhaps the overall energy use over the remaining lifetime of the dwelling after retrofit is more important than that immediately following the point in time at which the retrofit is carried out.

Having introduced the topic of new tenants moving into a retrofitted dwelling, the effect on S.H.E.U. of heating behaviour of different occupants in general (independent of retrofit) will now be considered. Figure 22 is essentially the same as Figure 21, without the arrows. This time, however, it is interpreted not in terms of one dwelling undergoing retrofit (a longitudinal situation) but three dwellings which are identical except for different values of the heat loss coefficient (a cross-sectional situation). The effect of variation in occupant behaviour is represented by the same vertical bands as in Figure 21:

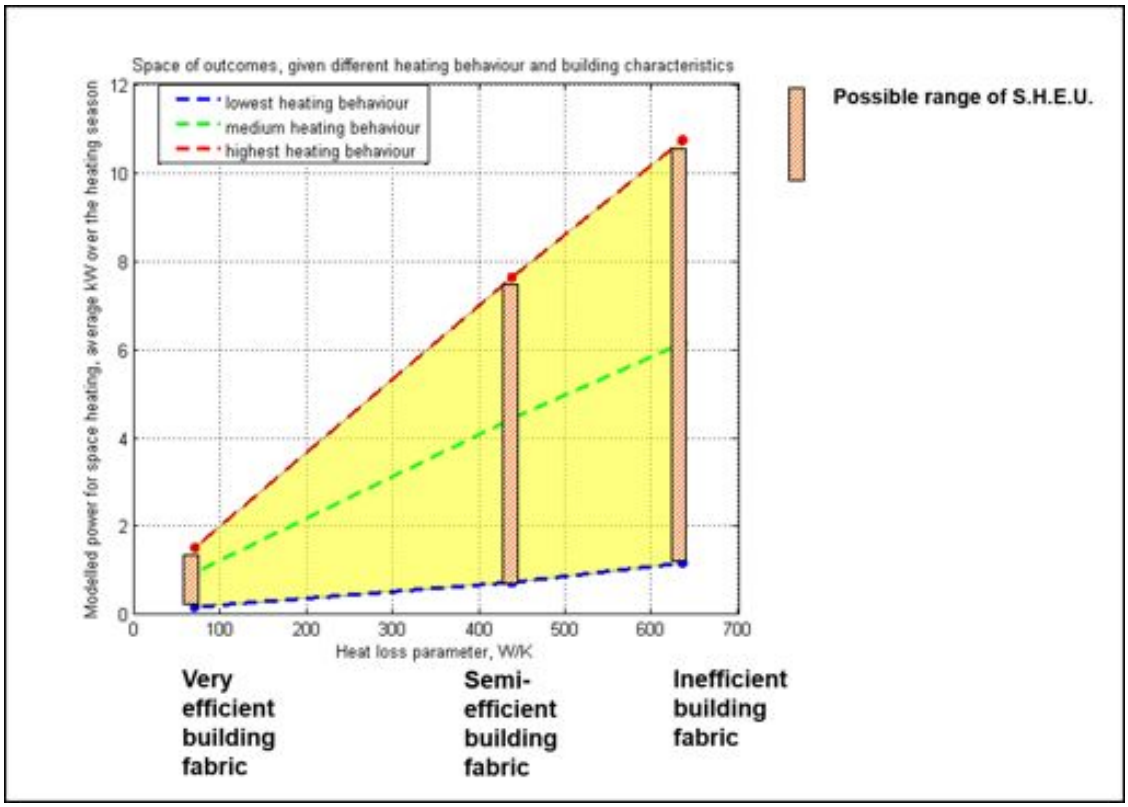



Figure 22: The model space showing the sensitivity of S.H.E.U. to behaviour at different dwelling efficiencies.

It can be seen that in inefficient dwellings, S.H.E.U. is very sensitive to occupant behaviour. If the building fabric is semi-efficient, for example a dwelling built with cavity wall insulation already present or a previously-leaky house which has undergone shallow fabric retrofit, there is still quite a lot of potential for high energy use, depending on the behaviour of the occupants. Behaviour is still very influential to the energy use of the dwelling, although not as much as in the inefficient dwelling. However, in very efficient dwellings, whatever the occupant heating behaviour, S.H.E.U. is physically contrained to be low and its allowed range is small. Behaviour does not matter much *in absolute terms* if dwellings are extremely efficient.

To summarise all of this, S.H.E.U. is robust to occupant behaviour at high building fabric efficiencies and sensitive to occupant behaviour at low efficiencies.

Now, the importance of behaviour *in absolute terms* was italicised above because variation in behaviour is normally given in relative terms. Recalling the literature reviewed in Section 3.6, all of the studies on the extent of variation in energy use due to occupant behaviour presented the results in terms of percentage variation from the mean, or percentage of total variation due to behaviour alone. This framing makes the variation

from the mean appear large ('significant' in the words of Gill et al. (2010)) in low-energy dwellings, and the role of behaviour is also argued to be large. The logical conclusion which authors reach is that 'behaviour change' programmes are recommended, such that occupants act as to decrease their energy use.

However, it can be seen from Figure 22 that since the extent of potential variation in S.H.E.U. depends on the building fabric, there is little point targetting behaviour change programmes at the occupants of highly efficient dwellings. This is because the absolute energy savings which could be atttained if these programmes were to succeed are small. Since one of the key motivators for such policies is mitigating manmade climate change, it is the *absolute* $CO_2$ emissions, and therefore the absolute S.H.E.U., as opposed to their *relative* counterparts, which are important.

It could then be argued that behaviour change programmes should perhaps be targetted at those in very inefficient dwellings who are known to be high users of heat. However, Figure 22 also shows that as soon as the occupants in inefficient dwellings who had been targetted in a behaviour change programme move out, a new occupant with higher comfort preferences could move in and still cause very high S.H.E.U. From this modelling exercise (some of the caveats of which are discussed later on), the logical conclusion is that deep retrofit is the only way to guarantee energy savings, and that behaviour change programmes cannot be relied upon to give savings throughout the lifetime of a dwelling.

The above conclusion is in partial disagreement with the recommendations from Sunikka-Blank and Galvin (2012). These authors argued that the deeper the retrofit, the more diminishing the returns in terms of marginal extra energy saved. They advocated modest retrofit (equivalent to the term 'shallow' used throughout this chapter), and behaviour change programmes, for reasons of cost-effectiveness:

*"...there is a growing realization that Germany's carbon reduction goals in respect of home heating cannot be met by demanding ever-deeper thermal retrofit standards. Retrofit standards were due to be tightened by a further 30% in 2012, but discussions with Federal policy-makers indicate that there is growing reluctance to do this. In fact a recent study by Tschimpke et al. (2011) showed that even if it were technically possible to retrofit the entire housing stock to twice the depth being currently achieved, the cost would be an order of magnitude higher than the state and homeowners could afford, and would divert funds from more economically efficient carbon reduction projects. Some policy-makers see this as an opportunity to think laterally as to how other approaches, such as a mix of modest retrofit measures and targeted behaviour campaigns, could increase the savings."*

The modelling exercise carried out in this chapter, and the arguments advocating deep retrofit, have not taken cost or cost-effectiveness into account, so it is not possible to disagree with Sunikka-Blank and Galvin (2012) using evidence arising from this chapter. However, findings from this chapter combined with literature can be used to point out that the propostion advocated in the above quotation (shallow retrofit with behaviour change programmes) lacks consideration of the short and long-term consequences if the behaviour change programmes do not work.

Effectiveness of behaviour change programmes is a large topic in itself and will not be fully subjected to exposition here; a few points will be drawn from some meta-studies of such programmes. Firstly, although 'effectiveness' is difficult to measure (Osbaldiston and Schott (2011)), it has been estimated that the energy reductions obtained from domestic behaviour change interventions range between 5-15% over the short term (Martiskainen (2007)) and in many studies the savings diminish over the next couple of years (Abrahamse et al. (2005)). Secondly, there is no evidence base describing how an intervention aimed at a particular set of occupants in their current dwelling translates into the context of the next dwelling they move to. Therefore, long-term energy savings from behaviour change programmes are by no means guaranteed.

It can therefore be argued that deep retrofit is more likely to save energy than shallow retrofit with behaviour change programmes. Whether the latter option is sufficient depends on the level of ambition of energy demand reduction.

### 4.3.4 *Caveats to this work*

There are an number of caveats to the results and implications of the above modelling exercise. Those deemed to be the key ones will now be set forth.

Firstly, the above analysis has not included the effect of changes in window-opening behaviour with increase in building fabric efficiency. As was discussed in Section 3.3.6 as part of the literature review, there is no literature investigating the possible link between building fabric efficiency and window opening. However, links between the latter and internal temperature and $CO_2$ concentration have been found, both of which can increase as dwelling fabric efficiency increases. Thus it could be hypothesised that window opening may increase following retrofit, or across the stock with increasing efficiency. If either of these hypotheses were shown to be true, this would increase the heat loss coefficient and thus move a given dwelling to the right in the model space, which in turn would allow for a larger range of S.H.E.U.

Still concerning ventilation, as the heat loss parameter improves, this requires not only reducing the conductivity of the building fabric elements, but also making the building increasingly airtight. Once the air change rate is reduced to 0.5 air changes per hour, it must not further decrease, or else relative humidity is likely to exceed 70% for prolonged periods of time and problems with mould are likely to occur (CIBSE (2001)). It is possible to keep on reducing the overall heat loss of the building fabric whilst still allowing 0.5 air changes per hour, but only through the installation of mechanical ventilation with heat recovery (MVHR). In other words, if dwellings were efficient enough to be placed in the very left hand side of the model space, their windows would not be opened in winter. This may alleviate the caveat in the above paragraph, but on the other hand the installation of a new technology would require electricity to run, increasing the space heating energy consumption.

This leads into a third caveat, which is that of occupants having to do something different to fall within the bounds of the model space in the highest-efficiency dwellings. The way the space was modelled, there were limits to energy use determined either by time and space or by the fact that occupants would feel unpleasantly warm and would turn something down. Thus, occupants would naturally keep themselves within the bounded model space, in which the efficiency of the heating system is assumed to be constant. However, MVHR is possible to run in an incorrect way such that energy is wasted - although it still must be converted to heat in the end, it is not the most efficient way to run the system. This could take the dwelling above the top 'behaviour' contour line and outside the bounded space. In an extreme case , occupants could switch off the MVHR and use simpler and less efficient ways of heating their home.

Another point falling within this third caveat concerns very efficient houses potentially requiring additional active maintenance not just to keep their energy use down but to keep their thermal conditions within an acceptable range. Summer overheating in Passivhaus dwellings in southern-European climates, or potentially in the UK in a few years due to climate change, is a well-known concern and can be mitigated by appropriate tilting of the windows[3]. However this requires occupant intervention; if this does not suit occupants, they may install mechanical cooling systems, again increasing their energy use and taking their dwelling outside the modelled space.

In summary, this modelling exercise is by no means a perfect representation of reality. It contains many caveats, some of which have been described above. However, the aim of the exercise was to facilitate a discussion, in which several phenomena in the literature (underheating, rebound) could be shown according to the same variables, and their

3 A discussion on this can be found at http://passipedia.passiv.de/passipedia_en/basics/summer

'worst-case' effects compared at different fabric efficiencies. The second aim was to then extend the current discussion in the literature to include the effect of new occupants whose energy behaviour is independent of that of the first set. The discussion can only be as valid as the modelling behind it, but it is hoped that the modelling makes the discussion around these topics more fruitful.

## 4.4 COMPARING THE MODEL SPACE WITH MONITORED DATA

The nature of the above discussion is theoretical, in the sense that all the outcomes were modelled as opposed to empirically observed. The arguments presented, advocating deep retrofit to guarantee energy savings in the short and long term, would be strengthened if some data on energy use (and its absolute variation) as a function of dwelling fabric efficiency were given.

This data is not trivial to obtain. This is firstly due to quantitative values for actual dwelling fabric efficiency (for example actual heat loss, Watts/Kelvin) not normally being available, and secondly because full access to an energy use dataset is required to be able to observe variation in energy use. Because of this, the two examples which follow do not contain quite the same parameters as were modelled.

The first piece of evidence to be presented consists of data from two groups of German dwellings. In one group are 41 'low-energy' dwellings constructed in 1991 to a standard better than the German building regulations at the time; the second group contains 106 dwellings built to the Passivhaus standard. The exact values of the heat loss parameters of both sets of housing are unknown, but the dwellings constructed to 1991 standards could represent somewhere between mid-range and efficient dwelling fabric in the scenarios in Figure 22, whereas the Passivhaus dwellings will probably be located on the far left of the model space. Figure 23, from PHI (2010), illustrates the difference in absolute variation between the two types of dwelling:

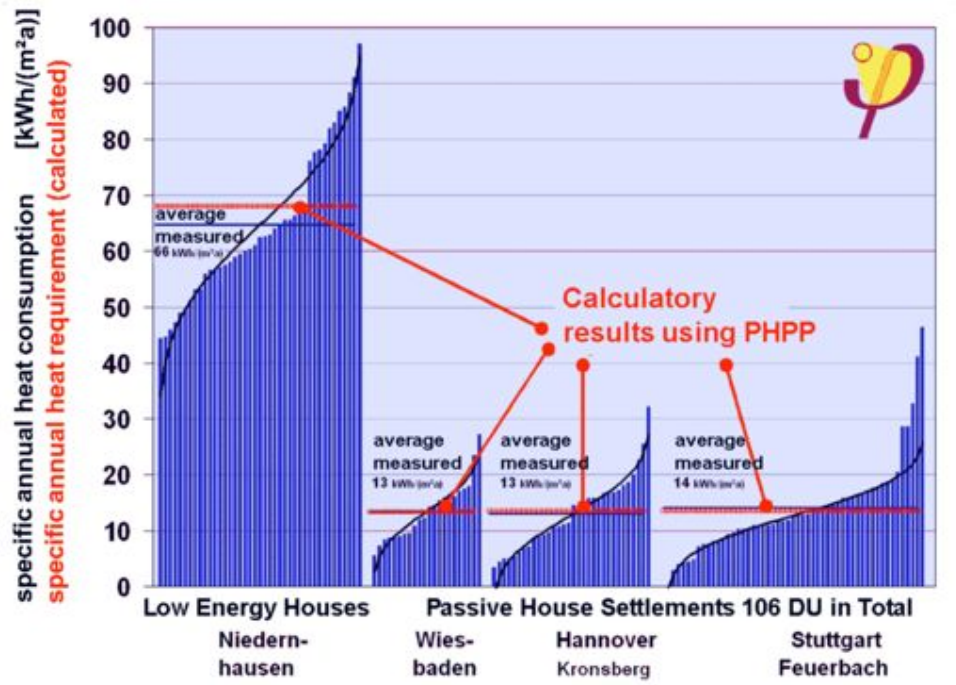



Figure 23: Illustrating actual variation in energy consumption in two types of dwelling, from PHI (2010).

It can be seen in Figure 23 that in the two types of housing, 'low-energy' and passive houses, whilst the proportional variation with respect to the 'average' (it is unclear whether this is the median or the mean) is similar in both groups, the absolute variation is much higher in the less efficient dwellings, even though they are still fairly efficient by UK standards. The authors of Figure 23 state that:

*"The influence of the user on the actual consumption is undeniable – it is even quite high"*

As with all studies which make such claims, the phrase 'quite high' is not qualified with the meaning of 'high' or how much this matters. It is clear that in absolute terms, the influence of the user matters less in the Passivhaus dwellings than the less efficient ones.

The above evidence, although interesting, does not represent the whole dwelling stock and does not represent UK dwellings. The next piece of evidence to be presented is more relevant in terms of its national origin and representativeness but less well-defined in terms of the heat loss variable. Figure 24, kindly given by Ian Hamilton to the author, shows kernel distributions of annual gas consumption normalised by floor area, for different age bands of properties. This data does not represent exactly the same variables as the modelled space in this chapter for several reasons: firstly,

the data represents gas consumption which includes space heating but also cooking and hot water demand; secondly, the gas consumption is annualised and thus not just during the main heating season, and thirdly the different curves represent age band as opposed to heat loss parameter. Concerning the latter, in *general* newer dwellings have a lower (modelled) heat loss coefficient, but one age band represents a distribution of values heat loss coefficient, partly because some older dwellings have undergone energy efficient refurbishment. Fourthly, in addition to the smoothing effect arising from the transformation between heat loss parameter and age band, an additional smoothing effect is created in plotting a kernel density function.

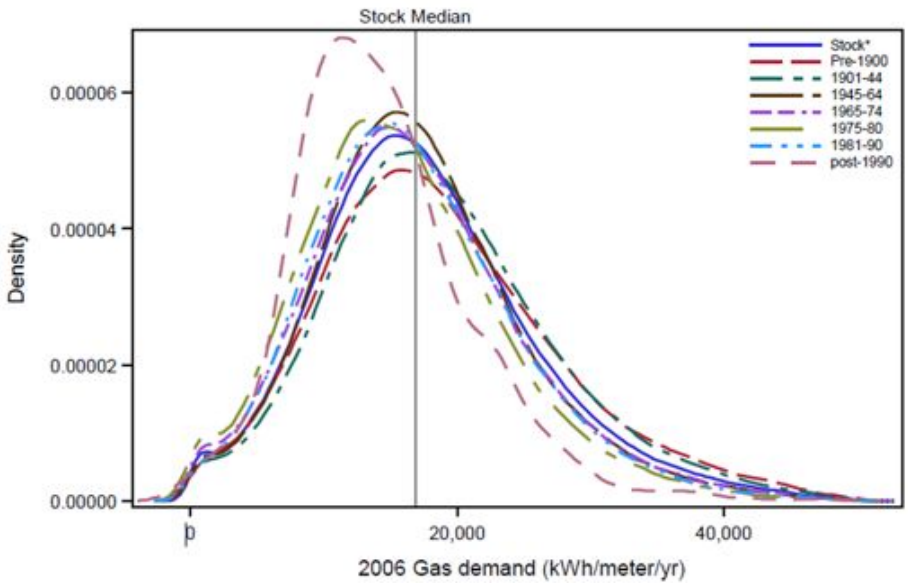



Figure 24: Kernel density plot of gas use by dwelling age band, across the UK 2007 dwelling stock. Provided by Hamilton (2013).

In short, the data shown in Figure 24 does not represent exactly the same parameters as are explored in the modelling exercise, however it can be used to support the theory that more efficient dwellings are more likely to result in low energy use. The distribution of post-1990 dwellings in Figure 24 is skewed to the left of the median with a long narrow tail. This represents most dwellings from this era using less energy than the rest of the stock, although some still use as much or more. Relating this to the theory in the modelling exercise, whereas in the latter efficient buildings cannot result in high energy use never mind what the occupants do, in the data there is still a tail on the distribution. Thus, instead of efficient buildings guaranteeing low energy use, efficient buildings are *more likely* to result in low energy use. Meanwhile, there could be several explanations for the tail of the distribution exceeding the modelled space: caveats in the modelling exercise mentioned above, features of dwellings included in gas consumption but not

modelled such as swimming pools, or quirks within the data such as multi-occupancy dwellings sharing a meter (Ian Hamilton 2013, pers comm.).

Both Figure 23 and Figure 24 above, which in some way (albeit expressed in not quite the right variables) show monitored data on variation in S.H.E.U. at different heat loss coefficients, indicate that variation in S.H.E.U. decreases as thermal efficiency increases. However, by themselves these graphs do not constitute enough evidence to support the theory, put forward in the discussion around the modelling exercise, that the only way to guarantee energy saving in the long term is deep retrofit. It would thus be helpful to know the long term energy effect of retrofit on either a given dwelling or across the whole UK stock.

In order to perform such analysis, one would need to obtain dwelling-level energy consumption data which could be matched with records of what energy efficiency measures had been installed in the dwelling. Current work performing this matching process was introduced in Section 1.7. It was mentioned that the effect of efficiency interventions on energy use had only been carried out within a 2-3 year time window; this is not long enough for long-term effects to be tracked. The reason for this window of time being selected is that it is the only period of overlap between good quality energy efficiency data and available energy consumption data (Simon Elam 2013, pers. comm.). If the latter were made available for subsequent years, this could be a useful resource for the building of an evidence base on the effect of retrofit on energy consumption over time. Furthermore, DECC are currently examining the potential of establishing a panel survey of energy use in UK dwellings which would document the evolution of comfort levels over time since retrofit (Tadj Oreszczyn 2013, pers. comm.).

## 4.5 SUMMARY

This chapter set out to explore the extent to which it matters in energy terms if occupants change their heating behaviour following building fabric retrofit.

It was shown through the modelling exercise that the answer to this question is not a constant but a function of the efficiency of the building fabric. Thus, the deeper the retrofit, the less the potential for variation in space heating energy demand due to occupant heating behaviour. This applies to the short term, when the pre-retrofit occupant may still inhabit the property, and also to the long term, when those occupants move out and new ones move in. This is important if energy savings are to be guaranteed

both in the short and long term: if the retrofit is deep enough, then no matter how much current or future occupants demand increased comfort compared to that of the pre-retrofit household, energy use is still forced down by physical boundaries.

This concludes the context section of the thesis which has been developed over the first four chapters through the discussion of theory, literature and modelling. The next five chapters constitute the empirical study. The context is returned to in Chapter 11 in the light of the empirical results.

# 5

# RESEARCH QUESTIONS AND METHODOLOGY

## 5.1 INTRODUCTION

### 5.1.1 *Summary of progress so far*

The previous four chapters, encompassing theory, literature and modelling, provided the context for a new empirical study. This context can be summarised as follows.

- Dwelling mean internal temperatures have been shown to increase following energy efficient building fabric retrofit (Section 1.9.2).
- The reason for this increase is not yet known. Two theories in the literature are:

  1. *The physics of the building fabric.* In dwellings in which there is transient heating, mean internal temperatures will naturally rise following retrofit if occupants do not change their heating timing or temperature settings (Section 2.2.2). However the calculated magnitude of this rise relies on a heating schedule with a fixed demand temperature determined by the thermostat setting (Sections 2.3.4 and 3.5.2). Whether people actually use heating like this is not yet known, especially as heating controls are often not used as intended (Section 3.3.4).

  2. *The occupants.* Microeconomic theory predicts that people might rationally decide to increase their comfort level following retrofit (Section 1.9.1). This is untested. It is known that lower efficiency homes are underheated to a greater extent (Section 3.4) but not whether this finding is applicable to one dwelling before and after retrofit.

- In fact, the reason is likely to come from the interaction between the building fabric, occupants' behaviour and heating system (Section 1.10). These three elements have been studied in isolation but not in their state of interaction. Furthermore, longitudinal studies all concern physical data (e.g. air temperature) but not social data.

- If occupants do change their heating behaviour following retrofit, there may be serious energy consequences, depending on the level of retrofit (Chapter 4). Therefore it is important to investigate whether this occurs.

- A suitable way in which to study the interactions between building fabric, occupants' behaviour and heating systems is therefore proposed to be to collect both physical and social data, before and after retrofit.

Given the above context, in this chapter research questions will be formally stated and a research design developed to answer them.

### 5.1.2 *A clarification before the research questions: a suitable sector to focus on*

In order that the research questions are not too general, at this point a particular housing sector should be identified upon which to focus the research. Social housing has been chosen for two reasons. Firstly, at the time of design of the study, the author hypothesised that social housing was the sector in which temperature change might be greatest and thus easiest to detect. This was based on a premise that low income leads to occupants' demand for space heating not being saturated, combined with a second premise that pre-retrofit unsaturated demand would lead to post-retrofit temperature increase. Concerning the first premise, evidence was given in in Section 3.4 that the extent to which actual demand falls below normative saturated demand is in fact not a function of income. Therefore, the assumption that post-retrofit temperature increase should be largest in low-income households transpired to be not necessarily valid.

The second reason for choosing social housing was a practical one: relative ease of meaningful empirical data collection. The exact nature of the data to be collected had not been decided when initally formulating the research questions, but it was known that physical monitoring of dwellings pre and post retrofit would be involved. To reduce variation due to known extraneous variables, a small region in which many retrofits of approximately the same nature were taking place in dwellings of a similar original con-

struction was specified as essential to the research design. Social housing was decided to be the most likely sector in which these criteria might be matched.

## 5.2 RESEARCH QUESTIONS

Based on the above sections, two research questions are stated as follows:

In social housing undergoing building fabric retrofit,

1. How does internal temperature change afterwards, during heating and non-heating hours and throughout the dwelling?

2. If internal temperature changes afterwards, why? What are the interactions between occupants, building fabric and heating systems which produce the temperature change?

## 5.3 RESEARCH DESIGN

In this section a methodology is developed to enable the research questions to be addressed.

Firstly, given that the research questions concern change following retrofit, a longitudinal study is desirable to be able to compare before and after. Secondly, the investigation of interactions between people, heating systems and building fabric means that data should be gathered on the influence of all these elements on each other. Thirdly, given the presence of occupants in this set of interactions, uncovering the reasons for their influence on the other two elements should involve a description from their perspective of their home environment, its changes after retrofit and their interaction with it.

The above aspects can be combined by proposing a longitudinal in-depth study using a mixed methodology, involving both physical monitoring and self-reported data from occupants. This, then, forms the methodology for the empirical part of the thesis. Two particular aspects of this methodology will now be clarified: *mixed methodology* and *in-depth*.

### 5.3.1 *Mixed methodology*

In the literature, mixed methodology normally alludes to the drawing of methods from two methodologies within the social science discipline. For example, pairs of methods drawn from different methodologies could include discourse analysis and interviews, or ethnography and interviews.

Conversely, mixed methodology in the field of energy and buildings usually involves the use of a physical method and a social method. These are often used quite separately, with a limited overlap. For example, Coleman (2011) monitored electricity consumption from ICT and entertainment devices in 14 households, and showed the data to the householders to form the basis of a discussion. The qualitative and quantitiative data were analysed separately, as they typically required very different analysis methods. However, the data were not combined in any way afterwards; thus no insight can be gained from this study on how to combine physical and social data. Similarly, analysis from each method used in Lowe et al. (2012), evaluating the Retrofit For The Future scheme using a mixed methodology, is presented separately. Concerning both of the above studies, the comment on lack of combination of different types of data is not a criticism, it is a demonstration of lack of precedent for the analysis to be undertaken later on in this thesis.

Despite the lack of precedent for intimately combining physical and social data, texts on combining different types of social data can still be of use here. Bryman (2006) performed a literature search and found 16 different types of combination of methods (not necessarily methodologies) in research design. These ranged from 'answering different research questions' (as above), right through to each method making up for the other's weaknesses ('offset'); from using one method to generate hypotheses to test with the other ('confirm and discover') to using one method to explain findings generated by the other ('explanation').

For this study, it was envisaged that the 'explanation' type of combination of methods from different methodologies would be used. The study is predominantly quantitative, because this is the expertise of the author, and qualitative data was anticipated to be used to explain the quantitative data where possible. However, the interactions aspect of the research questions cannot be answered purely by qualitative data collection. For example, if it were found that temperature had increased following retrofit, one would have to consider whether heating use had changed, both by quantitative measurement and from the occupant's point of view. Thus, proposition of mechanisms must involve

the interweaving of quantitative and qualitative data. This is quite unprecedented in this field and must be carried out with caution. It will be treated in detail in Section 7.15.5 when the specifc methods and metrics have been introduced.

Finally, please note the distinction between **mixed methodology**, discussed here, and **mixed methods**, the use of more than one method which can be drawn from the same methodology (e.g. self-report). The term 'mixed methods' is not used in this study, as 'mixed methodology' is clearer: the latter description implies mixed methods by definition, but in addition it clarifies that the methods draw from different methodologies and epistemologies.

### 5.3.2 *In-depth: a Muti-case study approach*

Due to the large number of factors relating to the occupants, building fabric and heating system which could affect a dwelling's mean internal temperature, an in-depth study has been proposed. A multi-case study approach will now be justified as a suitable way to carry this out.

#### 5.3.2.1 *Case studies and the multi-case study approach*

A case study is *"an empirical enquiry that investigates a contemporary phenomenon within its real-life context when the boundaries between phenomenon and context are not clearly evident, and where multiple sources of evidence are used"* (Yin (1991)), in Sarantakos (2005)). A multi-case study approach, a *"collection of case studies"*, is often used for purposes of replication of findings from one case study (Burns (2000)). However, Lowe et al. (2012) used a multi-case study research design with maximum variation sampling for a slightly different set of purposes: to allow the uniqueness of each case study to be explored and whilst also allowing *"key issues that cut across cases to emerge out of the heterogeneity"*. The difference between replication and emergence of common themes is as follows: the former is the intentional detection of the presence or lack of a phenomenon predetermined from another case study, whilst in the latter, in general the phenomena of interest emerge as the whole set of case studies is analysed together.

#### 5.3.2.2 *The type of knowledge gained by carrying out case studies*

The purpose of this section is to defend the use of case studies as a valid form of knowledge. This is necessary because case studies are not a commonly used approach

in the study of the outcomes of retrofit and as such require justification. One reason the approach is uncommon is that the purpose of the study of retrofit usually involves finding results which can be extrapolated to all or at least a much bigger section of the population than that represented in the case study sample. With this aim in mind, the small sample size and unrepresentative sampling methods are seen as a negative feature of case studies. This is a fair judgment: if knowedge gained from case studies is extrapolated to the population in the same way as is done in quantitative social research designed for this pupose, wrong assertions will be stated about the population.

However, it will now be tentatively argued that if case studies are designed and the insight from them used correctly, then they are a form of knowledge as valid as any other. The starting point for this defence will be selected arguments from Flyvbjerg (2006). Since his arguments are framed in the social science field which is not quite where this thesis is situated, they will be contextualised to energy and buildings; aside from using Flyvbjerg for justification of case studies, it will also be shown that not all of the arguments work in this new context.

The first of Flyvbjerg's arguments to be reproduced here is that there is not a clear-cut distinction between 'objective knowledge' and that obtained from case studies. He argues that there exists a continuum between the two, since such 'objective knowledge' actually consists of an accumulation of many case studies. This can be applied to the study of outcomes of retrofit in that there has never been a nationally-representative study of energy savings obtained following retrofit; the knowledge in the field is a collection of smaller studies, each one using slightly different measurands and focussing on different types of housing.

Secondly and regarding generalisability: this is often taken to be inextricably linked to representativeness of the sample. Authors such as Small (2009) advise those who do in-depth work with cases as opposed to large samples to not try to make their small samples 'representative', as they cannot be. His argument will not be examined in detail here; suffice to say that Flyvbjerg broadly agrees that representativeness is not a prerequisite for generalisability. One example he gives is that of the critical case: if a case is chosen to represent a particular extreme, where a phenomenon X is unlikely to happen, and X happens, then X can be assumed to happen in the less extreme cases. A similar logic applies in the opposite sense: if a case is chosen to represent an extreme where Y is most likely to happen, then if Y does not happen then Y is unlikely to happen elsewhere.

However, it is important to ask whether the method of the critical case can be applied to the study in this thesis: that is, the interaction between occupants, heating systems

and buildings in the context of retrofit. The author judges it unlikely, for the following reason: there is not yet enough evidence base for the 'likeliness' or 'unlikeliness' of phenomena Y or X. An example will be given which requires a result from later on in this thesis being brought forward into this early chapter. There was a case of an occupant who was thoroughly disinterested in energy savings and still managed to save energy after retrofit without trying. It could then be argued this is a critical case showing that retrofit saves energy whatever the occupant's level of interest regarding the retrofit and/or the extent to which he has been engaged with regarding retrofit. In other words, given that energy was saved in this critical case, it would be saved in all cases. However, this argument is incorrect, since it rests on the presence of only one independent variable: level of interest. Since real-world retrofit consists of a complex set of interactions between many variables of which 'level of interest' is only one, there could be cases in which level of interest was high but energy savings were not achieved, for example because the tenant was very interested in having a warmer home following retrofit and did not especially want to save energy. This occurred in another real case. In this way, it is very difficult in practice to find a critical case or to argue that one has been found, given all the other variables whose importance could be greater than the one upon which the choice of critical case has been based.

The above difficulty of finding a critical case is due to the complex set of interactions between occupants and building fabric. If, however, not all of these elements are involved; that is, if the case is more straightforward, it has been shown to be possible in the energy and buildings field to find something generalisable from just two cases. The study which demonstrates this is Lowe et al. (2007), in which it was found that there was a large degree of heat loss via a combination of conduction and convection up the cavity between the party walls separating semi-detached and terraced houses of masonry construction. This result can be generalised to all occupied dwellings of this construction as the main variables influencing the physical mechanism the authors discovered are simply: the presence of the cavity, and the heating being used as opposed to permanently off.

The third argument selected from Flyvbjerg concerns bias:

"*The case study contains no greater bias toward verification of the researcher's preconceived notions than other methods of inquiry. On the contrary, experience indicates that the case study contains a greater bias toward falsification of preconceived notions than toward verification.*"

This argument seems appropriate for the energy and buildings field. Given the ease which which subjectivity and bias can enter the methods normally used in the field

(physical modelling, statistical modelling), and at the same time the degree to which case studies allow the emergence of surprising findings (such as those in Lowe et al. (2007)), correctly-performed case studies have potential to be at least as unbiased as other methods.

This concludes the section discussing the appropriateness of case studies for gaining valid knowlege in the field of energy and buildings. Next, a process for carrying out a multi-case study research project is specified.

#### 5.3.2.3 *How a multi-case study design works*

A procedure for multi-case study research is described in Figure 25, from Yin (2003):

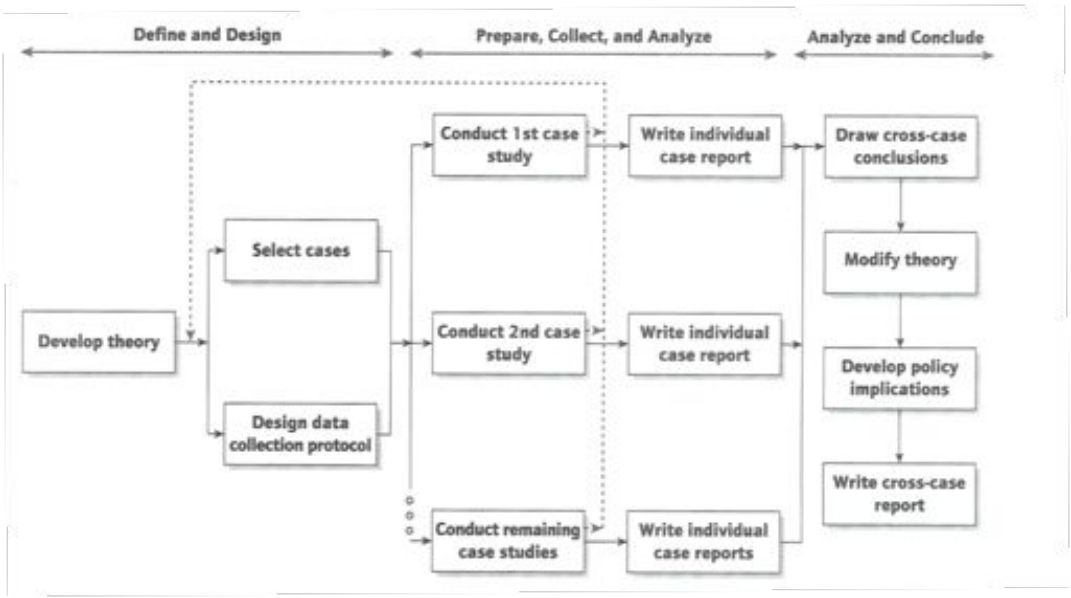



Figure 25: Diagram of the process of multi-case study research, from Yin (2003).

An important point to highlight from Figure 25 is the twofold data analysis process. Data is firstly analysed in the context of the particular case study in which it was obtained. This stage is in accordance with the part of the definition of case study research in Section 5.3.2.1 as *"empirical enquiry that investigates a contemporary phenomenon within its real-life context"* (Yin (1991)). The second stage of analysis consists of cross-case comparison, from which key themes cutting across cases can be identified and new theory developed.

Yin's process of multi-case study research was deemed appropriate for this thesis and will thus shape the analysis process later on.

The introduction of the approach of mixed methodology multi-case studies leads to a number of associated topics to be treated: validity, causality and theory. It is more suitable to treat validity, causality and properties of the sample later on, once the methods of data collection and construction of analysis techniques have been introduced, as then concrete examples of pursuing validity and inferring causality can be given. Theory, however, can be treated at this point in the discussion.

### 5.3.3 *Theoretical framework for a study combining physical and social approaches*

In this thesis, the novel approach of the combination of the physical and social elements of a household raises problems in terms of theory and interpretation. This is because there exist relevant theories which address the physical elements of the home (this was the subject of Chapter 2, which featured the derivation from Equation 5 of multiple physical principles to help interpret real data); there also exist theories (or ways of thinking) which are relevant to the social elements of the home, such as social practice approaches and behaviour change theories. By themselves, the physical and social ways of thinking are incomplete explanations of what is happening. Neither of these types of theory contains aspects of both the physical and the social elements of the home.

One problem arising from this is a tension between these methodologies of gaining knowledge through analysis of data, in that physical scientists normally use a positivist worldview and social scientists normally use a relativist one. If physical and social data are to be combined, which is the case in this thesis, this tension manifests itself in several places: how methods are designed, how data is analysed and how different types of data are combined. The researcher cannot progress unless one or the other elements (physical, social) is treated as fixed or 'true'.

Although this tension has not been fully resolved in this thesis, a proposed tentative solution (thanks to Adam Cooper 2013, Pers. Comm.) can be introduced in the longer term for a new class of theory: a socio-technical theory of home internal environment. This would presuppose that homes are socio-technical systems which have distinct technical properties, consistent with e.g. thermodynamic theory, and social properties, consistent with e.g. social practice approaches - but the theory would look at the interaction between the two. An example of this tentatively proposed later on in Chapter 11 is a theory of mean internal temperature, derived from both physical and occupant-reported relationships between variables.

When attempting to combine within one theoretical framework relationships derived from two methodologies, tasks which span the two - such as trying to link an occupant comment with a piece of monitored data - can be carried out by treating the social data more positively (i.e. taking more or less at face value what people are saying they are doing) and the technical data more relatively (including recognising framing issues described later on in Section 7.15.4.1).

## 5.4 SUMMARY

In this chapter, research questions around how and why internal temperatures change following retrofit were set out. A longitudinal multi-case study mixed methodology was proposed to gather and analyse both physical and social data and combine them. Since this is a new type of study, the theoretical framework is not fully developed, but this is also an exciting opportunity in that this thesis can contribute to the development of new theory.

The actual methods to be used within the methodologies introduced above are the subject of the next chapter.

# 6

# METHODS OF DATA COLLECTION

## 6.1 INTRODUCTION

In the previous chapter, a mixed methodology multi-case study approach was proposed to answer the research questions around how and why internal temperatures change following building fabric retrofit. This chapter explains the development of methods and their deployment in the data collection process.

Whilst full evaluation of methods is left to the Conclusion (Chapter 12), it will be made clear in the current chapter that not every aspect of the data collection went to plan. Yardley (2000) recommends that the data collection process be fully documented to increase the validity of the conclusions reached using that data. Here, the failures will be documented so that the reader can keep the limitations of the data in mind when the analysis and results are presented in subsequent chapters.

The reader is reminded that the research questions were stated as follows:

In social housing undergoing building fabric retrofit,

1) How does internal temperature change afterwards, during heating and non-heating hours and throughout the dwelling?

2) If internal temperature changes afterwards, why? What are the interactions between occupants, building fabric and heating systems which produce the temperature change?

Physical variables will be addressed in Section 6.2, followed by social variables in Section 6.3.

## 6.2 METHOD DEVELOPMENT: PHYSICAL VARIABLES

### 6.2.1 *What to measure?*

The following variables are particularly relevant in an investigation of internal temperature over time and space in a dwelling:

- *Air temperature:* Research Question 1 necessitates the recording of a timeseries of air temperature data, in order to observe the evolution of temperature over time during heating and non-heating periods. Furthermore, the profile of temperature throughout the dwelling is also specified in the research question and so it is necessary to measure air temperature in every room of each dwelling.

- *Radiator temperature:* This is to obtain the daily hours of heating (Martin and Watson (2006)), to observe whether this changes following retrofit.

- *Thermostat setting:* In some cases the thermostat setting is equal to the temperature demanded by the occupants during the heating period.

- *Use of space:* Qualitative evidence described in Section 3.5.1 introduced the phenomenon of occupants using rooms differently following retrofit - specifically, expanding their use of space as rooms become warmer. Use of space would then seem a relevant physical variable to measure if possible.

The remainder of this section will take each variable introduced above and derive a suitable method for its measurement.

### 6.2.2 *Air temperature (and the incidental variable of relative humidity)*

Air temperature is a relatively straightforward variable to measure, since tried-and-tested sensor equipment precisely for this purpose is available. One such sensor is the HOBO datalogger, which records a timeseries of air temperature at whatever frequency the researcher wishes. In practice there is an upper limit to this frequency, determined by the thermal inertia of the logger. The exact value of this is not stated on the HOBO dataseheet; it was nonetheless decided that 20 minutes is an appropriate measurement frequency.

In a purely thermodynamic sense, 'air temperature' usually refers to **dry-bulb** temperature. The latter is not exactly what is experienced by the occupant, which is **operative temperature**: a resultant temperature arising from a combination of convective and radiative heat transfer. The HOBO family of dataloggers introduced above are thought to measure a quantity which consists of roughly 80% dry bulb temperature and 20% radiant temperature (Sam Stamp 2013, pers. comm.). HOBOs should be placed at about waist height, out of direct sunlight and away from heat sources. The random error on a HOBO is quoted by the manufacturer as $\pm 0.35^{o}$C and they are robust against mild shock, for example falling off a surface.

HOBOs can measure several variables at once; they contain an inbuilt relative humidity (R.H.) sensor, therefore even though this is not stipulated in the research questions it is useful to measure R.H. for this thesis. Reporting of R.H. was also one condition of access to the site as will be explained in Section 6.5.1.

External temperature and R.H. can also be measured using a HOBO contained with a purpose-built shield which protects the logger from rain and wind.

The model used was HOBO U12-012.

### 6.2.3 *Heating use*

Some of the large-scale studies reviewed in Chapter 3 used air temperature to attempt to infer radiator activity. However, since the empirical study in this thesis was in-depth and therefore necessitated a small sample size, more equipment was available per dwelling. As such it was not necessary to economise on sensors in this way and therefore radiators could be monitored separately. Experience gained in other studies indicates that logging radiators as opposed to using air temperature as a proxy is a more informative method of monitoring heating use: BRE (2013c) and Martin and Watson (2006) refer to problems encountered by themselves or other researchers respectively concerning accurate conversion of air temperature into radiator state.

A method of directly monitoring the activity of the heating system devised by Martin and Watson (2006) was used. In their study, the placement of a temperature logger on a central heating flow pipe produced a very clear signal indicating whether the heating system was on or off. In this thesis it was decided to use a slightly modified version of this method: instead of just one sensor being placed on the pipe from the central heating to the first radiator in a circuit, in this study one logger was put on every radiator or

nearby. This was to enable information about which rooms were heated before and after retrofit to be collected: empirical monitoring of which radiators are turned off has not been carried out in the literature.

As with Martin and Watson (2006), the absolute temperature of the radiator was not considered as important in itself - the aim was to be able to discern a clear pattern of when there was heat flowing to the radiator. This pattern should also be able to distinguish between when the heating system is cycling (having reached the setpoint temperature), and when it is switched off and on again by a timer or the occupant. The former of these, cycling, would be very difficult to observe without directly monitoring the heating system as opposed to inferring its activity using air temperature information as was done in previous studies.

The HOBO datalogger introduced above for monitoring air temperature and relative humidity could be used to log the radiators as well, but a similar type of sensor called Tinytag is slightly more convenient for this purpose as it has a hole in it, allowing an elastic band to be put through it to attach it to part of the radiator. The model used, Tinytag Ultra, has a quoted random error of $\pm 0.45$°C.

Concerning the thermostat setting, it is difficult to log this throughout an entire monitoring period without asking the occupants to help with the recording process. It was decided to rely on photographing the thermostat at the start and end of the data collection periods and asking occupants to demonstrate how they use it, to determine whether its setting changes and if so what the unobserved values are likely to be. Although Shipworth et al. (2010) showed that occupant self-reported thermostat setttings did not correlate with those estimated from temperature data in their homes, it was assumed that occupants can at least state how they use the thermostat: i.e. not at all, or to turn the heating on and off, et cetera. Occupants' statements concerning how they use their thermostat should triangulate with their statements concerning how they use their programmer or boiler: for example, if an occupant reports never touching the thermostat, he/she must turn the heating on somehow, so should report interacting with the programmer or boiler.

### 6.2.4 *Occupant use of space*

It is constructive to have a specific metric in mind instead of the vague concept of 'occupant use of space'. The initial metric, later to be superseded, was which rooms in a

dwelling are used at what time. Before justifying the selected measurement technique, it is worth spending some time discussing how to ethically and effectively measure room use, since it raises interesting questions and trade-offs.

Other researchers have used the following methods to gather quantitative data on occupant location within a building:

- Self-completion time diaries (Merghani (2001) and Sawashima and Matsubara (2004));
- Fixed sensors (e.g. passive infrared sensor networks, as in Ekwevugbe et al. (2013));
- Sensors attached to the occupants in some way (Radio signalling, known as RFID, in Gillott et al. (2009), or taking photos of the surroundings, in Gauthier (2011b)).

As demostrated above, there exists a range of possible methods, of which some require the occupants to provide data themselves, and some rely on sensing equipment of some sort. Each method raises concerns associated with ethics and reliability of reporting. A discussion of ethics can be found in Section 6.4.1; here, reliability of reporting is considered. A well known example of loss of reliability is the so-called 'Hawthorne effect'. Although this term was first used for one particular type of bias in a psychology experiment, it is now the case that:

*"Generally, references to the Hawthorne effect all concern effects on an experiment's results of the awareness of participants that they are the subject of an intervention."* (Draper (2013)).

One could imagine that measurement methods which either require occupants to actively do something, or which feel intrusive, would have such an effect on the data obtained. However, there could exist a trade off between the Hawthorne effect and another dimension: the accuracy of the reporting technique. For example, filming participants may change their behaviour but would provide an accurate report of what happened (even though 'what happened' may not have been what would have happened in the absence of the monitoring). On the other hand, the least intrusive technique would perhaps be to interview occupants about their use of space over an already-elapsed period - in which case their behaviour would not have been influenced by the study but the reporting technique may not be accurate (see the discussion on validity of self-report in Section 6.8.0.2).

A conceptual diagram, Figure 26, is presented to help think through this problem. As indicated above, there are two dimensions of the problem when one is trying to measure

occupant use of space: the possibility of changing occupants' behaviour through the act of measurement, and the uncertainty in the measurement instrument. The aim of the researcher is to minimise both types of error, by selecting a technique which falls as close as possible to the bottom left hand corner of Figure 26.

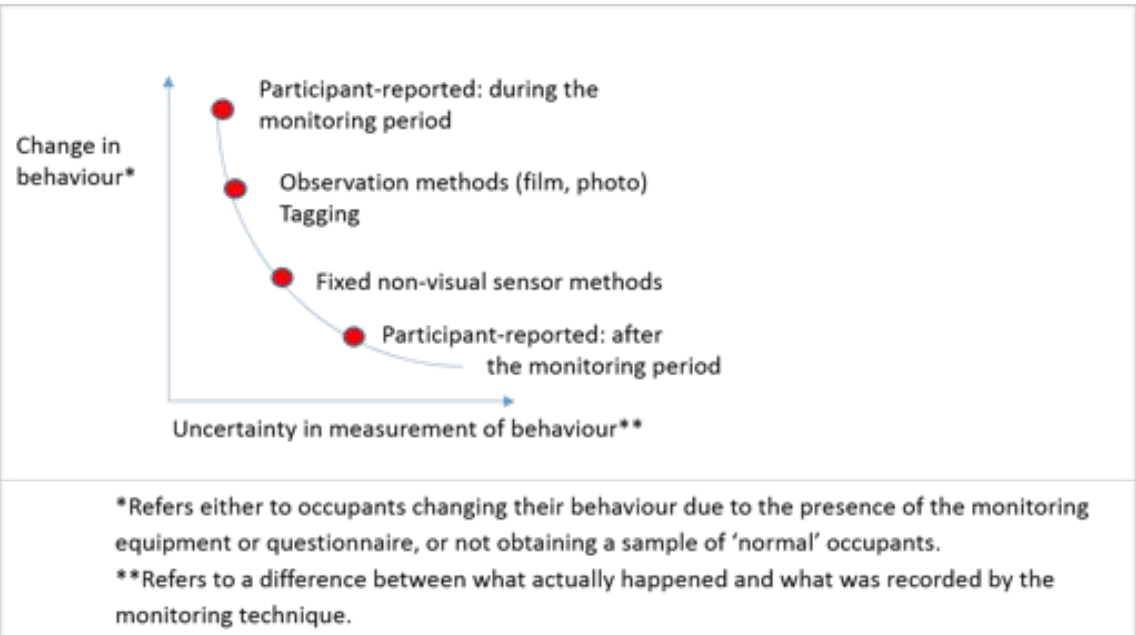



Figure 26: Two dimensions of error which could occur when monitoring occupant use of space.

It should be noted that Figure 26 is qualitative and should not be taken literally. For example, even though the line upon which the possible measurement techniques are plotted is drawn as a convex curve, it is not clear whether in reality there is an optimum point, or whether it should perhaps be a straight line; that is, there is no optimum technique. It should also be noted that included in the 'change in behaviour' axis is not just the effect of the study on the participants, but potential bias in who signs up to the study at all. This can be a problem in this field - for example Scott et al. (2011) used homes of Microsoft researchers for their study on predictive heating systems. Arguably this sample is likely to interact differently with the system to the rest of the population.

It was decided that a suitable optimum solution to the trade off between these two dimensions would be passive infrared (PIR) sensors. The first reason relates to both potential distortion of a household's typical behaviour and ethics: PIR sensors do not measure visible light and also their output is not an image but a binary signal, so the sensors cannot report on what occupants are actually doing aside from moving. Furthermore, they cannot distinguish between specific occupants so it is impossible to track one person around a dwelling unless he/she is the sole occupant. Thirdly, some

occupants are used to PIRs being present in their home in the form of burglar alarms, so it may be easier to explain to occupants the type of data recorded by the sensors[1].

Considering now the x-axis of Figure 26, reporting accuracy, PIRs have an immediate response and thus a high resolution in time. However, other researchers have highlighted the difficulty of drawing meaningful conclusions from PIR data when attempting to detect change in patterns over time. Sixsmith et al. (2007) tried to analyse PIR sensor data to detect when elderly patients changed their routines, as a potential warning sign that they need help. Upon being asked by the author of this thesis how they detected change, the authors replied:

*"In fact, the truth is, this was difficult because the data we got was so diverse, noisy and generally 'random' that it was difficult for any algorithm to have much success."* (Nick Hine 2011, pers. comm.)

In other words, the signal to noise ratio was too low to enable change to be detected.

A second point to be drawn out from Sixsmith et al. (2007) is that their sensing network was specially developed by their team. That is, they did not purchase such a system off the shelf. This is the case with many other studies in the field of domestic automatic sensing: ready made sensor networks are too high-end (e.g. for the purpose of controlling lighting in supermarkets) to be affordable for use by academics studying domestic contexts.

Therefore, two attempts at building a bespoke PIR occupancy logger were undertaken.

#### 6.2.4.1 *First version of the occupancy sensor*

The first attempt used existing equpiment owned by the author's research institution: HOBO loggers. A simple circuit was built which used the signal from a PIR sensor to be an external input to a HOBO sensor. Thus, the PIR took a measurement at a specified time interval (shown in Figure 27). This was not an ideal solution as movement is really event-based as opposed to continuous, thus an event-based not a time-based sensor should be used; however, this attempt made the most of existing equipment. It was decided that if it this solution did not work well enough, then a bespoke sensor would have to be designed, which would require far greater time, effort, cost and expertise.

1 However, since this study was completed, another study used PIR sensors with the effect that the occupants thought they were cameras (Tadj Oreszczyn 2013, pers. comm.)

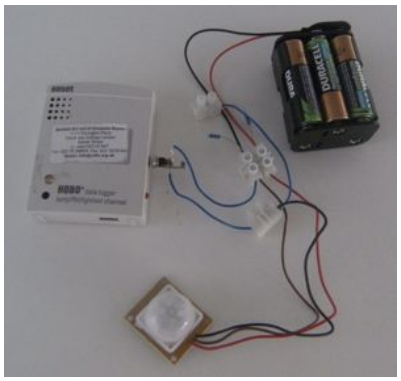


Figure 27: First attempt at creating an occupancy sensor.

This first version of the occupancy sensor was used in a pilot study of all the methods developed so far in this chapter. This pilot study is the subject of the next section.

### 6.2.5 *Piloting the techniques developed so far*

In developing the techniques and equipment to be used in a study, it is common to take advantage of one's family, friends or pets. The 18th Century poet Percy Bysshe Shelley was so interested in the science of his day that he accidentally killed the family cat whilst trying to give it electrotherapy. Here, testing monitoring techniques on the author's family proved to be helpful to further develop the study without injuring any animals.

The techniques to be tested ranged from those which had been demonstrated in the literature many times before - monitoring air temperature - through those which were not entirely new but were being extended here - monitoring radiators - to techniques which required a large amount of testing and development - monitoring occupancy. The air temperature and radiator monitoring was straightforward: sensors were placed at waist height in each room on a surface away from direct sunlight and external walls, and an additional sensor was attached to the radiator in each room. The occupancy sensors, however, required testing in several locations to investigate whether they could accurately determine when a room was occupied. Thus, a pilot study lasting one week was carried out in March 2011.

#### 6.2.5.1 *Testing the radiator method*

The aim of piloting the radiator monitoring technique was to ascertain how clear a signal emerged of 'on' and 'off' states, including cycling, and to provide some test data with which to develop the algorithm used to turn the temperature data into a binary signal.

Figure 28 shows the data obtained from the logger in the dining room of the pilot dwelling during 2 days of the pilot experiment. It can be seen that not only is it clear to the eye when the heating is on, but that cycling can also be observed (clearest between 16:00 and 21:00 on the first day). This is a satisfactory signal, although further work is required to turn such data into a binary string. This is documented in Section 7.7 in the next chapter.

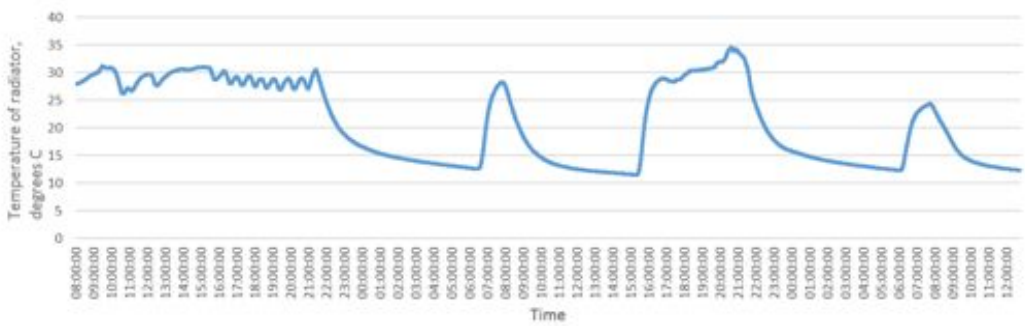



Figure 28: Example of data obtained from a radiator temperature logger in the pilot study.

#### 6.2.5.2 *Testing the first version of the occupancy sensors*

The questions concerning occupancy sensing to be answered in the pilot study were as follows:

1. Can sensors made from PIRs and other equipment already owned by UCL Energy Institute be used to adequately detect the periods for which rooms are occupied?

2. If so, where should these devices be placed to optimise the detection of occupancy of a room?

One PIR sensor was placed in the corner of each room and one on the internal door-frame, pointing into the room. To validate the PIR data, the author asked the occupants to write down whenever they went into or left a room in a diary. In most research scenarios this would not be seen as adequate validation since it is arguably less accurate

than the sensing method; however, this was the only validation method available at the time.

An example of the sensor data obtained from this initial test, compared to when the occupants reported being in a certain room on a particular day, is shown in Figure 29.

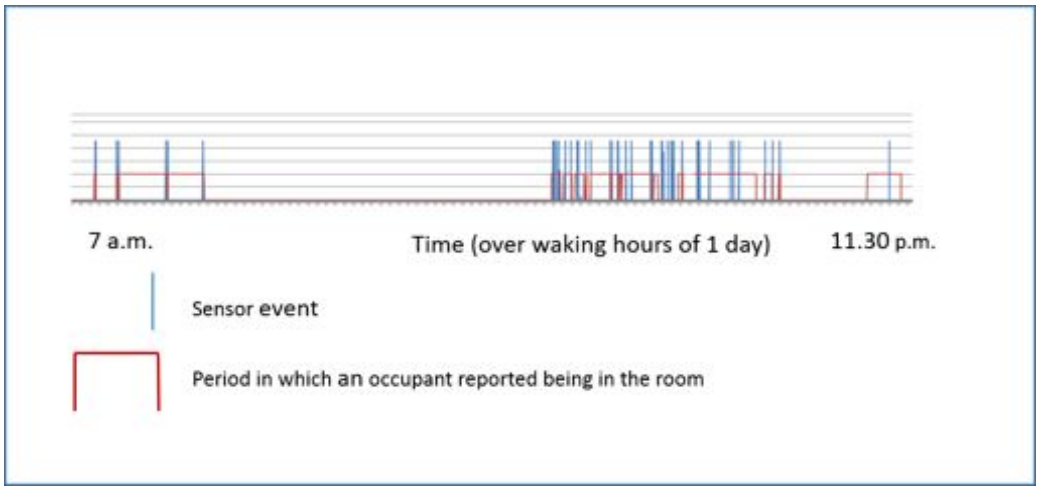



Figure 29: Testing the validity of the occupancy sensor data.

This example data was chosen as it highlights a few points:

1) In the left-most part of Figure 29, it can be seen that the sensors have clearly recorded the incoming and outgoing of the occupants. However, it is not clear which blue points are incoming and which are outgoing, and therefore which periods within the cluster of data are occupied.

2) The big cluster of activity in the figure shows that the sensors successfully capture the beginning and end of the period of much activity, but again it is impossible to tell, within that, when the room is actually occupied or not.

3) On the right of the figure is a single occupancy sensor point, representing a longer occupancy according to the time diaries. This is an example of the sensors not detecting incoming and outgoing of occupants but detecting movement during the occupied period. It is impossible to tell from the sensor data alone how long the occupied period is.

If the above problems had been considered for longer, algorithms could have been written to make estimates from this data. For example, estimates of the probability of occupancy of a room as opposed to a binary signal of 'occupied' or 'unoccupied' could have

been made. However, due to the above problems, the method of pointing occupancy sensors inside rooms was abandoned (upon reflection, too quickly).

The second method tested was to place two of the sensors on the inside and outside of a doorframe respectively, pointing downwards. This has the advantage of not 'looking at' occupants in a rooms and thus may be more socially/ethically acceptable. A second advantage is that, by entering or leaving a room, an occupant will necessarily be moving, and thus should be detected by the sensor. This latter point is important since Ekwevugbe et al. (2013) reported that PIRs pointing in a room failed to detect the presence of stationary occupants.

However, since the sensors in their current state were time-based and not event-based, their time resolution was not high enough for an occupant to pass one at a different recorded time from the other - that is, this combination of sensors could detect that an occupant had crossed its path, but it could not tell whether the occupant had gone into or out of the room.

The answer to the pilot study research questions was thus that it was not possible to use existing departmental equipment to construct occupancy sensors. This led to the need to develop a bespoke sensor, which was bi-directional, event-based as opposed to time-based, battery-powered, low-power so as to last a reasonable number of weeks, cheap, reliable (for ethical reasons it was not wished to transmit any data back to the researcher during the monitoring period) and possible to fix onto any type of doorframe. Such a sensor would measure how many people were in a room at a given time, as opposed to simply whether a room is occupied or not.

The development of this second occupancy sensor required a lot of work and was not very successful. The process will be described briefly here and reflected upon more in the Conclusion in order either that other researchers can avoid making the same mistakes, or that they can continue developing the concept of a non-instrusive PIR occupancy system.

### 6.2.6 *Further development of the occupancy sensor*

#### 6.2.6.1 *The principle and its development into a sensor*

Given the specification developed by the end of Section 6.2.5, the author did not have the technical skills to create such a sensor, and as described above there was none available

Figure 30: Showing the final occupancy sensor in place on a doorframe.

to buy, so the technical design was subcontracted to a UCL Electronic Engineering student under the guidance of the author. Its pricinple involved two PIR sensors at a certain angle from each other being triggered at slightly different times. The direction of travel of an occupant could then be inferred by which PIR fired first. Below is a brief description of the final unit, shown in place in Figure 30 and opened up in Figure 31 (the circuitboard can be found in Appendix D).

The unit consists of two PIR sensors, a battery pack, an SD card and a microprocessor, on a circuitboard programmed using the Arduino environment[2]. The code on the chip performs the following:

a) After initialisation, the microprocessor is sent to sleep (this is to reduce its power consumption).

b) The only event which triggers the microprocessor to exit sleep mode is an interrupt from either PIR ('left' or 'right').

c) If one PIR is triggered, the microprocessor waits for the other one to be triggered, which would signal that someone had traversed the doorframe. If this happens, it is recorded, then the microprocessor enters sleep mode again.

d) However if a certain time elapses before the seccond PIR is triggered, the system records this and enters sleep mode.

2 Arduino is an open source electronics prototyping platform. More information at http://arduino.cc/

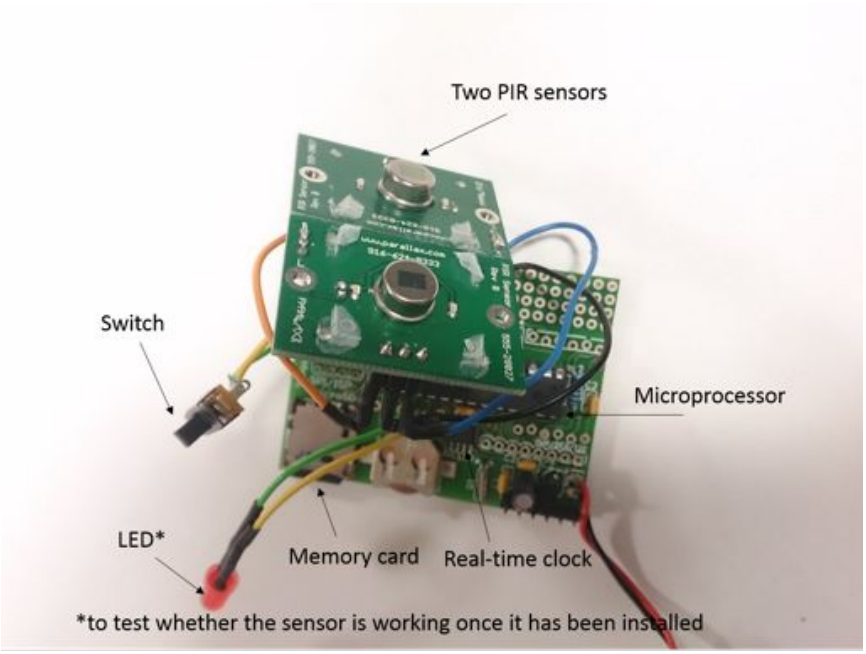



Figure 31: Showing the components of the final occupancy sensor.

e) There are four possible outputs: left PIR triggered then right, right triggered then left, right triggered but left not triggered in a certain period afterwards, left triggered but right not triggered in a certain period afterwards.

f) The outputs are stored on the SD card, accompanied by their time of occurrence, but no processing happens at this stage – the data is post-processed upon removal from the unit.

#### 6.2.6.2 *Testing*

At this point in the sensor development, problems started to occur. Due to a project management failure by the author, the final circuitboard was ready for handover to the author only two months before it was due to be deployed en masse in real dwellings. Before this it had to be tested in homes, the code refined and the correct angle of PIRs decided. In other words, between handover and deployment there were still a number of parameters to decide upon. The circuitboard was therefore produced by a company but excluded some components (PIRs, battery pack) whose positions on the board had yet to be decided. These components were soldered on by the author afterwards.

The testing method involved calibration with video camera data in the workplace of the author, with notification to all in the floor where the sensor and camera were placed, under an opt-out scheme of participation. This testing flagged up that although the

sensor detected and recorded the time at which someone passed under the doorframe, and did not miss an event, it sometimes wrongly reported which direction they were travelling (i.e. whether they were entering or leaving the room) since the wrong PIR was triggered first. An additional problem was its resolution in terms of determination of how many people passed through at once: there was no ideal value which could be set for this resolution parameter. A simplified explanation of this concerns step c) above: once one PIR had fired, the system waited a certain amount of time for the other one to fire. If this amount of time was set too low, it would reset before the person had passed through; if set too high, it would not detect a second person coming through the door.

If more development time had been allotted to this project, perhaps the code could have been redesigned to treat the aforementioned waiting period differently and the physical design could have been redesigned so that the directionality feature worked (since this was the main point of the development of a bespoke sensor). However, in the end the sensors had to be deployed at the end of January 2012 with the knowledge that the direction feature was not accurate and therefore that the data obtained would not yield the intended metric: how many people were in a given room at a given time.

There was one other main fault, which occurred once or twice before the start of the monitoring but not to the extent that it was investigated and remedied beforehand. In some sensors the real-time clock failed, in which case the backup clock (in the microprocessor) kept time. This second clock had a start time not of the start of the monitoring period but at a default of 01/01/2000 00:00:00. It did keep time, so if the time of switching on the sensor was known (which it was, to the nearest hour) then the data could be offset by the right time, plus or minus one hour. However, this uncertainty introduced by the offset meant that potential data on the movement of an occupant between rooms was lost: for example it would have been interesting to observe changes from one room to another, from one sensor signalling that someone had left a room, then, a few seconds later, another one signalling that an occupant had entered.

Furthermore, the main negative consequence of the above fault was that when the real-time clock failed and the microprocessor clock was relied upon, the sensor stopped working after 999 readings. Several colleagues were asked about why this might have happened but the reason was not found. 999 readings in many cases did not represent many days, especially given that a significant proportion of them represented movement of the sensor before it was put in place on the doorframe. Where there were multiple occupants and much movement, for example in dwelling 2, only a few days of occupancy data were obtained. It was decided not to put the sensors back in dwelling 2 for the second monitoring period as the first phase contained so few days of data.

The reader is referred to the Conclusion chapter for a discussion of lessons learned from this process and how other researchers can avoid certain mistakes. Meanwhile, this concludes the part of the chapter on development of quantitative methods. The next section concerns development of interview schedules to obtain the intended type of data from the occupants to answer the research questions.

## 6.3 METHOD DEVELOPMENT: SOCIAL DATA

### 6.3.1 *What to measure?*

It was proposed in Section 5.3.1 that the relationship between the physical and social data in the analysis to be carried out should entail social data being used to help explain physical data. This use of each data source should be kept in mind when considering what qualitative data to collect. Given that the quantitative dependent variable is observed change in temperature following retrofit, some theorising of how retrofit could affect occupants' perception of their environment is helpful to discern the most appropriate form of data. For example, do occupants notice a temperature increase after retrofit? If so, do they react to it - and how? Do they turn the heating down again, or do they suspect that heat is cheaper following retrofit and turn the heating up? It is this type of information which would help to explain quantitative data such as pre and post retrofit heating patterns. This information concerns heating behaviour, reaction to retrofit and thermal comfort. However this does not give a complete picture of why their behaviour is as it is. To contextualise any information occupants offer about heating behaviour, knowledge around their life at home and their daily activities would be helpful.

Thus, a method to obtain this information must be selected. Of the qualitative methods falling into the category of **self-reported** (interviews, written questionnaires, focus groups, diaries), face to face in-home interviews were selected as the most suitable. The main reason is that the interviews are then contextualised: the occupant is within the context he/she is describing, can point out specific features of note to him/herself, and can show the interviewer how he/she operates the heating system. The second reason is that the interviewer can get a better sense of what it is like to live in the property, which is helpful for analysis but also for the interview process, to be able to empathise with the occupant or ask follow-up questions based on things noticed during the interview. A third reason is a practical one: it is no extra effort to conduct the interview in

the occupant's home given that the author would have to go there anyway to collect the monitoring equipment.

Having justified the selection of face to face in-home interviews, more aspects of the interview type will now be clarified.

#### 6.3.1.1 *Which type of interviews?*

Although interviews fall into three categories: structured, semi-structured and unstructured, there exists in practice a continuum between structured and unstructured interviews (Tashakkorie and Teddlie (1998)); furthermore, an individual interview can contain elements of both structured and unstructured styles (Sarantakos (2005)). The point at which the researcher feels the particular interview design is located on the continuum depends upon the extent to which the themes to be covered and their order of discussion are predetermined, and also the extent to which the researcher asks spontaneous follow-up questions.

The research questions in this thesis suggest the use of both predetermined and non-predetermined questions. The predetermined aspects are derived from Research Question 2, concerning the interactions between occupants and their heating systems. This necessitates interview questions about the relationship between perceived temperature, occupant use of heating system, expectations of retrofit and other topics. However, it is not possible to anticipate all interactions, so there must be room to follow up on interesting and relevant topics which emerge.

It would seem that semi-structured interviews are most appropriate for a research design containing both predetermined and non-predetermined aspects. In this type of interview, the researcher usually has a list of themes and questions to be covered, although these may vary from interview to interview (Saunders et al. (2009)). The order is flexible, to maintain a flowing discussion, and the discussion is allowed to diverge to different topics with different participants if the researcher feels this is useful (Mason (2004)), but the researcher can bring the discussion back to the list of predetermined questions such that they are eventually all covered if desired. This type of interview can be described as 'conversations with a purpose' (Burgess (1982), in Mason (1996)). Semi-structured interviews also fit well into the pragmatic paradigm as the degree to which they are structured depends on the research objective (Sarantakos (2005)).

#### 6.3.1.2 *Interviews in the context of a mixed methodology research design*

When multiple streams of data are collected within a study, there exist in the literature different ways of ordering the collection in time. For example, some researchers use **sequential mixed methods**; an example of this is found in Coleman (2011), introduced in Section 5.3.1. Coleman collected and analysed physical data and then presented it to the occupants, capturing their reaction as social data.

It was decided in this thesis to use **concurrent mixed methods**: collection of both the quantitative and qualitative data at around the same time. Specifically, the interviews would be carried out upon collection of the monitoring equipment at the end of each monitoring period of the longitudinal study. The reasons for this were as follows. Firstly, it was advantageous to carry out the interviews at a time of year when the external temperature was likely to be low, so that upon being interviewed about the effect of cold on their lives the occupants would be speaking from current experience and not memory. This ruled out allowing time to analyse the quantitative data before designing the first round of interviews, since by that time summer would have arrived. This left two options: interviewing at the start or the end of the monitoring period. It was decided that interviews at the end would be less likely to influence occupants' behaviour throughout the monitoring period than if they were carried out at the start, so the end option was chosen.

#### 6.3.1.3 *Interviews in the context of a longitudinal study*

Most qualitative research on retrofit takes place after a given intervention; this was the case in the qualitative arms of both the Warm Front project (Gilbertson et al. (2006)) and the Retrofit For The Future projects (Lowe et al. (2012)). The implementation of a longitudinal study, including interviews pre- and post-intervention, raises methodological questions such as whether the the interview schedule should be the same both years. If it were, this could be advantageous in terms of ability to compare responses before and after retrofit as a way of assessing change. However, it was advised (Lai Fong Chiu 2012, pers. comm.) that this technique should not be carried out, as it may seem as if the occupants were being tested. Thus, the author was advised that the pre-intervention interviews should be about occupants' current experiences of living in the home, and the second set should explore the change the experienced by the occupants since the retrofit. Some further advice received concerning the post-retrofit interviews was that occupants should be asked about general changes in their life since the pre-

vious monitoring period which were *not* connected to retrofit (Russell Hitchings 2013, pers. comm.).

Aside from the longitudinal aspect of the study, an additional dimension was the distinction between two groups of occupants: those present for for the entire duration of the study, and those who changed between monitoring periods. Jumping slightly ahead to describe what actually happened during the data collection process, shortly before the post retrofit interviews took place the author was informed that there were 3 dwellings in which the tenants had changed since the works had been carried out. Therefore a separate questionnaire was designed for the new occupants, given that 'change since retrofit' was not an appropriate theme. For these new occupants, the themes covered were similar to that of the pre-retrofit questionnaire - life at home, heating behaviour, and so on. However, additional questions about their previous dwelling were also included, such as how they operated the heating, and how they would compare the thermal conditions of their previous dwelling to their current one.

#### 6.3.1.4 *Which topics to cover?*

The full interview schedules are included in Appendix B. However, the overall topics and their reason for being included are summarised below.

The first topic was context. The interview commenced with what brought them to the estate and their employment or lack of. It moved on to who was in their household and things they liked and disliked about their property. Questions about occupancy followed, including when they were in and out of the house in general and how they spent time at home. This included what activities they did throughout the day and which rooms they used for these activities.

This first section was to build up a broad picture of their life at home and whether they base themselves mostly in one room or move around a lot, and why. It was also partly for triangulation with the occupancy sensors, and partly to get an impression of their potential heating needs.

The second section consisted of a walk-through, similar to the method used in Chiu et al. (2012). The interviewer asked the occupant to take her to all rooms except the bathroom, and whilst in each room talk about how it was used and how comfortable it was. This was so that the occupant would be stimulated to point out things which he/she would perhaps not have remembered if the interview had taken place in just

one room. In each room the occupant was shown a comfort scale, also used in Chiu et al. (2012), which is a 7-point Likert scale ranging from 'Much too warm' to 'Much too cool', and asked to point to how they normally felt in the room. The scale is shown in Figure 32. This raised some problems of interpretation of the question which were not realised by the interviewer until partway through the first set of interviews, so the results from this question have not heavily influenced the analysis carried out later on in this thesis.


Figure 32: Comfort scale used in each room.

The subject of the third section was heating and fuel bills. The occupants were asked how they told the heating to come on and off (in those words), and under what circumstances this changed. If they did not mention the thermostat then they were asked if they ever touch the 'dial on the wall'. They were asked about the building: how long it took to warm up and cool down. Questions about comfort and cold, and their effect on life at home, were also asked. The purpose of this section was to ascertain how occupants controlled the heating and what their triggers were for turning it on and off, to inform the answer to the interactions aspect of Research Question 2.

The fourth topic was the retrofit. Questions involved how the occupants had heard about the works and their hopes and expectations (as well as how these had been formed). The post-retrofit interview also explored how the occupant had found the retrofit process.

The final section comprised of an evaluation of the author's empirical study. Questions included how they felt about the sensors being in their homes, how much the sensors had been noticed, and how the author had conducted herself.

Specific questions were devised for each section, and prompts were created for some questions in the event that the occupant did not know how to respond. Before commencing each interview, a briefing took place according to the standard protocol in the field, the contents of which can be found at the start of the interview schedule included in Appendix B.

#### 6.3.1.5 *Can people talk about their practices?*

The interview topics described in the previous section included how occupants operate heating, open windows, use space and generally go about their daily life at home. These could be seen as fairly mundane aspects of daily life, and thus the occupants had possibly never even had a conversation regarding them before, and/or were not aware of what their normal behaviour was. They may also have found it strange that the interviewer wanted to ask about such mundane things. Hitchings (2011) argues that people can talk about their practices, and gives advice on how to conduct interviews around them; this will now be described.

In his experiences of conducting research into how the elderly deal with cold (published in Hitchings and Day (2011)), *"there was some initial awkwardness as respondents came to realise how the intention was indeed to talk about certain very mundane aspects of their lives. In this respect, being clear about the purpose of the project and committed to questions that can initially feel uncomfortably banal helped."* Other advice given includes allowing time for the occupants to reflect on things they may have never been asked to explain, and also to use comparison to others whose practices may be different - although the author of this thesis did not consider herself experienced enough to be able to use this latter technique without influencing the occupants' responses.

On the basis of Hitchings' work, the interview schedules were designed under the assumption that people could talk about their practices. However, as the data were analysed, it became clear that this was not always the case. The Conclusion chapter contains a reflection upon the ways in which people reported different behaviour to what was observed in the quantitative data.

## 6.4 CONCERNS TO ADDRESS BEFORE THE START OF THE DATA COLLECTION

### 6.4.1 *Ethics (in theory)*

This chapter has already touched upon the fact that there are ethical dimensions involved in at least one of the variables to be measured (occupant use of space) in Section 6.2.4. However, no detail has thus far been given as to what the ethical issues are. This section will outline the ethical issues involved and what was done to make sure that ethical considerations were taken into account. However, not everything that could happen was anticipated. For this reason, this section is named 'Ethics (in theory)'. Section

12.4.5 in the Conclusion, named 'Ethics (in practice)', will describe some issues which arose in practice.

Before treating specific concerns, it should be noted here that consent for the study was granted by the Chair of the UCL ethics committee before it was undertaken, subject to simplification of the participant information sheet; this correction was performed before the start of the monitoring in January 2012.

Monitoring occupant use of space could be seen as the most ethically questionable of all the data collection techniques employed in this study, so it will be discussed first. One anticipated issue was that the occupants might feel as if they were being watched. It was important to avoid this situation as far as possible, partly since the fact that they were social housing tenants increased the likelihood that some of them were in vulnerable situations. Several strategies were therefore employed.

Firstly, the sensors were designed to point vertically down from the door frame, so that people inside and outside the room were not monitored; just those going through the doorframe. Secondly, if there were more than one person present in a dwelling, the sensors had no way of identifying which person is which. Thirdly, for the duration of the monitoring period the sensors stored the data on their internal memory card and did not transmit it outside of the dwelling or even outside of the sensor. It was then impossible to 'watch' the occupants in real time, unlike in many studies where such data is transmitted wirelessly back to the researcher. This sort of data could be used to know when the occupants are out, which could have implications for burglary, for example. Fourthly, it was deemed important to explain the nature of the sensors to the occupants in person upon recruitment and again at the start of each monitoring period, and to answer all their questions about what type of information the sensors recorded.

### 6.4.2 *Other concerns*

The study was registered under and conducted according to UCL's data protection policy, which involved committing to certain regulations, including anonymisation of the households, password protection of the document identifying anonymous dwelling labels ('dwelling 1', 'dwelling 2' etc.) with addresses, and not storing any personal data on servers outside the E.U.

As is best practice, a DBS (Disclosure and Barring Service) check of the author was undertaken, as it was not known before the start of the study whether the sample of housholds would contain children. A risk assessment was also carried out.

## 6.5 THE DATA COLLECTION PROCESS

### 6.5.1 *Finding a suitable estate*

A suitable estate of properties had to be located, from which a sample of case study dwellings could be selected. The selection criteria for the estate were as follows:

- Retrofit of the building fabric, ideally as the only energy-related intervention, had to be scheduled to take place between March and December 2012.
- Access had to be available to a sample of (the same) dwellings the winter before and the winter after the retrofit in order to make a longitudinal study possible.
- The estate had to be inhabited by low income occupants.

Finding an estate fulfilling the above criteria proved difficult, for a number of reasons. Access to dwellings had to be agreed with the Registered Social Landlord (RSL) by which the estate was managed. Some RSLs approached by the author were suspicious of the occupancy sensors. Some were interested but not to the extent they were prepared to help the author get access to the properties. Eventually only one RSL agreed so there was no choice involved.

Through a pre-existing relationship between UCL and a senior figure in a construction company, contact was made with the building surveyor of a RSL in the Midlands, who was interested in the effect of some upcoming works on the internal conditions of their stock. The chain of communication which eventually led to a working relationship between the author and the RSL proved to be a lengthy process, and still at this point there was not sufficient trust between this 'gatekeeper' and the author for easy access to the properties on the estate to be granted. A sufficient level of trust for the latter was present only after the results of the study had been presented back to the RSL almost two years after initial contact. This is a useful methodological aside: gaining access to properties is extremely difficult, so once trust is present within a given relationship it is advantageous to work with those partners again as opposed to forming new relationships from scratch.

### 6.5.2 *Physical construction of the dwellings pre and post retrofit*

Table 5, Figure 33 and Figure 34 describe and show typical dwellings from the estate, in their pre and post retrofit state. The retrofit of the building fabric consisted of external insulation of the previous Wimpy no-fines concrete walls with 100 mm phenolic insulation ('Weber.therm PHS'), double glazing of the windows where this had not already been carried out, and new front and back doors.

Please note the following two points regarding Table 5:

- All stated U-values are theoretical; their values were calculated from R-values which were quoted in the manufacturer's calculations, and it is not clear from which source these R-values were drawn. There exist large variations in the theoretical U-values of the same construction, and furthermore great heterogeneity in empirically determined U-value in a given construction (Craig et al. (2013)); as such, the figures given in Table 5 are to be treated with caution.

- The wall construction of the case study dwellings is not especially common amongst solid walled properties in the U.K. The experimental design in this thesis was not set up to be generalisable to the entire UK stock, so this is not necessarily a problem. However, there are likely to be slight differences in some of the findings compared to tradiational brick solid wall dwellings. For example, many of the latter cannot currently be externally insulated unlike the case study dwellings, due to planning restrictions. If internal wall insulation were carried out instead, the findings on pre and post retrofit thermal time constant later in the thesis would be likely to change.

| | Pre retrofit | Post retrofit |
|---|---|---|
| Approximate date of construction and retrofit | Constructed in 1950s, retrofitted in 2012. | |
| Wall construction, outside to inside | Rendering, no-fines concrete, dense plaster (see Figure 34) | Rendering, EPS insulation, rendering, no-fines concrete, dense plaster (see Figure 34) |
| Theoretical wall U-value, $\frac{W}{m^2K}$ | 2.1 | 0.29 |
| Window construction | Single glazed, wooden framed (although some occupants had double glazed their own windows) | Double glazed, uPVC frames, with trickle vents |
| Window U-value, $\frac{W}{m^2K}$ | 4.8 if single glazed, 2.0 if double glazed | 1.6 if double glazed in CESP scheme, 2.0 if double glazed previously |
| Door construction | Wooden | Steel surfaces separated by insulation |
| Door U-value, $\frac{W}{m^2K}$ | ~2 | 0.6 |
| Loft | Not upgraded in this scheme; probably insulated with fibreglass but unknown how thick. | |
| Estimated fabric heat loss of a typical 3-bedroomed mid terrace ($\sum UA$), Watts/Kelvin | 140 | 70 |
| Total floor area of a typical 3-bedroomed mid terrace, $m^2$ | 67 | |
| Estimated fabric heat loss / $m^2$ floor of a typical 3-bedroomed mid terrace, Watts/(Kelvin.$m^2$fl) | 2.1 | 1.0 |
| Primary heating system | Gas central heating, Worcester Bosch boiler | |
| Fixed secondary heating system | Gas fire in every living room. | |

Table 5: Characteristics of the dwellings on the site.


Figure 33: A pre-retrofit mid terrace (left) and post-retrofit end terrace (right). Right hand photo from Google Maps (2013).

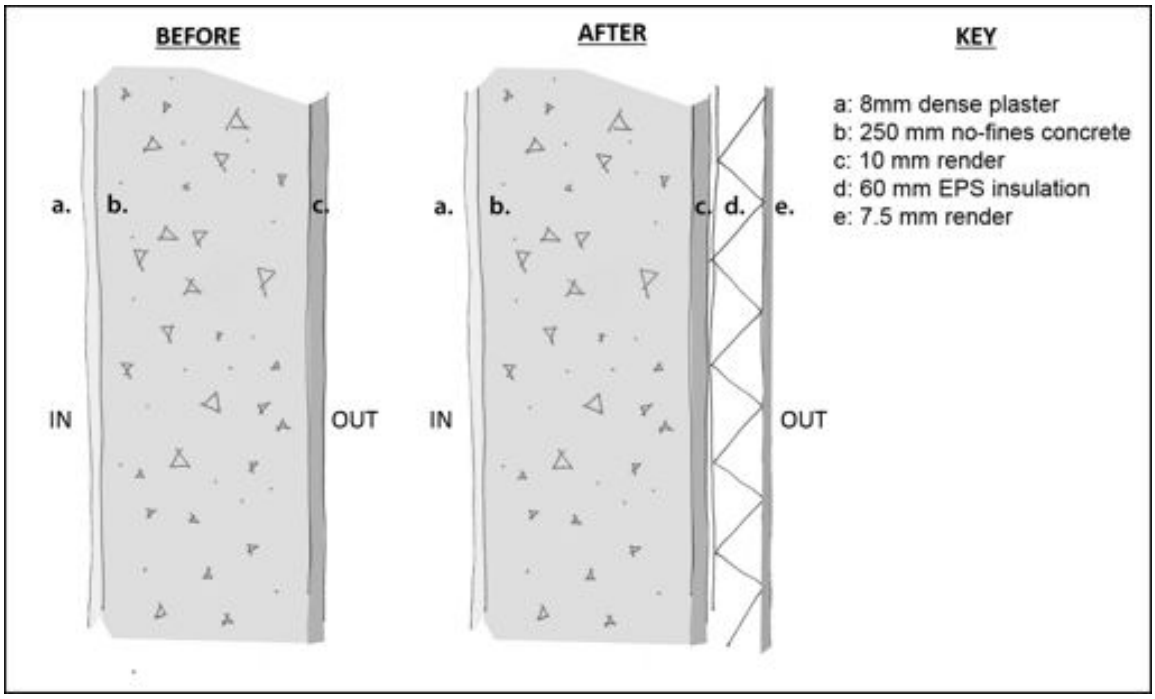



Figure 34: Illustration of wall construction pre and post retrofit (images by Sofie Pelsmakers).

It should be mentioned here that as well as fabric retrofit, some dwellings on the case study estate were also having solar PV panels fitted and would thus benefit from some free electricity. This aspect of the works is not discussed in this thesis since only two of the case study dwellings received PV panels and the occupants reported that not much difference was made to their electricity bill during the winter months.

Information on exactly which building elements were upgraded in each case study dwelling can be found in Table 12 in Chapter 8.

### 6.5.3 *Sampling of multiple case studies*

It was difficult to find a sampling strategy which suited both the research design and the practical constraints of the study. The process of compromise between the two will now be described.

A principle often applied in quantitative research to decide upon a sampling strategy to discern the effect of, for example, an intervention on a group, is the 'MAXMINCON principle' (Tashakkorie and Teddlie (1998)). It states that the researcher should MAXIMISE the experimental variance (make sure the signal is inherently large enough), MINIMISE the error variance, and CONTROL for the extraneous variance (i.e. other variables which might affect the dependent variable). This principle could apply to the current study as follows: the intervention is the retrofit, and the effect of this needs to be somehow isolated. In practice this means finding out what other changes could have caused heating behaviour to change and temperatures to increase or decrease. Other than the weather, for which it is possible to control in a quantitative manner (as was demonstrated using Hong (2011) in Section 1.9.2), other 'extraneous variance' would consist of changes of occupant, changes of income, work perfomed on the heating system separately to the retrofit works, and other such changes. Much of this could be discerned from the interviews upon asking appropriate questions.

Turning now to sampling methods specific to case study research, Flyvbjerg (2006) describes two overall types of selection: random methods and information-oriented methods. The latter is where something is known about the particular case studies before they are chosen, and thus strategic sampling can take place according to the type of cases the researcher wishes to study. Informaton-oriented selection could not be carried out in this study as the author did not particularly know who was going to live in each property due to data protection.

However, random sampling methods were not used either. In fact the actual sampling type employed was not either of those described by Flyvbjerg, but **convenience sampling** (see e.g. Marshall (1996)), in which sampling is carried out on the basis of availability and ease of data collection. Although it is regarded by Marshall and other authors as the least rigorous type of sampling, there was actually no choice in the type of

sampling due to the way in which the RSL allowed access to properties. The following description will illustrate how the case study households came to be so.

Access was gained to properties as follows. Firstly, a letter was sent out by the RSL to a subset of the households about to undergo retrofit works, asking for a reply if they were interested in participating in the study. This is not an effective way of sampling in this type of research due to the immediate introduction of potentially large bias: for example one can imagine occupants interested in the works, or the effects of the works, being more likely to reply, and thus self-selecting (Lavrakas (2008)). Under 5 households replied positively and one replied negatively. The low response rate is not surprising given that replying involved an effort to be made by occupants.

Therefore, the author was permitted by the RSL to set up a stall at an open day on the estate to which occupants could come to choose their colour of render for their property. Again, this introduces bias as attendance was not obligatory, but households who had not replied to the letter signed up for the study. However, there were still under 10 households recruited by this point, so following some negotiation the RSL allowed the author to knock on the doors of those households who had received the letter and not replied negatively. This last method was less biased in terms of the level of interest of the tenants but more so in terms of it being carried out during the day, thus excluding occupants who are at work at this time. Every household who opened the door agreed to be in the study, showing the potential benefits of this recruitment method if used correctly.

The total sample was made up to 13 before time ran out for new recruitment; this point was judged to be one week after installation of the monitoring equipment in the first dwellings to be recruited, as the author wished to have a relatively similar monitoring period for all the dwellings. The households who participated, and the typology of their dwelling, are shown in Table 6:

| Dwelling unique identifier | Dwelling typology | Pre retrofit household | Post retrofit household |
|---|---|---|---|
| 1 | Two-bedroom ground floor flat | Single mother with two children | |
| 2 | Three-bedroom mid-terrace | Couple with grown up son | |
| 3 | Two-bedroom ground floor flat | Single retired man | |
| 4 | One-bedroom ground floor flat | Single middle aged man | Single middle aged man |
| 5 | Top floor flat with no separate bedroom | Single elderly man | |
| 6 | One-bedroom ground floor flat | Single middle aged man | |
| 7 | Three-bedroom mid-terrace | Middle aged couple | Single mother with two daughters |
| 8 | Two-bedroom top floor flat | Middle aged woman | |
| 9 | One-bedroom mid-floor flat | Young man | |
| 10 | Three-bedroom mid-terrace | Man with teenage daughter (who moved out between the two study periods) | |
| 11 | Three-bedroom mid-terrace | Couple with two children | |
| 12 | One-bedroom top floor flat | Single retired man | Couple with newborn baby |
| 13 | Two-bedroom ground floor flat | Woman with grown up son | |

Table 6: Case study dwellings and households.

Fabric and ventilation heat loss coefficients were calculated using the BS EN 12831 standard methodology and are presented in Table 7.

| Dwelling | Pre retrofit fabric component of heat loss coefficient: $\sum U \times A$,W/K | Post retrofit fabric component of heat loss coefficient: $\sum U \times A$, W/K | Pre retrofit ventilation component of heat loss coefficient: $0.33 \times n \times V$, W/K | Post retrofit ventilation component of heat loss coefficient: $0.33 \times n \times V$, W/K | Pre retrofit total heat loss coefficient (including thermal bridging), W/K | Post retrofit total heat loss coefficient (including thermal bridging), W/K | % Change in heat loss coefficient |
|---|---|---|---|---|---|---|---|
| 1 | 187 | 82 | 28 | 26 | 216 | 108 | -50 |
| 2 | 158 | 69 | 31 | 28 | 189 | 97 | -49 |
| 3 | 192 | 77 | 27 | 25 | 219 | 102 | -53 |
| 4 | 93 | 41 | 18 | 16 | 111 | 57 | -49 |
| 5 | 113 | 27 | 14 | 13 | 127 | 40 | -69 |
| 6 | 140 | 37 | 19 | 18 | 160 | 55 | -66 |
| 7 | 129 | 52 | 33 | 30 | 162 | 82 | -49 |
| 8 | 161 | 46 | 27 | 25 | 188 | 70 | -63 |
| 9 | 106 | 21 | 21 | 19 | 127 | 41 | -68 |
| 10 | 172 | 67 | 35 | 31 | 207 | 99 | -52 |
| 11 | 219 | 69 | 33 | 30 | 253 | 99 | -61 |
| 12 | 176 | 44 | 28 | 25 | 203 | 69 | -66 |
| 13 | 186 | 71 | 31 | 28 | 217 | 100 | -54 |

Table 7: Heat loss coefficients for the case study dwellings.

Upon first contact, the occupants received a participant information sheet. If they agreed to participate, then an appointment was made to return to their property to install the monitoring equipment. As an incentive/thank you gift, the households were promised £20 of ASDA vouchers upon completion of the study around one year later.

Before the installation process was started, each occupant was asked to sign a consent form. At this point it was realised that not all of the participants could read - a factor which had not been considered when the particpant information sheet and consent form were designed.

## 6.6 DOCUMENTATION OF THE STUDY

Figure 35 shows the timeline of the data collection, which will now be documented, starting from the first monitoring period in January 2012.

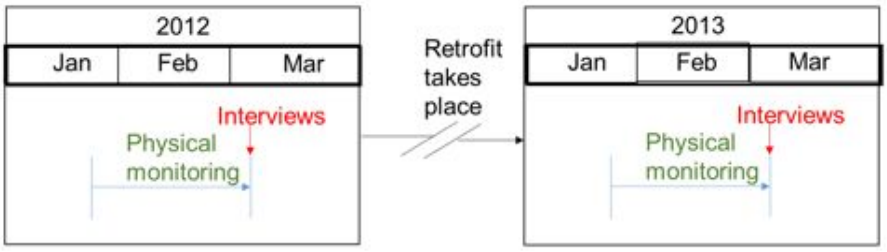



Figure 35: Timeline of empirical data collection.

Accompanied by a colleague each time, the author entered every property and installed the occupancy, air temperature and radiator sensors at the end of January/start of February 2012. Where secondary heating sources were spotted, the occupants were asked whether they ever used them and if so they were monitored in the same way as radiators. Since the dwellings were all on the same housing estate, data from one external temperature sensor was deemed appropriate to describe conditions outside every dwelling. It was placed in one houshold's garden in a purpose-built shield protecting it from solar gain and rain. Upon returning to collect the sensors one month later, most were still in place, although in dwelling 1 according to the occupant the children had thought they were toys and moved most of them, and in dwelling 13, according to the occupant the cat removed one of the occupancy sensors. The former should have been anticipated; the latter perhaps not.

The 2012 interviews took place upon collection of the sensors in March. In each dwelling, the author carried out the interview whilst her colleague photographed and removed the sensors, and made a floor plan. The author and her colleague stayed in the same room with the occupant where possible.

After the end of the first monitoring period, each of the case study dwellings underwent retrofit of the buliding fabric, as in Figure 36:

Figure 36: Installation of external wall insulation in progress, summer 2012.

In 2013, it transpired that three of the original households had left their properties and three new ones had moved in. The question was raised of whether to keep these dwellings in the study, as the retrofit was not the main change between the monitoring periods so its effect would not be isolated. It was decided to retain these dwellings, as even though the group sizes of existing and new occupants were small, comparison of the size of effect in both groups would be interesting, as would be information gained on occupants' experiences of moving into a retrofitted dwelling. Thus, permission was obtained from the RSL to recruit the new tenants through knocking on their doors. All three new households agreed to be part of the study. It was decided not to monitor occupancy in these dwellings, as by this point the pre-retrofit use of space data had been observed to be noisy and thus the complication of a new occupant would make the signal of retrofit very difficult to extract from the noise.

Concerning the group of 10 households who had been present pre retrofit and were still there post retrofit, all of them agreed to the installation of the same sensors in the post retrofit monitoriong period as in the previous one apart from in two cases. These were dwelling 1, whose occupant was concerned about the occupancy sensors falling

off the doorframe and hurting her children, and dwelling 3, in which the occupant had a guest round and did not want the author to spend time in the dwelling installing the occupancy sensors. They also all agreed to be interviewed, but there were two housholds in which this did not happen satisfactorily post retrofit. Firstly, in dwelling 3, the occupant was very distracted by a horse race on television and had also forgotten that he had an appointment starting 15 minutes after the start-time of the interview. Secondly, in dwelling 11 where the mother of the household had been interviewed pre retrofit, only her husband was at home at the time of the post retrofit interview, and he did not want to talk. Thus, only a small amount of qualitative data was gathered from this dwelling afetr retrofit.

## 6.7 THE RESULTING DATASET

From thirteen dwellings on the same estate, ten of which were inhabited by the same occupants before and after retrofit, the data obtained is shown in Table 8:

| Data | Air temperature | R.H. | Radiator temperature | Occupancy | Interview |
|---|---|---|---|---|---|
| How many dwellings before + after | 13 | 13 | 13 | 7 | 12 |
| How many dwellings before or after | 0 | 0 | 0 | 3 | 1 |
| Location | Living room, kitchen, hall and bedrooms | Living room, kitchen, hall and bedrooms | Living room, kitchen, hall and bedrooms | Should have been living room, kitchen, hall and bedrooms but few worked | - |
| Temporal nature of data | 20-minutely timeseries | 20-minutely timeseries | 20-minutely timeseries | Event-based data with second-level resolution | - |
| Was dataset as intended in the research design? | Yes apart from approximately one failed sensor per dwelling | Yes apart from approximately one failed sensor per dwelling | Yes | No: not directional, and not from all rooms | Yes |

Table 8: Description of the data obtained.

Having presented a summary of the data obtained, this chapter now turns to some validity issues raised throughout the data collection process.

## 6.8 ADDRESSING VALIDITY CONCERNS IN DATA COLLECTION

This is the first of two sections on validity in this thesis; a topic which is relevant firstly at the point of data collection, and secondly at the point of data analysis (including combining different types of data). The former is addressed here and the latter in the next chapter.

Some sources of potential bias have already been introduced above in different sections. These concerned which households agreed to participate in the study given the convenience sampling procedure (Section 6.5.3) and the Hawthorne Effect (Section 6.2.4). The latter was introduced in theory as part of the decision of a method to measure occupant use of space, but the actual effect of the chosen method on the behaviour of the occupants has not yet been discussed. To attempt to identify part of the effect, the occupants were asked at the end of each interview whether they had minded the sensors being in their home, and most reported that after about a day they had forgotten about them. This method does not yield to what extent their behaviour was subconsciously affected but at least conscious behaviour does not appear to have been influenced.

Another source of error is known as 'instrument error'. This will now be discussed regarding both the observational and self-report instruments used.

#### 6.8.0.1 *Validity issues in deployment of observational instruments*

Monitoring instrument error shall first be discussed, in terms of systematic and random error. Random error is unavoidable, but systematic error can be mitigated to some extent by calibration of the sensors in a thermal chamber under known conditions. The exact error on the occupancy sensors is unknown but in testing they never missed a stand-alone event and never reported one when none occurred; however as mentioned above their resolution was about 5 seconds so they could not distinguish between people going into a room in close proximity; furthermore their direction information was unreliable.

#### 6.8.0.2 *Validity issues in in self-reported data collection*

In terms of the qualitative instruments, that is, the interviews, the language of terms representing validity has to change as 'error' and 'uncertainty' are not associated with qualitative research.

There are some causes for loss of validity which can be minimised with training, such as the interviewer asking leading questions. Therefore each interview schedule was piloted three times and the recording listened to by the author to spot such potential mistakes. However there are also some well-known phenomena related to occupants reporting what they think they should say as opposed to what they really think. De Vaus (2002) in Shipworth et al. (2010) reports that social desirability response bias could prompt householders to report lower thermostat settings than are actually maintained. Shipworth et al. (2010) concluded that this type of 'bias' could help explain why monitoring equipment and occupants did not report the same thermostat settings, although it did not account for the entire discrepancy observed in their data.

However a different issue present in the self-reported data had not been anticipated and was not even realised by the author until the post-retrofit interview: that of 'negative orientation' (Gary Raw 2013, pers. comm.). This means that a person has a negative mindframe in general, and in the context of this study is therefore negative about their dwelling pre-retrofit and also negative about the effect of the insulation. This was noticed around the estate in general but only noticeably occurred in one case study houshold. Discerning whether to take the negative responses at face value or not was difficult.

## 6.9 BASIC DATA CLEANING

The final procedure to describe before moving on to the analysis in the next chapter is data cleaning.

#### 6.9.0.3 *Qualitative*

The interviews were transcribed verbatim ready for the coding process, which is documented in Section 7.2.

#### 6.9.0.4 *Quantitative*

The quantitative data required cleaning to remove values which were either missing or invalid as a result of some kind of sensor failure. An appropriate technique to aid this process is visualisation of each dataset. This was carried out for all three types of quantitative data through the construction of Matlab code which plotted rows of daily timeseries of data. In this way it could be seen if a logger stopped working part-way through the monitoring period (the occupancy data was deemed usable if there were at least 10 consecutive days of it before the sensor stopped logging), or was moved by an occupant. The occupancy data from those sensors which had the clock problem described earlier was treated as follows. It had been observed in general that bursts of events occur at aroud the same time for different sensors within one dwelling. Given this, data from sensors whose real-time clock had failed was plotted on top of data from a normally-working sensor from the same dwelling in a different colour, so that the required offset for the former data, to the nearest hour, could be discerned to set this data back to the correct time.

In all three types of quantitative data, the start and end of the dataset were deleted according to the start and end times the sensors were places in the dwellings. Often, the entire first and final days were deleted so that mean daily quantities could be calculated without including partial days.

Once the data had been cleaned, processing could be undertaken with a view to constructing variables. This will be treated in the next chapter.

## 6.10 CONCLUSION

This chapter described the process of developing and deploying methods to collect both social and physical data concurrently. Once the raw data had been collected, the next step involved processing and analysing it to create the constructs of interest for the research questions. These constructs, named 'metrics', are developed in the next chapter.

# 7

# ANALYSIS OF DATA AND CONSTRUCTION OF METRICS

## 7.1 INTRODUCTION

The aim of this chapter is to turn the raw data obtained from the empirical study into meaningful infomation, by the structuring of qualitative data and the construction of **metrics** (derived variables) from quantitative data. By the end of the chapter, these structures and metrics are in a form ready to be used to answer the research questions in the three results chapters which follow.

Concerning the qualitative data, the process of creation of a hierarchy of cross-related themes is described. This is then drawn upon in Chapters 9 and 10. Concerning the quantitative data, metrics are constructed representing the following concepts which have already been introduced in earlier chapters:

- Change in mean internal temperature following retrofit;
- Attribution of this change to heated or unheated periods;
- Change in heating schedule;
- Definition of and change in 'demand temperature';
- Percentage of mean internal temperature increase attributable to the night cooling period;
- Inter-room temperature gradient.

The metrics are then used in Chapters 8, 9 and 10.

It is important to carry out the process of construction of metrics thoughtfully and transparently, to ensure that the resulting metrics are meaningful and can be compared to those used in other studies. As mentioned at the start of the thesis, it is common in the field of energy and buildings to use certain terms without justifying why the particular definition employed represents the theoretical concept of interest. 'Demand temperature' and 'mean internal temperature' were both discussed in Chapter 3 as examples of terms calculated in several different ways in the literature. Adoption of different definitions across the field renders cross-study comparison difficult. The reader is reminded that an italicised variable name in this thesis means that it is strictly defined according to a mathematical definition or process in this chapter.

## 7.2 QUALITATIVE DATA ANALYSIS

### 7.2.1 *Theoretical approach*

In Section 5.3.3, some of the theoretical and methodological problems regarding combining social and physical approaches in one study were discussed. This led to the working solution of treating the social data from more of a positivist approach to that which might have been taken if the study involved social data only. In other words, the interview data is taken at face value more than is normally the case in social research.

### 7.2.2 *Method*

Semi-structured interviews were chosen in Chapter 6 because it was anticipated that some of the data could be classed into predetermined themes, whilst still allowing for the emergence of unanticipated concepts. These latter concepts will be termed 'emergent themes'. Thus, the analysis of the interview data in this study had to be performed in such a way that both types of theme could exist.

Another dimension to the analysis was the longitudinal nature of the data. It was mentioned in Section 6.3.1.3 that the post-retrofit interview schedule was not the same as the pre-retrofit one. One aim of the longitudinal data collection was to enable construction of a narrative which was consistent yet not confined to the same themes both years.

Taking all of the above into account, the chosen analysis method will now be described.

The pre retrofit data were coded once, shortly after the set of interviews was completed, using some predetermined themes and some emergent themes. The predetermined themes were often related to interview questions - for example, 'use of space' and 'ventilation'. The emergent themes on the other hand consisted of recurring specific attitudes or behaviours which came up, such as 'heating for children' and 'factors more important than temperature'.

Two sets of analysis were carried out on the post retrofit data. One used the same themes as before, so that direct comparison could be made between the two years. The other analysis method was completely free, in that it used purely emergent themes from the post retrofit data. This latter method was carried out first, to limit potential influence of the predetermined themes on this other type of analysis. Examples of emergent themes in the post retrofit data were 'resentment towards the energy company' and 'occupants' perception of energy saving'.

NVivo was the software used to code the data. However, qualitative data analysis software was not used beyond the coding as it was discovered that it hindered rather than helped the author's thought process when examining the relationships between themes.

The themes were thus arranged with respect to each other by hand, into a hierarchy, and relationships between them in the form of quotes linking two or more themes were superimposed. From the complex web that resulted, it was obvious that no aspect of life, thermal comfort or retrofit was independent from others. This network represented a way of visualising much of the dataset at once, and it started to become easier to draw out general observations from the whole dataset. Four categories of observation then emerged: commonalities within the sample (e.g. 'A main driver of heating use and zoning of spaces is the presence of children'), diversity within the sample (e.g. 'What the occupants thought the purpose of the retrofit was'), ideas which show that the occupants do not think like a building physicist (e.g. 'We're too poor to be energy efficient'), and aspects of the occupants' lives in which their cold home made a notable negative impact (e.g. a vicious cycle of cold and illness which is described in Section 9.4.1).

### 7.2.3 *Purpose*

The reasons for going through the above analysis process were twofold. One purpose was to better get to know and understand the qualitative data. This was especially

helpful when quantitative data was being examined, as in some occasions a statement the occupant had came to mind whilst analysing a section of monitored data. The other point was to aid theory development by highlighting relationships between variables which might not be possible to observe in the limited quantitative data. Some of these insights will be given in the two cross-case comparison chapters: Chapters 9 and 10. An additional outcome of the mixed methodology study to that of answering the research questions, formally introduced in Chapter 11, is the drawing together of relationships observed in the physical and social data into a theory of mean internal temperature.

This concludes the description of the analysis of qualitative data. The discussion now turns to the quantitative data analysis.

## 7.3 QUANTITATIVE DATA ANALYSIS: INTRODUCTION

The outcome of interest in this thesis is change in the internal temperature of a dwelling following retrofit, as stated in Research Question 1. Three key metrics related to internal temperature are constructed in this chapter: *mean internal temperature* (M.I.T), *M.I.T. Increase*, and *inter-room temperature gradient*.

## 7.4 MEAN INTERNAL TEMPERATURE

### 7.4.1 *Definition of mean internal temperature in this thesis*

There does not exist in the literature a single standard way to measure the mean internal temperature of a dwelling. For example, there is no protocol for how many rooms should be monitored to give an adequate estimate of the mean. Recent results from Gauthier and Shipworth (2014b) compound the problem: the authors recorded internal temperatures at four heights (0.1m, 0.6m, 1.1m and 1.7m) in different rooms (living room, main bedroom). They found that within the small sample used in their study, within-room temperature variation was as great as between-room variation. Thus, the spatial dimensions of dwelling internal temperatures are clearly complex.

Given that in this PhD, data was collected from almost all the rooms and dimensions of the rooms were also collected, it was possible to calculate volume-weighted mean (over time and space) temperature of the living room, bedrooms, kitchen and hall. It was

also possible to compare this relatively detailed calculation method to that using the living room only, or the living room and bedrooms. It was found that upon inclusion of one more room into the calculation of the mean, there was no pattern regarding the direction in which the result changes. Thus, in these dwellings, extrapolation from an average temperature over one room or a few rooms to that over all rooms cannot be made (this also indicates that researchers need to monitor as many rooms as there exists equipment for).

To summarise the above discussion, the *mean internal temperature* of a dwelling is defined in this thesis as volume-weighted mean temperature of the living room, bedrooms, kitchen and hall. The time period over which this mean is taken can vary but is usually a day, as will be explained in Section 7.5. This strict definition will often be abbreviated to *M.I.T.* Please note that the italicised versions, *mean internal temperature* and *M.I.T.*, are used to refer to this definition as applied to data collected from the empirical study in this thesis.

## 7.5 CONSTRUCTING METRICS OF M.I.T. INCREASE

The research questions set out in Chapter 5 were phrased in terms of change in internal temperature, as opposed to 'temperature takeback', 'comfort taking', 'rebound' or any related term used in other studies.

The reason for this was a preference for a metric which only used empirical internal temperature data, as opposed to a modelled counterfactual. This was firstly to limit uncertainties introduced when combining monitored data with model predictions (see Section 1.9.2) and secondly to be able to quantify the error on the metric.

The metric to be constructed in this section will be named *M.I.T. increase*. Quantifying the increase in mean internal temperature following retrofit requires more care than it would first appear. To explain why, consider Figure 37:

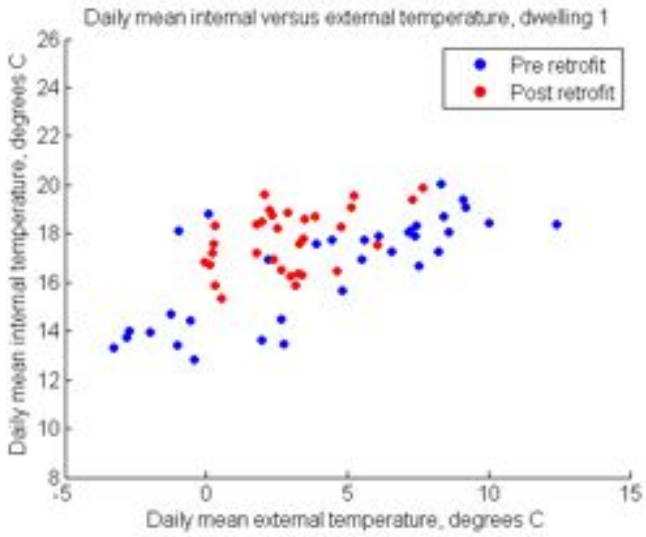



Figure 37: Example of daily *mean internal temperature* data before and after retrofit.

It seems from Figure 37 that *mean internal temperatures* are higher after retrofit than before, but to describe by how much requires some thought.

Two features of Figure 37 should be considered. Firstly, if straight lines (for now - this will be questioned later) are autofitted through each year's data, the gradients differ. An example is shown in Figure 38:

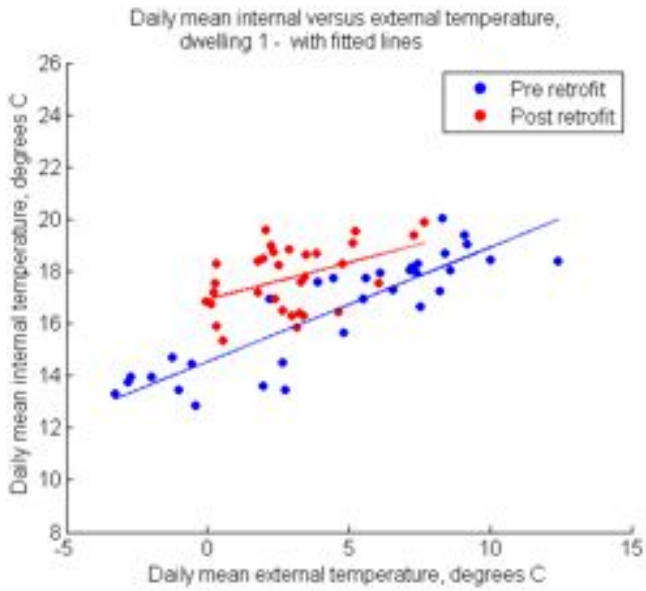



Figure 38: Example of daily *mean internal temperature data* with autofitted straight lines.

The difference in gradients as seen on Figure 38 means that the increase in *M.I.T.* is different at each value of the external temperature. Therefore, the metric of temperature

increase could then either be a mean over all the increases in a particular range of external temperature, or a vertical line drawn on the graph at a particular external temperature to give a result 'standardised' to an external temperature. Furthermore, the increase in *M.I.T.* could either be given in its absolute form as degrees Celsius, or as a proportion of the starting temperature: the latter requires a suitable denominator to be suggested. These options will now be discussed.

#### 7.5.0.1 *Accounting for external temperature*

Accounting for the effect of external temperature can be carried out in several ways. Hong (2011) subtracted mean external temperature from mean internal temperature over the monitoring period; Oreszczyn et al. (2006a) carried out a more sophisticated procedure which involved deducing a relationship between internal and external temperature for each dwelling, selecting a single external temperature (5°C), and predicting the internal temperature in each dwelling at that external temperature using the derived relationship. Performing the latter pre and post retrofit and taking the difference between them shall be termed the **standardised metric** of M.I.T. increase, and has the advantage of allowing multiple dwellings to be compared to each other. On the other hand it does not take the mean over the entire monitoring period, and as such does not take all of the data into account.

An alternative single point estimate of temperature increase to the standardised metric will be termed the **mean metric**. As with the standardised metric, lines are fitted through the pre and post retrofit internal versus external relationships for each dwelling. Then, instead of finding the difference between the lines at only one external temperature, 5°C, the difference is found at all the real external temperatures in one of the monitoring periods (here, the post retrofit one). For example, for each post retrofit daily data point, one would find the external temperature, find the y-value on the post retrofit line, and find the distance down to the pre retrofit line. After doing this for every day the mean of these distances would be calculated. This method has the advantage of taking all of the data into account, but its main disadvantage is that if the time and place of monitoring differs between dwellings, they cannot be compared to one another.

#### 7.5.0.2 *Absolute vs proportional*

Some studies report change in mean internal temperature following retrofit as a proportion; that is, expressed over some other quantity. For example, Hong (2011) used a metric shown in Equation 17:

$$\text{Proportional increase in temperature} = \frac{T_{post} - T_{pre}}{T_{pre}} \tag{17}$$

Now, given that the Celsius scale of temperature is arbitrary and hence so is the denominator of Equation 17, this metric would seem to produce results of an arbitrary size. It would be more useful to express the denominator in a way such that the overall quantity is meaningful in some way. For example, given that the temperature of a building depends on the input of heat to lift its temperature above its starting temperature, which is in turn the external temperature plus the temperature rise from free heat gains (the $\frac{G}{H}$ term in Equation 7), it would be useful to have a metric whose denominator were this temperature lift, then the numerator could be the *extra* change in temperature following retrofit:

$$\text{Proportional increase in temperature} = \frac{T_{post} - T_{pre}}{T_{pre} - (T_{ex} + \frac{G}{H})} \tag{18}$$

The metric would then represent the extra heat in the building after retrofit compared to that in the building before, in both cases to keep the building warmer than outside.

However, since the temperature rise from free heat gains would be very difficult to measure empirically, a proportional metric of M.I.T. increase was not used in this thesis.

#### 7.5.0.3 *Chosen metrics*

The chosen metrics of *M.I.T. increase* are then as follows:

Absolute standardised metric of *M.I.T. Increase*:

$$\text{M.I.T. Increase} = T_{post,line}(T_{ex} = 5) - T_{pre,line}(T_{ex} = 5) \tag{19}$$

Absolute mean metric of *M.I.T. Increase*:

$$\text{M.I.T increase} = \frac{1}{n} \sum_{t=\text{day1}}^{t=\text{day } n} \left( T_{post,line}(t) - T_{pre,line}(t) \right) \tag{20}$$

where $T_{post,line}$ and $T_{pre,line}$ are internal temperatures read off the lines fitted through the data points of daily *M.I.T.* versus external temperature.

This concludes the section on construction of metrics for *M.I.T. Increase*. The discussion will now move on to how to obtain the parameters for these metrics from empirical data.

## 7.6 FITTING LINES THROUGH M.I.T. VERSUS EXTERNAL TEMPERATURE DATA

This section concerns fitting the most appropriate lines through plots such as Figure 37.

### 7.6.1 *Minimising the scatter - should an internal-external temperature graph account for time lag?*

Building physics theory predicts that there will be a time lag between the occurrence of a particular external temperature and the influence of that temperature on the interior of a dwelling, due to the **thermal admittance** of the building fabric. Thus, if this time lag could be estimated and used to offset the internal temperature dataset in time, the scatter in the relationship between internal and external temperature may be reduced. This was attempted by an empirical method, using data from the case study dwellings, to discern whether a suitable offset could be detected and whether it made a difference to the aforementioned scatter. The optimum offset was then compared to the results of a theoretical method for calculating the effects of admittance.

#### 7.6.1.1 *1. Empirical method*

Hourly $T_{in}$ versus $T_{ex}$ data points were plotted for each dwelling for a set of time offsets of $T_{in}$ from $T_{ex}$: 0, 2, 4, 6, 8, 10 and 12 hours. Figure 39 gives a clear way to visusalise which offset minimises the scatter.

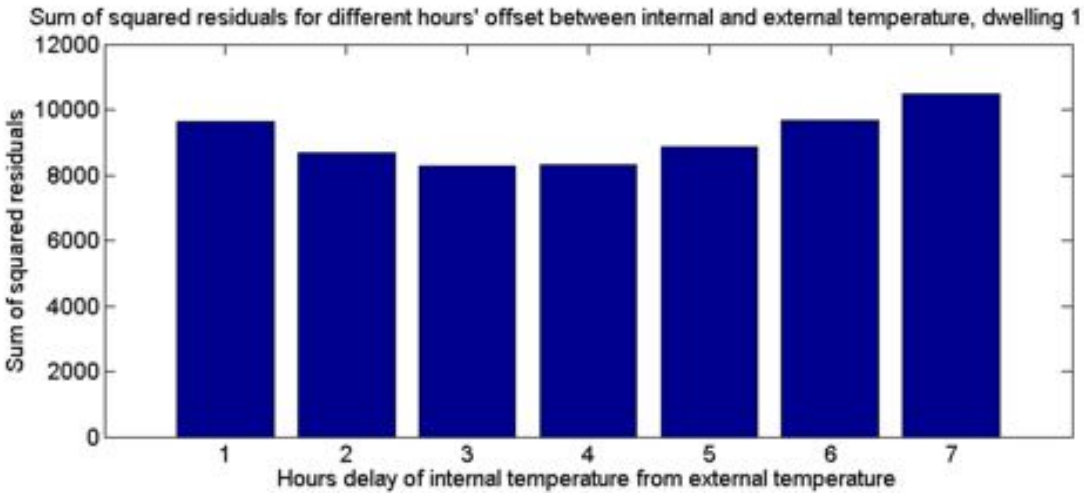



Figure 39: Assessing the impact of offsetting the *M.I.T.* from the external temperature, in time.

Other dwellings gave a similar result to Figure 39: that is, there existed an optimum offset representing minimised scatter between internal and external temperature. The mean of the optimum offsets across the sample was 6.7 hours pre retrofit and 7.2 hours post retrofit, although the standard deviation was 1.5 hours, which is considerably larger than the difference between the means.

#### 7.6.1.2 2. *Theoretical method*

The parameter representing the effect of thermal admittance in time is known as **decrement delay**. This is defined by ARUP (2010) as the time lag between the timing of the internal temperature peak and the peak heat flow out of the external surface. It can be calculated in steady state according to the Admittance Method in CIBSE (2006), or a more sophisticated calculation can be carried out which incorporates dynamic heat flow. A calculator developed by ARUP performs a hybrid of these two types of calculation, and this was used here. Calculation of decrement delay was performed using inputs of no-fines walls with and without insulation using the inputs in Table 9:

| Layer | Thickness ($mm$) | Density ($\frac{kg}{m^3}$) | Specific heat capacity ($\frac{J}{kg.K}$) | Thermal conductivity ($\frac{W}{m.K}$) |
|---|---|---|---|---|
| Plaster (dense) | 13 | 1300 | 1000 | 0.57 |
| No-fines concrete | 250 | 2000 | 1000 | 1.33 |
| EPS insulation | 60 | 40 | 1400 | 0.04 |
| External render | 15 | 1800 | 1000 | 1.00 |

Table 9: Inputs used for the ARUP calculator.

The resulting decrement delays were calculated as 7.9 hours before insulation and 9.9 hours after. These are compared to the empirically determined values in Table 10 below:

| | Empirical method | Theoretical method |
|---|---|---|
| Best offset, 2012 (hours) | 6.7 | 7.9 |
| Best offset, 2013 (hours) | 7.2 | 9.9 |

Table 10: Comparison of two methods of determining the decrement delay.

Comparing the empirical and theoretical results shows that the empirical post retrofit decrement delay is lower than the theoretical value. Since the aim of this exercise was to minimise scatter, the empirical values of offset will be used as opposed to the theoretical ones. However the exercise has also shown that retrofit does not appear to have as large an effect as expected - it is unknown whether this indicates that the retrofit did not perform as expected, or whether occupant behaviour changed in a manner which would decrease the observed decrement delay (such as increased use of ventilation), or whether the problem arises from the uncertainty introduced when trying to compare modelled and monitored results.

### 7.6.2 *Deciding upon the model of M.I.T. as a function of external temperature*

When fitting a line through data points, one can either have in mind an idea of the relationship between the y and x variables, or one can judge which relationship the data suggests. In the case where internal temperature ($T_{in}$) is plotted against external temperature ($T_{ex}$), it was shown in Section 2.2.3 that the possible space allows a broad range of relationships, and then in Section 2.4 that the lines made by modelling assumptions form just one possible set of relationships within that space. Behaviour, dwelling fabric

and the heating system are all interacting together, and thus the researcher does not know the mathematical relationship of $T_{in}$ versus $T_{ex}$ beforehand.

The method decided upon involved fitting straight lines through scattered $T_{in}$ versus $T_{ex}$ daily data points over a range of 0-8°C, as shown in Figure 40:

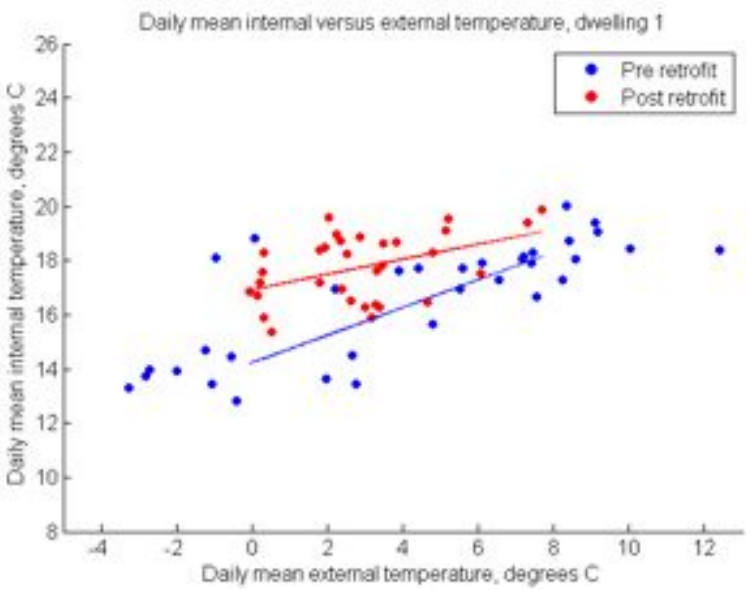



Figure 40: Example of daily *mean internal temperature data* and fitted models before and after retrofit.

The fitting of lines on Figure 40 was as follows:

- It was necessary to use the same external temperature range for both the pre and post retrofit lines, so that comparison between them could be undertaken at a common external temperature. In the data, the range of external temperatures post retrofit was 0°C to 8°C; this fell within the range pre retrofit which was between -3.5°C and 12.5°C. Thus, the post-retrofit range of temperatures was used as shown in Figure 40.

- Furthermore, it appeared that over the external temperature range of 0°C to 8°C described above, the relationship was linear, although often outside that range it was not linear (see Figure 40, which flattens off below 0°C and above 8°C). The model used for comparison pre and post retrofit was forced to be linear.

- The gradient and the intercept were optimised by Matlab's autofit function to minimise the variance.

- A non-trivial issue which arose was how to judge whether certain points were classed as 'outliers'. In the scientific method, where the model is often known or hypothesised, points which fall far from the modelled line are generally ascribed to be due to measurement error and are discounted. However, in this study of people and buildings in which the true model is unknown and, unlike building fabric, people do not follow physical rules, it cannot be assumed that points which lie far from the others are erroneous. There may be scatter due to, say, an occupant using more heating than he normally does one day due to the presence of guests. To treat such points, the author used her knowledge of the qualitative data to discern whether those points should be in the model or not - normally the points were left in as there were not sufficient grounds to exclude them.
- However, days where the occupants were known to be away (discerned from the occupancy data) were excluded because here there would be abnormal heating behaviour.

This concludes the section on constructing the metric of *M.I.T. increase* and obtaining its input parameters from air temperature data. The next variable to be constructed uses the radiator data.

## 7.7 HEATING PERIOD

In Section 6.2.3, a study carried out by Martin and Watson (2006) was introduced in which the authors constructed an algorithm to convert radiator temperature data into a binary signal of when the heating system was on. Since their monitoring method was adapted for this thesis, a similar conversion algorithm was needed here. The discussion below of how it was constructed begins with the desired end result.

### 7.7.1 *Two possible ways to quantify heating use*

It was decided that the metric of interest concerning heating use was the number of hours per day in which the heating was on in each dwelling, as change in this following retrofit would be useful to know. In this thesis the variable describing this is called *daily heated hours* and will now be derived.

There are two ways of defining whether the heating is 'on': when a heating system is actually doing work (an indication, although not a proxy, of energy consumption), and

when a heating system is switched on but may or may not be doing work (the latter would occur if the internal temperature had reached the setting of either the thermostat or the T.R.V. in that room). The former output shall be termed *Approximate Heated Hours (A.H.H.)*, and the latter *Potential Heating Period (P.H.P.)*. The reason that both variables could be of interest in this thesis is that change in the former following retrofit indicates change in energy use, and change in the latter is due to occupant behaviour in terms of heating timings.

To demonstrate the difference between *A.H.H.* and *P.H.P.*, the top subplot in Figure 41 shows some actual data from a radiator in dwelling 8, in which it is thought that the heating sytem turned off as the air temperature reached the thermostat setting, then turned on again when the temperature had sufficiently dropped. Any algorithm developed to output *A.H.H.* should give the output in the middle subplot, whereas any algorithm designed to output *P.H.P.* should give the output in the lowest subplot of Figure 41. Please note that on the y-axis of the bottom two subplots, '1' represents heating being in the state of 'on' and '0' means 'off'.

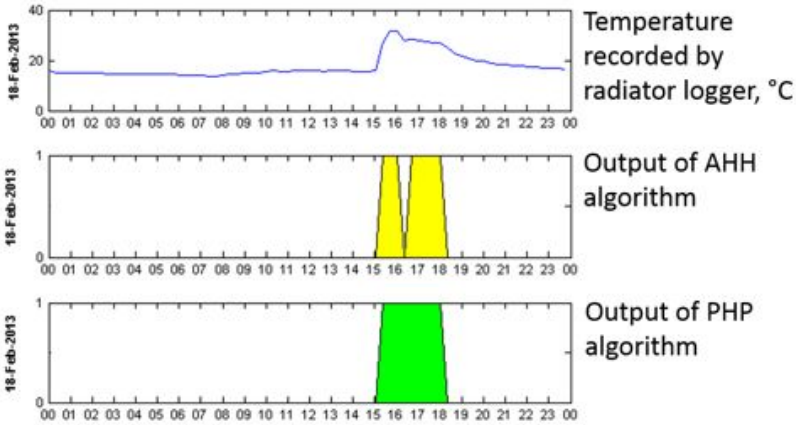



Figure 41: Two algorithms giving different outputs from the same data.

Although both *A.H.H.* and *P.H.P.* are useful variables in theory, the particular measurement technique used in this thesis measured *P.H.P.* more reliably than *A.H.H.* Upon examination of the radiator temperature data it became clear that twenty-minutely measurements gave a clear signal as to when the heating system was on but not as to when the boiler was doing work. For example, it was unclear as to whether observed cycling was due to T.R.V.s or the room thermostat, and also since the cycling frequency was unknown it could be that the twenty minutely measurements were not frequent enough to capture cycling.

Furthermore, initially it had been assumed that the functioning of the boiler could be determined by a signal at the radiator, and also that the length of this signal could be multiplied by the power of the boiler to obtain energy use for space heating. However, it was pointed out to the author later on that the boiler performs its own internal cycling separately from that discernible from the radiator. Thus, not only does the radiator signal not indicate whether the boiler is doing work, it also cannot be used to calculate energy use. Given this error, suggestions for what could have been monitored instead of the radiators are given in Section 12.4.2.3

Therefore, *P.H.P.* is the variable to be used in the rest of the analysis to discern whether the heating is on or off; *daily heated hours* is then a sum of the *P.H.P.* over a day.

### 7.7.2 *P.H.P. algorithm*

The algorithm used in Martin and Watson (2006), designed to measure P.H.P., was used on some test data to explore its reliability in predicting the radiator state. It was found that a few modifications were needed to improve its reliability. The original and modified algorithms are shown in Figure 42, in which $T(t)$ symbolises radiator temperature at time $t$:

| **Original algorithm (Martin & Watson)** | **P.H.P. algorithm** |
|---|---|
| if Radstate = 0 | if Radstate = 0 |
| if T(t)-T(t-1) ≥ 2 | if T(t)-T(t-1) ≥ 2 |
| Radstate = 1 | Radstate = 1 |
| else if T(t) ≥ 35 | else if T(t) ≥ 25 |
| Radstate = 1 | Radstate = 1 |
| else if Radstate = 1 | else if Radstate = 1 |
| else if T(t)-T(t-1) ≤ -2 | else if T(t)-T(t-1) ≤ -1.5 |
| Radstate = 0 | Radstate = 0 |
| else if T(t) < 18 | else if T(t) < 18 |
| Radstate = 0 | Radstate = 0 |

Figure 42: Martin & Watson's algorithm, with modifications for this thesis highlighted in red.

Use of the above *P.H.P.* algorithm allowed heated and unheated periods to be determined. This could then be combined with the *M.I.T. increase* variable derived in Section 7.5 to attribute the change to either heated or unheated periods. This is described in the next section.

## 7.8 ATTRIBUTION OF M.I.T. INCREASE TO HEATED AND UNHEATED HOURS

It would be useful to know whether any observed increase in *M.I.T.* occurred during heated or unheated periods, to begin to uncover the separate roles of the occupant, heating system and building fabric. A method was devised to attribute *M.I.T. increase* to several categories: heated hours becoming warmer, unheated hours becoming warmer, and hours which change between heated and unheated following retrofit. This was done by devising a slightly different metric to *M.I.T. increase* which consists of a sum of the temperature effects of these categories.

Simply observing whether heated hours have increased in temperature, and similarly whether unheated hours have increased in temperature, is not difficult: heated and unheated hours are separated out each day, and plotted against the external temperature that day. An example is shown in Figure 43.

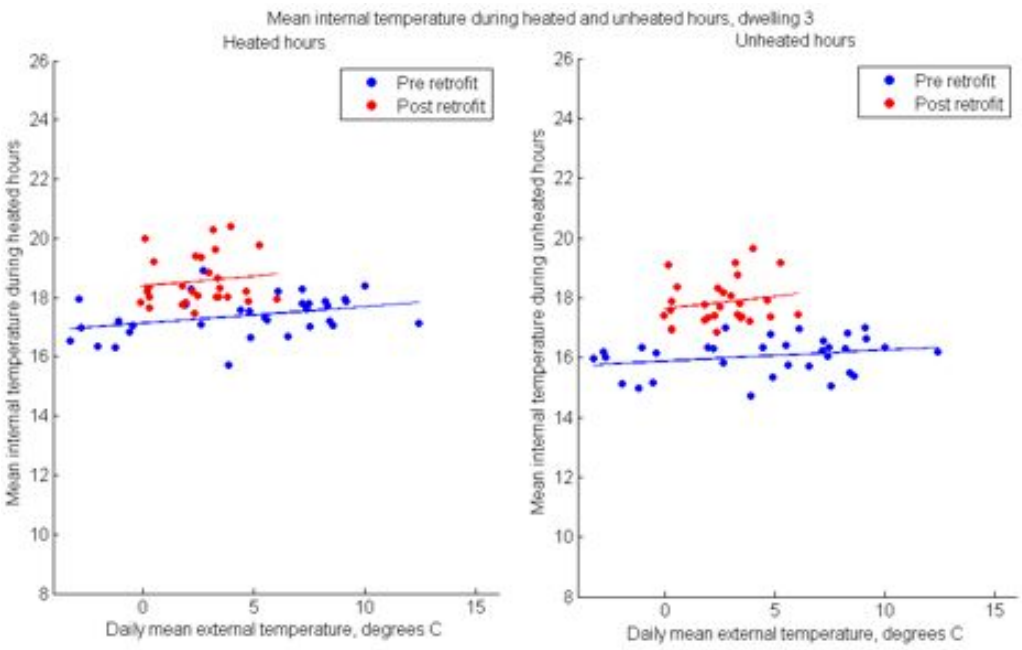



Figure 43: Example of observing mean internal temperature increasing during heated and unheated hours.

However, attributing the proportion of total *M.I.T. increase* which occurred due, say, heated hours increasing in temperature is not as simple as weighting the observed increase in the left hand subplot of Figure 43 by the proportion of total hours which were heated. This is because the latter usually changes after retrofit. That is, in most dwellings, *daily heated hours* reduced following retrofit.

The complication introduced by this change in *daily heated hours* is is easiest to explain pictorially. An idealised version of the temperature changes which occurred after retrofit, for a given day, is shown in Figure 44.

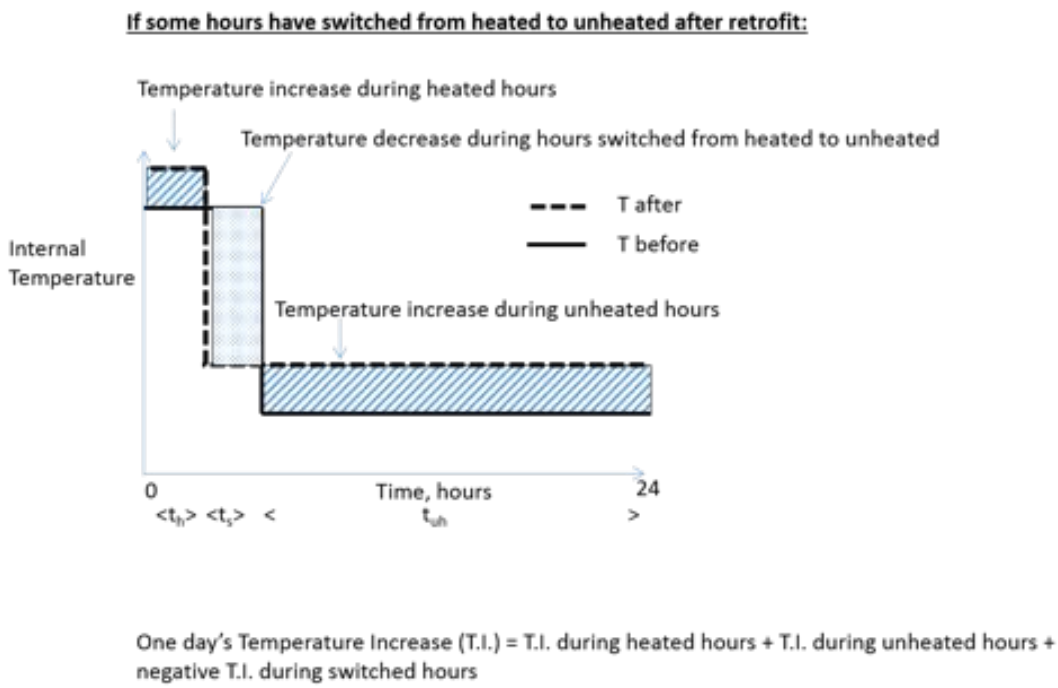



Figure 44: Separating M.I.T. increase into heated, unheated and switched components - 1.

Figure 44 is used here to show how total *M.I.T increase* can be constructed from a sum of that occurring in heated hours, that occurring in unheated hours, minus a component representing a decrease in temperature as number of heated hours per day decreased.

Conversely, in a minority of dwellings, the number of heated hours per day increased following retrofit. An idealised version of the temperature over a day before and after retrofit for these dwellings is shown in Figure 45.

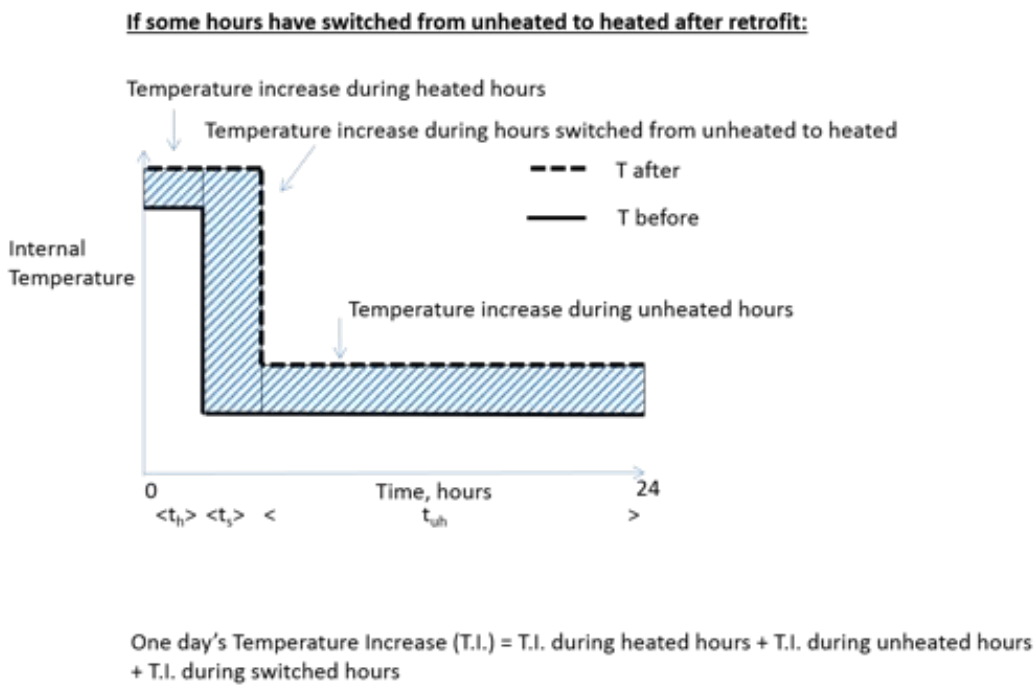



Figure 45: Separating M.I.T. increase into heated, unheated and switched components - 1.

Figure 45 is used here to show how *M.I.T increase* can be formed from a sum of temperature increase during heated hours, temperature increase during unheated hours, and a component representing the increase in temperature occurring as a result of more hours per day being heated following retrofit.

A general equation for daily temperature increase as a sum of the temperature increase (T.I.) during the different parts of the day is given in Equation 21:

$$T \text{ increase for one day} = \text{T.I. during heated hours} + \text{T.I. during unheated hours} + \text{T.I. due to switched hours} \tag{21}$$

To translate Equation 21 into the language of mathematics, there are two forms depending on whether hours became heated or unheated following retrofit. For each day, the numerator of each form contains a heated, unheated and switched temperature increase term, and is made by summing the relevant areas in Figures 45 and 44. The outcome is then summed over the monitoring period.

If, in a dwelling, some previously heated hours became unheated:

$$M.I.T.\ Increase = \frac{\sum_d \left[T_h(d_{post}) - T_h(d_{pre})\right].t_h(d_{post}) + \sum_d \left[T_{uh}(d_{post}) - T_{uh}(d_{pre})\right].t_{uh}(d_{pre}) + \sum_d \left[T_{uh}(d_{post}) - T_h(d_{pre})\right].t_s}{24\ hours}$$

(22)

If, in a dwelling, some previously unheated hours became heated:

$$\text{M.I.T. increase} = \frac{\sum_d \left[T_h(d_{post}) - T_h(d_{pre})\right].t_h(d_{pre}) + \sum_d \left[T_{uh}(d_{post}) - T_{uh}(d_{pre})\right].t_{uh}(d_{post}) + \sum_d \left[T_h(d_{post}) - T_{uh}(d_{pre})\right].t_s}{24 \text{ hours}} \tag{23}$$

In this way it is possible to extract the heated, unheated and switching components of the *M.I.T. increase* as the first, second and third components of the numerator in Equations 22 and 23. The sum of the components should ideally equal *M.I.T. increase* as calculated using the method in Section 7.5. In most cases the two quantities were the same to the nearest 0.1°C; in two cases they differed by up to 0.2°C.

This concludes the section on attribution of *M.I.T. increase* to heated and unheated hours. This separation of heated from unheated periods can also be used to investigate demand temperature, the subject of the next section.

## 7.9 DEMAND TEMPERATURE

In Chapter 2, the BREDEM definition of 'demand temperature' was introduced as the temperature assumed to be desired by the occupants during hours in which the heating is doing work. Chapter 3 then introduced a variable constructed by Huebner (2013) for the purpose of ascertaining 'demand temperature' from real data: the highest achieved stable temperature (over at least 2 consecutive measurements) during a monitoring period. In this thesis this variable was termed *stabilised demand temperature*. If temperatures do not stabilise, according to this definition there is no demand temperature.

The author suspected that in the case study dwellings, internal temperatures may not stabilise during heating periods. The reason for this suspicion involved the observation that **manual heating control** was prevalent across the sample, often without thermostatic control. Manual heating control is defined in this thesis as heating timing being determined by occupants each time as opposed to an automatic timer: either the occupants pressed 'on'/'off' at the programmer or turned the thermostat to zero to turn the heating off and back up again to turn it on.

Since manual heating control was the predominant type of control across the sample, and since most of the households were conscious of energy costs and thus tried not to have the heating on very much, it is likely that the temperature was still increasing when they turned off the heating and hence that stabilisation did not occur.

To account for such situations, an alternative definition of demand temperature was developed, to be used alongside the original (stabilised) one:

*Stabilised demand temperature*: highest temperature during a heating period if the temperature plateaus over two or more measurements.

*Achieved demand temperature*: highest temperature achieved during a heating period.

### 7.9.1 *Capturing demand in social housing: stabilised or achieved temperatures?*

To observe the relationship between stabilised and non-stabilised temperatures pre and post retrofit, all heating periods were categorised as those in which the temperature stabilised and those in which it was still rising at the end of the period. A summary of this information is presented in Table 11. The reason for the 'N/A' entries in dwellings 6 and 7 are that in the former dwelling the heating periods are not known and in the latter the heating was on all the time during the pre retrofit monitoring period.

| Dwelling | Mean length of heating period pre retrofit, hours | Mean length of heating period post retrofit, hours | % of pre retrofit heating periods in which the temperature stabilised | % of post retrofit heating periods in which the temperature stabilised |
|---|---|---|---|---|
| 1 | 4.3 | 1.9 | 63 | 53 |
| 2 | 2.3 | 3.0 | 3 | 40 |
| 3 | 5.0 | 3.5 | 97 | 40 |
| 4 | 1.3 | 1.2 | 29 | 3 |
| 5 | 1.5 | 2.2 | 15 | 36 |
| 6 | N/A | N/A | N/A | N/A |
| 7 | N/A | 2.1 | N/A | 50 |
| 8 | 2.4 | 1.7 | 11 | 16 |
| 9 | 2.4 | 3.2 | 67 | 50 |
| 10 | 1.9 | 1.9 | 15 | 73 |
| 11 | 6.1 | 5.9 | 60 | 56 |
| 12 | 2.6 | 1.5 | 16 | 13 |
| 13 | 6.4 | 2.7 | 59 | 73 |

Table 11: Characteristics of heating periods in each dwelling.

In order to be able to use stabilised temperatures as the definition of demand temperature, there needs to exist adequate data both pre and post retrofit to ascertain what the stabilised temperature was. Yet Table 11 contains a wide range of percentage of heating periods in which the temperature stabilised (3%-73%). Furthermore, there is no trend showing whether post retrofit stabilisation was more likely than pre retrofit stabilisation. To explore this further, two contrasing examples are given below.

Figure 46 shows internal temperature data from the heating periods in dwelling 2. It can be seen that in most heating periods, the temperature did not stabilise. However in the post retrofit monitoring period the temperature was more likely to stabilise than in the pre retrofit period. Part of the explanation can be proposed from the qualitative data from this dwelling: it is known that the occupant turned down the thermostat after the retrofit due to her mental model of how heating systems work (further explored in Section 9.4.4.1). It is therefore hypothesised that the combination of the lengthening of the heating period (Table 11), the decreasing of the thermostat setting and the increased ability of the insulated building to reach that setting may have caused this increased degree of temperature stabilisation.

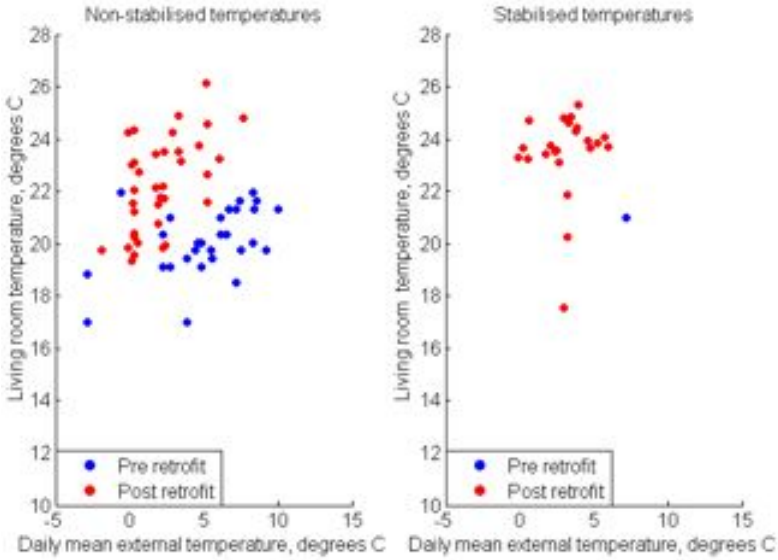



Figure 46: Dwelling 2, characteristics of the internal temperature during the heating period.

A contrasting example, from dwelling 3, is shown in Figure 47. Here, more heating periods stabilised than did not, and after retrofit a lower proportion of heating periods stabilised. Table 11 shows that the average length of heating period decreased following retrofit, which could provide an explanation.

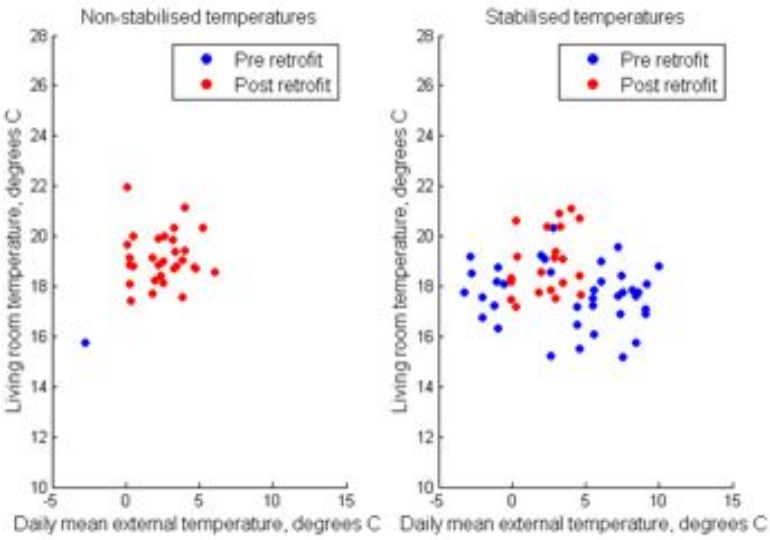



Figure 47: Dwelling 3, characteristics of the internal temperature during the heating period.

It appears that in dwellings in which the occupants control the heating manually, the stabilised definition of demand temperature, *stabilised demand temperature*, can miss out a large proportion of the heating periods and perhaps not represent the type of heating the occupants are actually demanding.

The achieved definition of demand temperature, *achieved demand temperature,* will be used for the analysis in the subsequent chapters, partly due to the above and partly because there is often not enough data to ascertain a set of stabilised temperatures over the monitoring periods (which were each only one month long).

## 7.10 PARAMETERISING THE COOLING RATE: THE THERMAL TIME CONSTANT

In Section 2.2.2.2 a parameter known as the *thermal time constant* ($\tau$) was introduced. This represents the rate of cooling of a dwelling, depending on its capacitance and heat loss. Since the heat loss is expected to decrease following building fabric retrofit, $\tau$ is expected to increase. If appropriate data were collected, an empirical estimation of $\tau$ before and after retrofit could be inferred from the rate of change of internal temperature of a dwelling as it cools after a heating period. These values could then be put into Equation 9 under standard conditions to model a temperature time series pre and post retroft, and the difference between them used to discuss the relative contribution of slower cooling post retrofit to the total observed *M.I.T. increase*.

If one is to attempt to find the value of $\tau$ from temperature time series, night time is the most appropriate period to use, for two reasons related to internal gains. Firstly, occupant activity and solar gain during the daytime interfere with the supposedly exponential signal from the temperature data as the dwelling cools. Secondly, Equation 9 involves internal gains, whose values pre and post retrofit are unknown. If night time data is used, the free heat gains are minimised and can be assumed to be negligible.

Attempting to attribute a proportion of observed temperature increase following retrofit to the building cooling more slowly has to the author's knowledge never been attempted in the literature using empirical data. However, some of the lessons learned from 3 pieces of work attempting to discern $\tau$ from empirical data will now be described.

FITTING CURVES TO TEMPERATURE DATA Veitch (2011) attempted to measure thermal time constant of different rooms in an occupied dwelling using night-time temperature time series. Sections of these time series, from here on termed the **cooling curve**, were taken each night for 80 nights. Exponential curves were then fitted to them using an inbuilt Matlab function, and the exponents were extracted, from which the time constant could be obtained. The method proved successful for differentiating between the time constants of different rooms, that is, spaces with an external wall as opposed to

those without. However, there was in a large variation in derived thermal time constant for any individual room across the set of cooling curves used.

Veitch also tried to correct for the time lag in the influence of external temperature on internal temperature, using a trial-and-error method of offsetting the internal from the external temperature time series by different amounts of time. (see Section 7.6 for how this trial and error method was combined with a theoretical one in the author's own data analysis). This did not reduce the variation in thermal time constant obtained. He then substituted the external air temperature with the sol-air temperature, which is supposed to take into account radiative losses, but again no reduction in variation of thermal time constant was observed. His conclusion was as follows:

*"The results show that time constants do not appear in their pure theoretical form due to the complexity of real-world dwellings and the large number of influences on heat transfer".*

#### PLOTTING THE LOG OF THE INTERNAL-EXTERNAL TEMPERATURE DIFFERENCE

Sweetnam (2011) tested three methods of extracting the thermal time constant from cooling curves: assuming the curve is a straight line, versus fitting an exponential function to the data as in Veitch (2011), versus plotting the natural log of the internal-external temperature difference. The results were generally in agreement but, as was found in Veitch's work, all exhibited a large amount of variation on the obtained value of the time constant. Some of the proposed reasons for the variation were already explored in Veitch (2011) (wind, radiative losses, changing external temperature); internal gains were also suggested here.

A similar conclusion was reached:

*"All of the time constant calculations have proved too sensitive to the multitude of confounding factors that affect the rate of heat loss from an occupied building to provide an accurate picture of the thermal properties of the home."*

#### DISCERNING A DIFFERENCE IN THERMAL TIME CONSTANT AFTER INSULATING A PROPERTY

The third useful piece of work to review is not published but the method can be described here (Jez Wingfield and Sam Stamp 2013, pers. comm.). It is an empirical piece of work in which the authors were able to reduce noise in the data to some extent by recording the cooling of a dwelling after a coheating test. This is beneficial since more of thermal mass of the property is saturated - that is, most of the mass starts off at the same temperature (it should be noted that a temperature

gradient still exists across the external walls). It was found that the monitored internal temperature closely matched a modelled curve for about the first 5 hours of the cooling period, then deviated to a slower cooling trajectory. There are two implications of this: firstly, that their model was reasonably accurate, and thus it is possible to theoretically estimate the thermal time constant from estimates of the thermal mass and heat loss coefficient. However, the theoretical value used to plot the modelled curve only matched real cooling for about 5 hours, after which the authors believe that the importance of other factors (the property next door, internal gains) became significant.

The coheating test was performed before and after the property was insulated, and a difference of the correct direction can be observed in the empirical temperature decay curves. However, since this experiment was only performed once it is not clear what the variation in the pre- and post-retrofit empirical cooling curves would be if it were performed many times.

To summarise the above three studies, empirical traces of the building physics theory describing temperature increase following retrofit purely due to slower cooling are visible, yet difficult to spot. The above studies were used to inform the development of a method for use in this thesis, described below.

#### 7.10.0.1 *Thermal time constant calculation method used in this thesis*

The chosen method was as follows. The log of the internal-external temperature difference was plotted against time, only using the first five hours of cooling, and assuming that if the resulting lines were not straight, this was a result of different masses cooling at different rates. If the lines were straight then *thermal time constant* could be obtained using the gradient, and any difference after retrofit noted. Otherwise, if the lines were not straight the plots could give a qualitative view of whether the lines are less steep after retrofit, but the *thermal time constant* could not be obtained.

An algorithm was therefore written to only select nights to use in which the rate of change of internal temperature was negative over the entire 5 hours of data. This filtering condition meant that in a few dwellings, very few nights passed the criterion to be selected, and there was not enough data to be able to estimate the gradient of the log plots. The main issue, however, was that most of the log plots were not straight lines but curves (as anticipated above), indicating different masses cooling at different rates or different depths of the mass being reached by the heat flux depending on the length of heating period. However, in a few cases the log plots were straight and the *thermal time constant* could be extracted. Section 8.4 presents the results.

## 7.11 INTER-ROOM TEMPERATURE GRADIENT

The inter-room temperature gradient was defined in theory in Section 2.2.2.3 as the difference in temperature between the warmest and coolest room in a dwelling over a specified time interval. The metric to be used with the empirical data in this thesis, *inter-room temperature gradient*, is as shown in Equation 24, where $n$ is the number of twenty-minutely time steps chosen to average over ($n$ is usually set to 72, to represent one day) and $i$ and $j$ are rooms, selected so as to maximise the result.

$$\text{inter-room temperature gradient } = max\left[\frac{\sum_1^n T_i(t)}{n} - \frac{\sum_1^n T_j(t)}{n}\right] \tag{24}$$

## 7.12 ENERGY USE

Energy use is not one of the metrics to be developed in this chapter. The reasons for neither measuring nor modelling it are described below.

### 7.12.1 *Why was energy use not measured?*

In this study, there was no longitudinal measurement of energy use. This was due to the fact that, as described in Section 7.7, it had initially been believed that data from the sensors on the radiators would allow conversion from daily hours of heating to space heating energy consumption. After collecting the data this assumption was shown to be false.

Gas meter readings were taken at the start and end of each monitoring period in dwellings where this was possible. However, it was decided that this was not enough information to discern quantities of interest such as daily energy use for space heating. Carrying this out would have required an aspect of modelling, to first of all split space heating energy use from that used for hot water and cooking, and subsequently to interpolate daily energy use from monthly given other information such as daily mean external temperature. It would have been problematic to use internal temperature to infer energy use as it is precisely the relationship between internal temperature

and energy use that is of key interest, therefore one should not be used to infer the other. However, this option was considered nevertheless, for example calculating space heating demand using part of the SAP/BREDEM methodology.

In the end, it was decided that the use of modelling in this thesis should be limited to the illustration of concepts, such as the possibility space of energy use mapped out in Chapter 4, as opposed to using modelling to try to discern what actually happened in the case study dwellings. The reason for this was to avoid the uncertainties introduced when combining and/or comparing modelling with and monitored data described in Section 1.8. Therefore a full SAP calculation was not carried out for the case study dwellings.

## 7.13 RELATIVE HUMIDITY

In Chapter 10 a discussion of the effect of the insulation and in some cases double glazing on the relative humidity of the case study dwellings will be presented. When performing this calculation it is more difficult to account for the effect of external conditions than the equivalent calculation for internal temperature (Section 7.5). This is for the following reason: in a *M.I.T. increase* calculation, there is only one extraneous variable to take into account: external temperature. R.H., however, is a function of external R.H. and also internal temperature (and therefore external temperature). This means that internal R.H. must be adjusted to account for external R.H. *and* external temperature. The method used to do this is described below.

Although internal and external R.H. are not related by an additive relationship, internal and external Vapour Pressure ($VP_{in}$ and $VP_{ex}$) are, with the difference between them comprising of Excess Vapour Pressure ($VP_{gen}$), generated within the dwelling from occupant activity.

$$VP_{in} = VP_{ex} + VP_{gen} \tag{25}$$

Now, assuming that $VP_{gen}$ is constant over a particular monitoring period[1], but that $VP_{gen,post}$ is allowed to differ from $VP_{gen,pre}$ , the following pair of equations can be written down:

$$VP_{in,pre} = VP_{ex,pre} + VP_{gen,pre} \tag{26}$$

$$VP'_{in,post} = VP_{ex,pre} + VP_{gen,post} \tag{27}$$

Where $VP'_{in,post}$ is an adjusted $VP_{in,post}$, to represent pre-retrofit external conditions.

The next equation to introduce relates Vapour Pressure to R.H. and Saturated Vapour Pressure (S.V.P.): Equation 28.

$$VP = \frac{RH \times SVP}{100} \tag{28}$$

$SVP$ is a function of temperature[2] and so will be written as $SVP(T)$. Equation 27 can then be rearranged to obtain Equation 29:

$$RH'_{in,post} = RH_{ex,pre} \times \frac{SVP(T_{ex,pre})}{SVP(T'_{in,post})} + 100 \times VP_{gen,post} \tag{29}$$

Equation 29 creates an adjusted post retrofit R.H., which can then be fairly compared to pre retrofit R.H.

1 This assumption probably does not hold since occupant window opening behaviour is likely to change with external temperature

2

$$\log_{10} SVP = 30.59051 - 8.2 \log_{10} T + (2.4804 \times 10^{-3})T - \left(\frac{3142.31}{T}\right)$$

From CIBSE (1988)

## 7.14 occupancy

Due to the failure of the occupancy sensors to accurately report direction (that is, whether an occupant was entering or leaving a room), the data obtained from them was not an indication of which rooms people used at what times, as had been intended. The data therefore needed a new purpose which better described what it actually represented. It was decided that one such purpose was reflecting the extent and frequency of movement between rooms. Interestingly, this conceptual metric partly came about after an occupant mentioned during an interview how she liked to 'potter' around the house, implying she changed rooms frequently. This could have two implications: firstly, metabolic rate increases with activity level and thus heating use can be offset by activity (this was documented qualitatively in DECC (2013b)); secondly, in models it is usually assumed than an occupant stays in one place for at least an hour, and this is the basis of some types of modelled heating zoning. In reality it could be that heating zoning is inappropriate if the occupant is not in one room for very long; in this situation the dwelling is essentially one zone.

Unfortunately, since the direction problem was not the only problem with the sensors and the sensor failure rate per dwelling was therefore high, a complete longitudinal whole-house dataset was not obtained for most case study dwellings. This meant that quantification of number of times the occupant changed room, for example per hour, was not generally possible at a whole-house level. Instead, one sensor per dwelling was chosen as a representative sensor for movement around the dwelling. This is a much less useful measure than had originally been anticipated when designing the sensors; however the author needed to make the greatest use of the data without making unsubstantiated claims. From the pre retrofit interview data, it seemed that in most dwellings there was one room per dwelling which the main occupant considered him/herself as based in most of the time. The sensor on that doorframe was thus taken as representative of movement around the dwelling. In this way, longitudinal comparison was possible as the same rooms were compared before and after retrofit. A metric *hourly occupancy events* was then defined as the number of times per hour the sensor on a particular doorframe logged movement.

It was found to be most helpful to plot *hourly occupancy events* on a histogram of hourly events against time of day, termed a **daily occupancy plot**. Upon this plot, other data could be superimposed: probability that the heating is on against time of day, and internal temperature against time of day. With all three datasets on one plot, it was

possible to start to build a picture of occupant patterns of, say, settling down in the evening and turning the heating on. Examples of this are given in Section 10.8.

The conclusion chapter presents a full reflection of how the project could have been carried out differently to obtain occupancy data more closely representing the intended metric in the research design.

This concludes the documentation of construction of metrics. The discussion is however not quite at the point of being ready to present the results. Before this, the important topic of validity must be returned to. So far in this thesis validity was discussed in Section 6.8 in the context of data collection; this second part of the validity discussion concerns data analysis and how error is introduced throughout this process. This includes the topic of the relationship between the physical and social data.

## 7.15 VALIDITY IN DATA ANALYSIS

The order of this discussion on validity is as follows. Firstly, validity in qualitative data analysis will be discussed, followed by validity in quantitative data analysis. Then, triangulation of physical and social data will be addressed to ascertain the validity of each one in the context of the other. After this, attention will be turned to how to combine the physical and social data to investigate interactions as specified by Research Question 2.

### 7.15.1 *Validity of qualitative data analysis*

Having previously discussed validity in conducting interviews in Section 6.8, the next aspect to treat is validity of analysis of the data obtained. For a reminder of the analysis method, the reader is referred back to Section 7.2.

Thinking about validity in qualitative analysis does not consist of ensuring that the 'right' method is used, as there is not a great deal of consensus as to how qualitative analysis should proceed, or what makes an acceptable analysis (Sarantakos (2005)). Validity is not even found in inter-researcher replicability in qualitative research, unlike in quantitative work, since there is not one set of themes which is 'correct', given that texts are open to a variety of readings (Yardley (2000)).

Therefore, whichever method is chosen, demonstration of validity requires application of rigour. Examples of rigourous analysis include considering phenomena from more than one angle, and ensuring that the process of coming to conclusions is transparent: for example explaining why certain quotes were chosen to illustrate a point compared to those which were not, or how certain sections of data were justifiably woven together (Mason (1996)). It is impossible to eliminate subjectivity entirely, but it is possible to use self-awareness to minimise its effects on the interpretation.

Relating this to the analysis in this thesis, the two forms of rigour described above were important at multiple stages of the process. Deciding upon the emergent themes, populating them with appropriate data, arranging them into the hierarchical structure mentioned in Section 7.2.2 and drawing insight from this processed structure were tasks which required consideration from more than one angle. Selecting quotes as evidence to combine with quantitative data (a process explained slightly later on in Section 7.15.5) required neither accidentally nor deliberately neglecting other quotes which may give evidence to the contrary.

Thus, all the way through, the researcher is making decisions which could change the course of the rest of the analysis. As instructed by Mason (1996), awareness of this is absolutely essential. An example from this thesis is as follows. Whilst analysing the first interview of the set, 'children' came through as a very significant driver of heating and comfort needs. Thus, care had to be taken not to project this theme onto all of the other interviews from households containing children. However, this theme emerged anyway, since all households talked a lot about heating for their children even though they were not asked. Therefore 'children' was judged to be an important theme in the analysis.

### 7.15.2 *Validity of quantitative data analysis*

Two topics will be covered in this section: reporting of error and subjectivity of interpretation.

#### 7.15.2.1 *Statistical significance*

Reporting of error and significance on results is not trivial in this thesis for two reasons: small sample sizes and multi-stage construction of metrics entailing compounding of error.

Several of the quantities of interest, for example *M.I.T. increase*, are calculated from the difference between two lines. Although it often appears that two lines are different, and thus that there is an increase in *M.I.T.* following retrofit, demonstrating mathematically that the lines are statistically significantly different is not always possible with such small sample sizes. Given the effect size (e.g. a few degrees C) compared to the sample size (30 points or so), performing a standard freqentist difference test often leads to large p-values. However a Bayesian approach is not entirely suitable either as not enough is known about the underlying model to form adequate prior distributions. Therefore a suitable significance test was not found.

Therefore, instead of trying to demonstrate whether an increase was 'significant' or not, the results have been presented with error, calculated according to the following procedure.

#### 7.15.2.2 *Error*

The error on an observed change of a variable after retrofit was determined using the aforementioned two lines as follows.

The Root Mean Square (R.M.S.) error was the chosen error metric, representing the mean distance of the points from the line fitted through them. Since the purpose of fitting lines through points was to construct metrics such as *M.I.T. increase*, the error on individual lines could be translated into the error on the final metric by applying uncertainty propagation formulae, as in Taylor (1997):

1. If $q$ is a sum or difference, $q = x + ... + z$, then

$$\delta q = \sqrt{(\delta x)^2 + ... + (\delta z)^2}$$

2. If $q$ is a product or quotient, $q = \frac{x \times ... \times z}{u \times ... \times w}$ , then

$$\delta q = \sqrt{\frac{(\delta x)^2}{(x)^2} + \frac{(\delta u)^2}{(u)^2} + ... + \frac{(\delta w)^2}{(w)^2}. + \frac{(\delta z)^2}{(x)^2}}$$

In some sets of results in this thesis, error is not reported. One example of this is the technique attributing *M.I.T. increase* to heated and unheated hours, in which there is not only error on the original *M.I.T. increase* quantity, but also within the process of attribution to heated and unheated hours (due to the error on the lines plotted through number of heated hours against external temperature). These errors compound in a manner which results in them being so large they could overshadow the quantity being

calculated. Although it is not good practice to hide this fact, it is also not very helpful to show the error - the exploratory nature of this piece of analysis means that the best estimate of the quantity still has some meaning despite sizeable uncertainty.

At this point it is useful to comment on the size of the R.M.S. error on the *M.I.T. increase*. Figure 48 compares this error to the difference between the *mean metric* and *standardised metric* of M.I.T. increase (Section 7.5.0.1). The observation that the error is larger than the difference means that it does not especially matter which of the two metrics for *M.I.T. increase* is used.

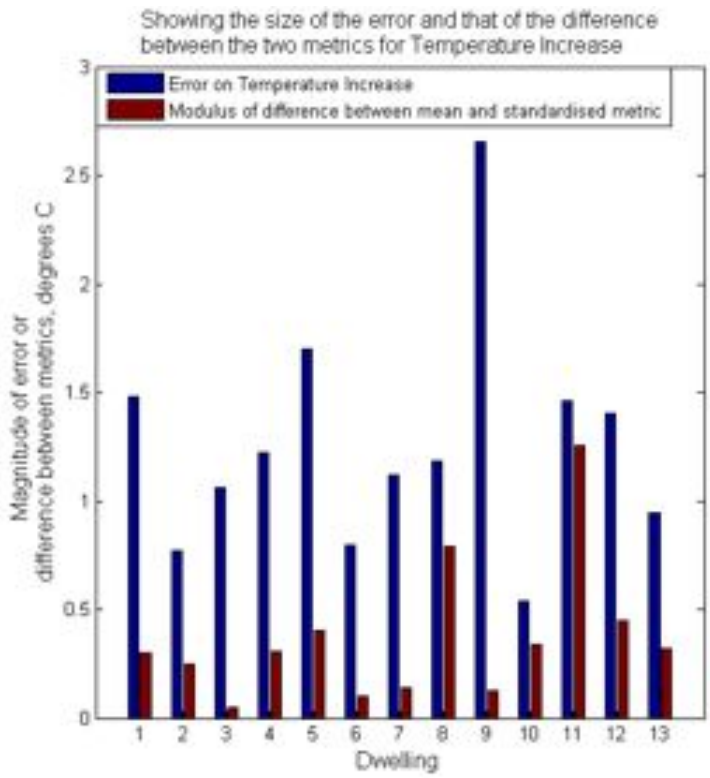



Figure 48: Size of both the error and the difference between the two metrics of *M.I.T. increase*, for each dwelling.

### 7.15.3 *Quantitative properties of the sample*

A multi case study approach is usually used within a qualitative research design. After cases are analysed in their own context, the sample (i.e. set of cases) is treated as a whole, and cross-cutting themes are highlighted at this sample level (see Figure 25 in Section 5.3.2.3). Application of the concept of sample-level analysis to the research design in this thesis which is partly quantitative must be carried out with caution. An

example will to be used to illustrate this: statement of the average *M.I.T. increase* across the sample.

Calculation of the *M.I.T. increase* is a valid exercise for one dwelling: a method was created at length in Section 7.5. However, presenting a summary statistic for the mean across the sample is less valid. There are two reasons for this. Firstly, the sample size is small (only 13) so the uncertainty is large. Related to this, 'outliers' have a very large influence on any sample-level statistics such as the mean. For example, in dwelling 7 the occupants changed over the two monitoring periods; the pre retrofit occupants used constant heating at 24°C, whereas the post retrofit occupants heated to a mean of 16.6°C through more typical behaviour. This decrease of over 7°C skews the sample *M.I.T. increase.*

Despite these problems associated with quantities such as the mean *M.I.T. increase* across the sample, it is sometimes useful to state their values such that, for example, one can say whether retrofit generally increased the internal temperatures of the case study dwellings. Finding the mean *M.I.T. increase* across the sample involves a subjective judgment of which dwellings are to be considered outliers and therefore excluded. In general in this thesis, the three dwellings (4,7,12) in which the occupants changed between the monitoring periods and the one dwelling (6) in which the central heating system was broken throughout one of the monitoring periods are excluded from calculation of the mean of a variable; in some cases the exclusion criteria are slightly different and thus are stated. In each use of a mean on a graph, the line is dotted to remind the reader that it should be interpreted with caution and is unlikely to be representative of the mean of a larger sample.

### 7.15.4 *Triangulation of the physical and social data*

Given that triangulation is an exercise generally carried out within the social science disciplines, definitions of the term tend to refer to this context. Two such definitions are presented below:

*"Triangulation: the use of more than one method or source of data in the study of a social phenomenon so that findings may be cross-checked."* (Bryman and Bell (2003))

*"Triangulation has its origins in attempts to validate research findings by generating and comparing different sorts of data, and different respondents' perspectives, on the topic under investigation."* (Torrance (2012))

The commonality in these definitions is that one of the purposes of triangulation is validation. That is, the different sources of data between them do not tell the researcher anything new (this will be called 'combination' and treated in Section 7.15.5); instead they can highlight whether the data themselves are reliable.

The difference between the above definitions of triangulation is that the first one requires different methods and the second requires different types of data. If triangulation is to be used for validation purposes, it could be argued that the second definition, using different types of data as opposed to simply different methods from the same methodology, should be used. This is so that then the validity concerns within each methodology are different; as such, when data collected using different methodologies is compared and found to be consistent, the researcher can be more sure that the data is valid. The reason for this can be explained by using a contrasting example: collecting data using two different methods within the same methodology (for example, questionnaires and interviews which both rely on self-reported data). Here, even if the two data sources appear to give consistent findings, the same validity concern could have affected them both in the same way, and thus they could still be 'invalid' but appear consistent with each other.

As was previously mentioned, the above definitions of triangulation were taken from social science texts and are therefore likely to implicitly assume the use of two social science methodologies and methods. In this study, a self-reported social science method (interviewing) is combined with an observational physical method (sensors). The methodologies are different and hence they give different types of data (self-reported and observational). This, then, enables triangulation as specified by Torrance (2012).

#### 7.15.4.1 *What if the physical and social data contradict?*

*"It may be of course that different data sources generate discrepant accounts, but such a possibility has often been interpreted as simply warranting further investigation. Discrepant accounts are treated as interesting but puzzling findings that inform us that our original understandings have been inadequate and thus require further data to be gathered and further interpretive activity to be undertaken."* (Torrance (2012), from Patton (1980) and Mathison (1988)).

The above excerpt makes the discovery of contradictory pieces of data sound extremely positive; even fun. This section will describe how the advice in this quotation was not appropriate in the context of this study, and how then apparent contradictions were investigated.

Upon discovery of an apparent contradiction, several factors led to the collection of further data (either of the same type or of another type) to be either impossible or inappropriate. Firstly, the monitoring periods were fixed and took place just before the cold season ended; thus any further physical data collection would not have been in the context of the heating season as was stipulated in the research design. This left the possibility of contacting the occupants later on in the year and asking them to give their opinion on why a particular finding may have been obtained. This option had not been stated on the participant information sheet when the participating households were recruited, and the author thus did not want to bother them more than absolutely necessary. There were two occasions in which it was deemed necessary and worthwhile to telephone the occupants after the monitoring period. One involved dwelling 10 where the temperature in one bedroom had decreased by 3-5°C following retrofit; the other involved dwelling 11 in which the retrofit works seemed to make very little difference to the internal temperature and heating use. In neither situation did contacting the occupants again aid the investigation: in dwelling 10 the occupant could not think of any reason the temperature in that room could have decreased by so much; dwelling 11 could not be contacted.

Therefore, in light of the lack of extra information, there are two principles to help decide which out of the qualitative (self-reported) and quantitative (observational) data is more reliable where two particular pieces of data contradict.

The first principle supports the observational data being more reliable than the self-reported data. This is the topic of 'validity of self-report'. Extensive experimental testing has shown that there are many factors which affect occupant responses in different circumstances (Brener et al. (2003)). This is a large topic, but a brief summary is as follows: memory can be distorted either by later information contained in the questioning of the interviewer or by the interviewee's perceived expectations of the interviewer.

The second principle supports the self-reported data over the observational data, and is the topic of 'framing'. In this context, framing shall be interpreted as when data collected during the specific monitoring period gives a false idea of what happens in general. Since the monitoring equipment was only in place for one month but the occupants were encouraged to respond in the context of 'winter', it is possible that the latter represents their experience more generally than the former, which could have been an exceptional month for a number of reasons. That is, framing inherent in the monitoring methods might cause results to be at odds with the self-reporting method.

To proceed, it will be assumed in this thesis that the observational (physical) data is more reliable than the self-reported (social) data unless there is a framing issue apparent with the physical monitoring. There is an example of the latter in Section 12.4.3.2.

### 7.15.5 *Combination of the physical and social data*

In this research design, after triangulation comes combination. That is, once the researcher is satisfied with the validity of a piece of, say, monitored data, and separately, with that of a section of interview data, they can be used together to construct a new inference. In order that this can be carried out with rigour, the topic of causation must now be discussed.

#### 7.15.5.1 *Causation*

The type of causation to be invoked in the proposition of mechanisms, as specified in Research Question 2b, is 'generative causation': analysis of the process by which some events influence others. This type of treatment of causation is predominant in qualitative research (Robson (2011)) and it is proposed here that it is suitable for mixed methodology research such as that in this thesis. Causation here cannot be proved, only proposed. An example from the real data will aid the discussion of the extent to which causal mechanisms can be proposed.

#### 7.15.5.2 *An example, and discussion of whether the causality proposed is valid*

The example to be given here can be found in its full form in case study 2 in Section 9.4. Monitored data showed that the mean internal temperature of this dwelling rose after retrofit, and that the heating period became more likely in the evening and less likely in the morning. Secondly, in the post retrofit interview, the occupants talked about their bedroom being cold post-retrofit. This self-reported data can be considered 'valid' as they offered the information spontaneously several times during the interview.

This led the author to investigate in the monitored data not just the mean internal temperature, nor the mean internal temperature in only the bedroom, but the temperature in the bedroom at the time when the occupants normally go to bed (termed 'evening'). It was shown that this temperature was lower than that in the rest of the dwelling.

This validity of this statement is lower than that of the other quantitative information stated thus far since the author had to subjectively judge which time periods to put into 'evening' and 'non-evening', and also the reason was unknown for the bedroom being colder at this time (i.e. there was no triangulation).

Returning to the qualitative data, the occupants talked about needing to have the heating on for a while before bedtime post-retrofit. This was also spontaneously offered.

From all of the above, it was proposed that since one effect of the retrofit was to make the bedroom relatively colder than the other rooms at bedtime, the occupants felt the need to put the heating on every evening so that their bedroom would be warm by the time they went to bed. This was not explicitly stated by the occupants but inferred from combining the monitored and self-reported data.

What is the validity of proposing causal mechanisms from pieces of monitored and self-reported data such as the one above? It cannot be known whether this is the 'right' causal mechanism, therefore the question is how likely is it? There are two features of data/explanation which can improve its validity, which will be used in this thesis:

- Spontaneity in self-reporting: if the occupants offered a piece of information themselves without being asked about it, this means it was more likely to be important to them, and thus they may have been more likely to do something about it.
- Contestability: if there is not obviously another explanation as likely as that proposed, then the researcher proposed the most likely explanation given the data.

In conclusion, there remains much scope for further work in this difficult area of combining monitored (physical) and self-reported (social) data to infer causal mechanisms, and to analyse the overall validity of inferences made, given the individual validity concerns associated with each of the methodologies.

## 7.16 CONCLUSION

In this chapter, quantitative metrics to be used throughout the rest of this thesis were derived and justified, and the method of analysis of the qualitative data was documented. The combination of the monitored and physical data was anticipated by the discussion of internal validity followed by issues which arise when different types of data are combined. The thesis is now at the point where results can be presented.

# 8

# RESULTS 1: HOW MEAN INTERNAL TEMPERATURES CHANGE

## 8.1 INTRODUCTION TO THE RESULTS CHAPTERS

The reader is reminded of the research questions below:

In social housing undergoing building fabric retrofit,

1) How does internal temperature change afterwards, during heating and non-heating hours and throughout the dwelling?

2) If internal temperature changes afterwards, why? What are the interactions between occupants, building fabric and heating systems which produce the temperature change?

There are three results chapters in this thesis. This chapter will address Question 1, and Chapter 9 will address Question 2. Following this, there is an extra results chapter (Chapter 10) which is composed of findings on topics not specifically stated in the research questions but which emerged from the data as important to understanding how people use heating in their homes.

Two simultaneous streams of data analysis took place to write these results chapters. A purely quantitative stream, performing the same analysis for each case study dwelling, was used to answer Research Question 1 which concerns quantitative outcomes. To study why these outcomes occurred, however, a multi-case study approach was used. The data were analysed firstly by case study then by cross-case comparison as specified by the case study process shown in Figure 25 in Section 5.3.2. Thus, Chapter 9 begins by presenting two example case studies before going on to the cross case comparison.

The purpose of Chapters 8 to 10 is to present the results. A discussion of their significance for retrofit policy and their contribution to the literature can be found in Chapter 11.

## 8.2 SUMMARY TABLES AND GRAPHS

The key quantitative metric in this thesis is *M.I.T. increase*; two further important variables are change in *daily heated hour*s and change in *achieved demand temperature*. Two tables and two graphs summarising the key quantitative outcomes will now be presented, with the rest of the results chapters devoted to explaining them.

### 8.2.1 *Mean internal temperature*

A summary of some key characteristics of the case study dwellings and how *M.I.T.* changed following retrofit in each one is presented in Table 12 on the following page. The *M.I.T. increases* are given according to both the standardised and mean methods of calculation, derived in Section 7.5. Subsequent analysis in this chapter mostly uses the mean method, firstly as it captures the diversity of what occurred at different external temperatures better than the standardised method, and secondly because the error procedure described in Section 7.15.2.1 produces a mean error across all external temperatures. The final row of Table 12, representing the mean across the sample, has been calculated excluding dwellings 4, 6,7 and 12 according to the justification in Section 7.15.3.

| Dwelling I.D. | Type of property | Type of household | Retrofit measures installed | External temperature over pre retrofit monitoring period, °C | External temperature over post retrofit monitoring period, °C | *M.I.T.* pre retrofit, °C, standardised to 5°C externally | *M.I.T. increase* (standardised method), °C | *M.I.T. increase* (mean method), °C, with error |
|---|---|---|---|---|---|---|---|---|
| 1 | Ground floor flat | Single mother with two children | EWI, double glazing, and separately radiator repairs | 4.1 | 3.1 | 16.3 | 1.6 | 1.9 ±1.5 |
| 2 | Mid-terrace | Couple with grown-up son | EWI | 6.1 | 2.9 | 17.2 | 2.3 | 2.6±0.8 |
| 3 | Ground floor flat | Single man aged 70 | EWI | 4.3 | 2.6 | 16.4 | 1.8 | 1.7±1.1 |
| 4 | Ground floor flat | 2012: Single man, middle-aged. 2013: Single man, middle-aged | EWI | 5.9 | 2.9 | 12.7 | 3.2 | 3.5±0.8 |
| 5 | Top floor flat | Single man aged 60 | EWI and double glazing | 4.7 | 3.1 | 11.8 | 1.5 | 1.9±1.7 |
| 6 | Ground floor flat | Single man, middle-aged | EWI | 4.6 | 2.9 | 15.9 | 3.5 | 3.4±0.8 |
| 7 | Mid-terrace | 2012: couple, middle-aged. 2013: single mum and two children. | EWI | 4.4 | 2.6 | 24.1 | -7.5 | -7.6±1.1 |
| 8 | Top floor flat | Single woman, middle-aged | EWI | 6.1 | 2.5 | 16.5 | -0.1 | 0.7±1.2 |
| 9 | Mid-floor flat | Single man, aged about 40 | EWI and double glazing | 5.5 | 3.5 | 13.7 | 3.8 | 4.0±2.7 |
| 10 | Mid-terrace | Single man, with his daughter there in 2012 and not in 2013 | EWI | 4.3 | 2.5 | 16.7 | -1.1 | -0.8±0.5 |
| 11 | Mid-terrace | Couple with 2 children | EWI and double glazing | 5.4 | 3.1 | 18.3 | 0.6 | 1.9±1.5 |
| 12 | Top floor flat | 2012: single man, retiring age. 2013: couple with newborn baby | EWI and double glazing | 5.9 | 2.8 | 16.4 | 2.8 | 2.4±1.4 |
| 13 | Ground floor flat | Single woman with grown-up son | EWI and double glazing | 5.4 | 3.1 | 16.4 | -0.5 | -0.9±1.0 |
| Mean | | | | 5.1 | 2.9 | 15.9 | 1.1 | 1.4 |

Table 12: Key characteristics of the case studies, with *M.I.T. increase*.

Figure 49 displays the final column of Table 12 graphically.

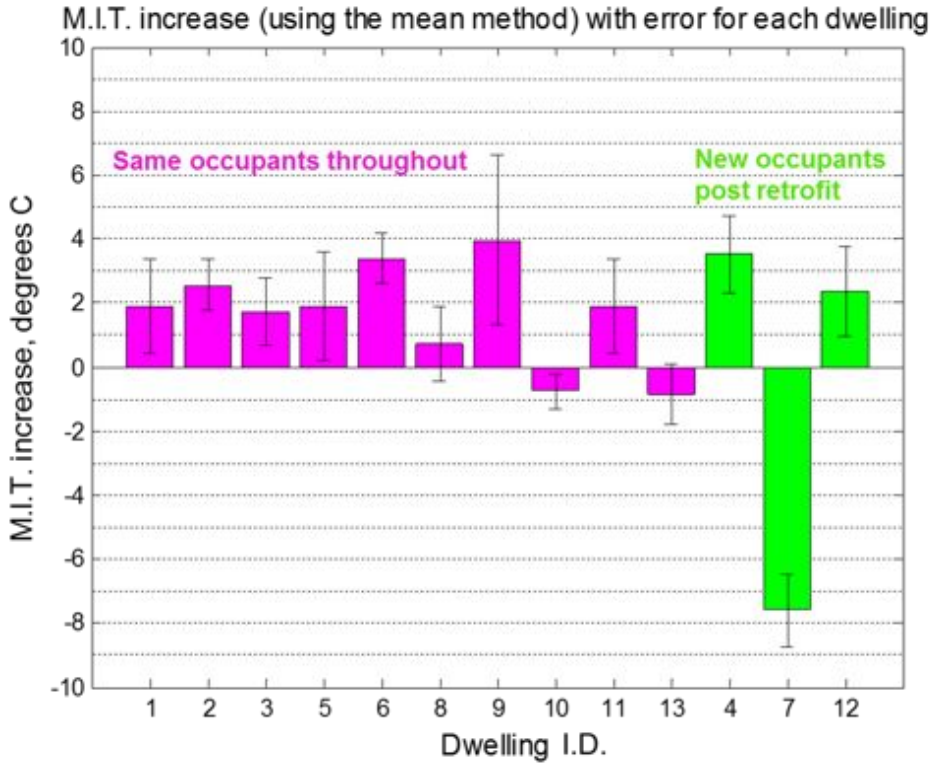



Figure 49: *M.I.T. increases* across the sample.

It can be seen from Figure 49 that mean internal temperatures increased in most dwellings following retrofit, although in two dwellings there was no significant change and in two dwellings a decrease occurred. In dwellings with the same occupants throughout, the range of *M.I.T. increase* was between 0°C and 4°C. Where occupants changed between the monitoring periods, there was a wide range of change (-7.5°C to 3.5°C).

Amongst other factors, *M.I.T.* is directly influenced by heating schedule and the temperatures attained during heated hours (Chapter 2), so the next summary table and graph display the change in *daily heated hours* and *achieved demand temperature*, calculated according to the procedures in Sections 7.7 and 7.9 respectively.

### 8.2.2 *Daily heated hours and achieved demand temperature*

The pre and post retrofit *daily heated hours* and *achieved demand temperature* are shown in Table 13; their respective changes are given in the table and visualised in Figure 50.

The final row, displaying the mean across the sample, is again calculated excluding dwellings 4,6,7 and 12.

| Dwelling I.D. | *Daily heated hours*, pre retrofit, hours | *Daily heated hours*, post retrofit, hours | Change in *daily heated hours*, hours | *Achieved demand temperature* pre retrofit, °C | *Achieved demand temperature* post retrofit, °C | Change in *achieved demand temperature*, °C |
|---|---|---|---|---|---|---|
| 1 | 9.1 | 2.6 | -6.5 | 18.0 | 18.1 | 0.2 |
| 2 | 3.3 | 3.9 | 0.6 | 19.6 | 22.8 | 3.2 |
| 3 | 6.1 | 5.4 | -0.7 | 17.6 | 19.0 | 1.4 |
| 4 | 0.4 | 1.5 | 1.1 | 13.7 | 18.3 | 4.6 |
| 5 | 2.5 | 3.3 | 0.8 | 12.8 | 14.7 | 1.9 |
| 6 | N/A | N/A | N/A | N/A | N/A | N/A |
| 7 | 24 | 6.5 | -17.5 | 26.2 | 20.3 | -5.9 |
| 8 | 4.8 | 3.0 | -1.8 | 18.3 | 20.5 | 2.2 |
| 9 | 2.3 | 2.8 | 0.5 | 23.5 | 25.9 | 2.4 |
| 10 | 3.3 | 2.0 | -1.3 | 18.4 | 18.5 | 0.1 |
| 11 | 7.0 | 6.7 | -0.3 | 18.9 | 20.1 | 1.2 |
| 12 | 6.4 | 4.6 | -1.8 | 17.5 | 19.7 | 2.3 |
| 13 | 8.8 | 0.9 | -7.9 | 17.6 | 18.1 | 0.5 |
| Mean | 5.2 | 3.4 | -1.8 | 18.3 | 19.7 | 1.5 |

Table 13: *Daily heated hours* and *achieved demand temperature*.

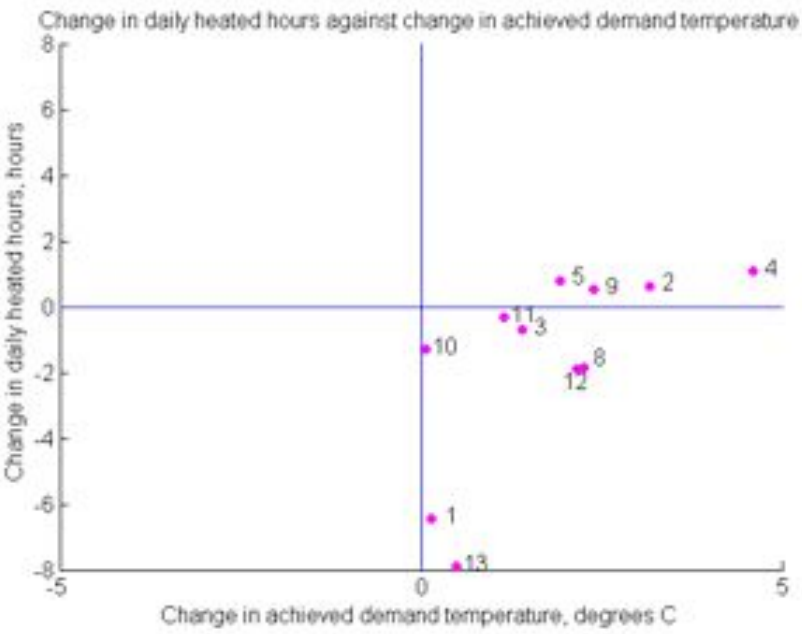



Figure 50: *Daily heated hours* and *achieved demand temperature* change.

Table 13 indicates that although there was a spread in pre retrofit *daily heated hours*, most of the dwellings were heated for significantly less than the average of 11 hours assumed by SAP (9 hours on weekdays, 16 hours on weekend days), and also less than the 8.3 hours determined empirically from the CARB dataset (Section 3.3.3). Furthermore, *daily heated hours* often decreased following retrofit, although in some cases they increased. Overall, since a low proportion of hours per day were heated, this suggests that most of the observed *M.I.T. increase* occured during unheated periods rather than heated periods. This is the subject of the next section.

It can be seen from Table 13 and Figure 50 that in most dwellings the *achieved demand temperature* increased. This finding will be returned to in the next chapter, to explore why this was the case.

## 8.3 ATTRIBUTION OF M.I.T. INCREASE TO HEATED AND UNHEATED PERIODS

Of the overall increase in *M.I.T.* following retrofit, it is useful to attribute proportions to heated and unheated periods, as this is a first step to knowing whether occupants did anything differently or whether the increase was purely due to physical processes. Table 14 summarises the breakdown by type of hour of when increase in mean internal temperature occurred, according to the method developed in Section 7.8. The mean metric of *M.I.T. increase* was used here as opposed to the standardised metric, as each individual day's data needed to be taken into account for this calculation. Also, dwellings whose temperature decreased are represented in Table 14 by *M.I.T. increase* summing to -100% instead of 100%.

| Dwelling | 1 | 2 | 3 | 4 | 5 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of *daily heated hours* common to pre and post retrofit | 2.6 | 3.3 | 5.2 | 0.4 | 2.4 | 2.9 | 2.2 | 2.0 | 6.3 | 4.5 | 0.9 |
| % *M.I.T. increase* occurring in heated hours | 5 | 14 | 16 | 2 | 9 | 15 | 12 | -5 | 23 | 9 | -1 |
| % *M.I.T. increase* occurring in unheated hours | 78 | 82 | 83 | 91 | 87 | 80 | 86 | -84 | 77 | 87 | -38 |
| % *M.I.T. increase* occurring in hours switched from heated to unheated | 16 | no such hours | 1 | no such hours | no such hours | 6 | no such hours | -10 | 0 | 4 | -61 |
| % *M.I.T. increase* occurring in hours switched from unheated to heated | no such hours | 4 | no such hours | 7 | 4 | no such hours | 2 | no such hours | no such hours | no such hours | no such hours |

Table 14: Percentage of *M.I.T. increase* occuring during heated, unheated and switched hours.

General cross-case observations about Table 14 are most usefully made by considering only dwellings whose occupants did not change after retrofit and whose temperatures increased after retrofit, and not including the dwelling whose heating system was broken during the pre retrofit monitoring period. This leaves dwellings 1, 2, 3, 5, 8, 9 and 11. It is then possible to state that:

- As stated above, there is not much potential for most of the *M.I.T. increase* to have occurred during heated hours since most hours were unheated.
- Therefore, most of the *M.I.T. increase* occurred in hours when the heating was off: ranging from 77% (dwelling 11) to 87% (dwelling 5). The mean *M.I.T. increase* during unheated hours was 82%.

- There was a small amount of *M.I.T. increase* which occurred when the heating was on: ranging from 5% (dwelling 1) to 23% (dwelling 11). The mean *M.I.T. increase* during heated hours was 13%.

- A very small amount of *M.I.T. increase* is attributed to hours which were unheated before retrofit but became heated afterwards: from 2% (dwelling 9) to 4% (dwelling 2).

- Perhaps surprisingly, out of the four dwellings in which some heated hours pre retrofit became unheated afterwards, in three of them post retrofit unheated hours were warmer than pre retrofit heated hours.

## 8.4 CONTRIBUTION OF NIGHT COOLING TO M.I.T. INCREASE

Following on from the previous section, given the predominance of unheated hours in the *M.I.T. increase* following retrofit, is is natural to postulate that some part of this occured during the night. Cooling curves as defined in Section 7.10 can be plotted for each dwelling, for example Figure 51 shows cooling curves from dwelling 8 pre and post retrofit, each line representing one night, for 5 hours after the heating was turned off:

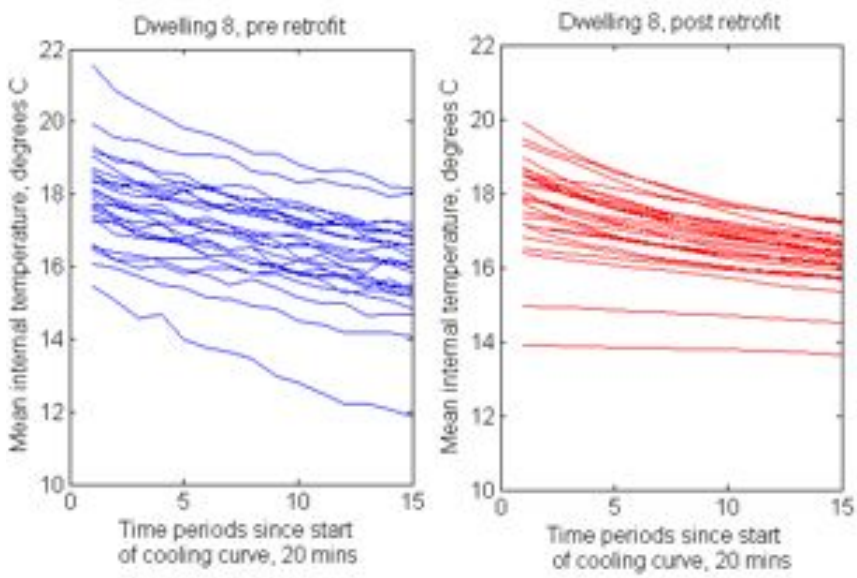



Figure 51: Dwelling 8, cooling curves.

However, it is not possible to identify the effect of the retrofit using the cooling curves in Figure 51 in their currrent form, due to differences in external temperature and the internal temperature from which each line starts. In Section 7.10, a method was derived based on combining aspects of other researchers' work for using cooling curves such as those above to calculate the *thermal time constant* of a dwelling, which can then be used to make a modelled version of Figure 51 under standardised conditions. The method involved finding the gradient of the log of the internal-external temperature difference against time, having selected only nights in which the temperature decreased in every timestep, and only dwellings in which the resulting log plot contained straight lines. It was found that this combination of criteria resulted in the time constant not existing in any dwelling, so the former filter was relaxed. Given this compromise, please note that the following is exploratory analysis only, with potentially unsuitable data.

An example log plot is shown in Figure 52, again from dwelling 8:

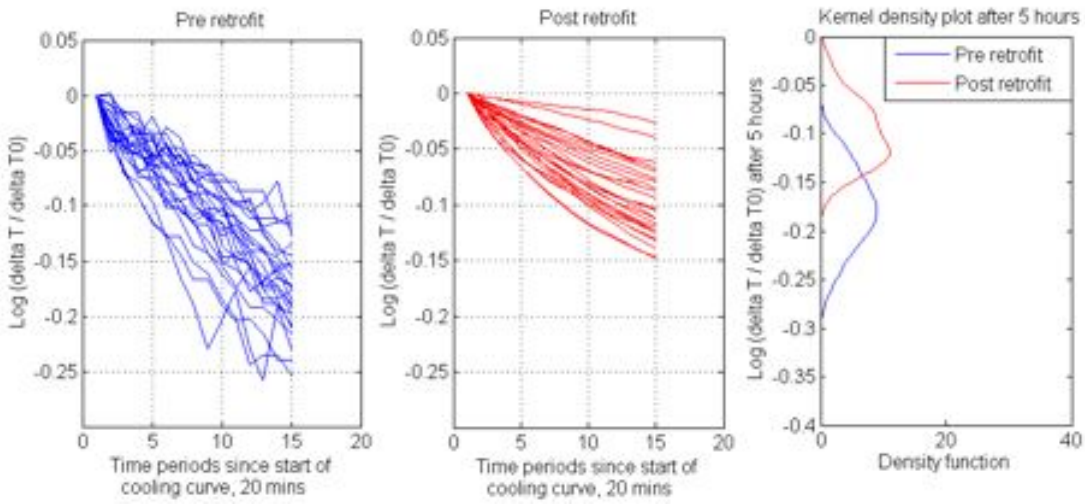



Figure 52: Dwelling 8, log plots of night-time temperatures pre and post retrofit with kernel density after 4 hours.

The *thermal time constants* before and after retrofit , $\tau_{pre}$ and $\tau_{post}$, are then derived from the mean gradient of the log plots in Figure 52 using Equation 10:

$\tau_{pre} = \frac{-5\text{hours}}{-0.18}$ = 28 hours

$\tau_{post} = \frac{-5\text{hours}}{-0.10}$ = 50 hours

It would at this point be useful to compare the derived values of $\tau$ to those in the literature to discern whether the answers are in a reasonable range. However, literature on the subject of empirical determination of *thermal time constant* is rare, and what there

is suggests large variation in results (Veitch (2011)). Furthermore, there does not appear to be any attempt in literature at the calculation for the type of construction of the case study homes. However, intuitively these derived values seem high. This could be as a result of the relatively little exposed wall area of this dwelling; other than this it is not clear why the values are so large.

Continuing to the next stage of investigation, $\tau$ can be put back into Newton's law of cooling, reproduced in Equation 30:

$$T_{in}(t) = T'_{ex} + \left(T_0 - T'_{ex}\right) e^{-\frac{t}{\tau}} \tag{30}$$

The purpose of this is to use the *thermal time constants* extracted from the empirical data to plot a modelled cooling curve for the pre and post retrofit dwelling, under standard conditions. This allows prediction of the effect of the different values of $\tau$ pre and post retrofit on the internal temperature over time, whilst holding other variables constant. For dwelling 8, the standard conditions used were as follows: $T_0$ = 18°C, $T'_{ex}$ = 2.5°C.

Figure 53 shows the modelled cooling curves, and the difference in modelled pre and post retrofit mean internal temperature after 5 hours:

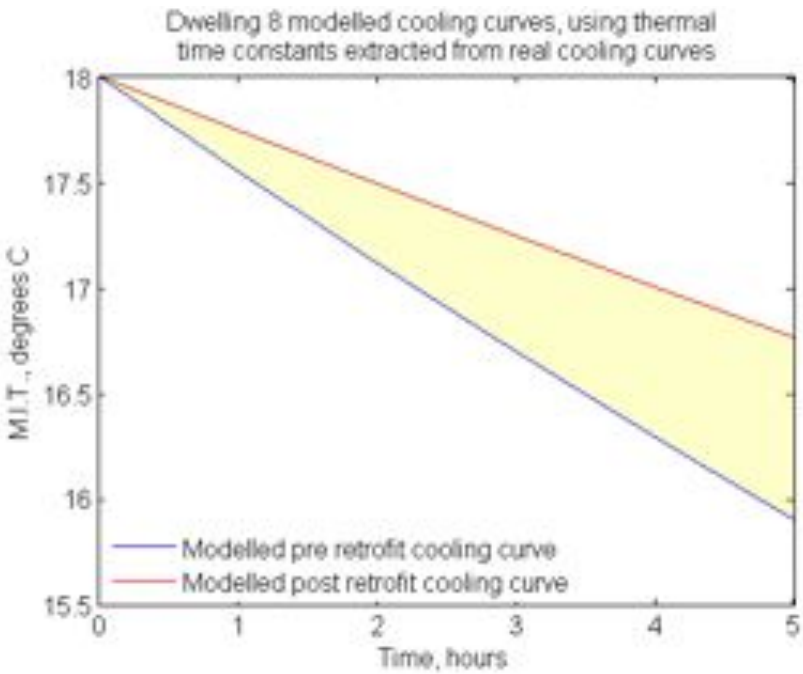



Figure 53: Dwelling 8, result of putting the empirically-determined *thermal time constants* back into the cooling equation.

The shaded area between the pre-and post-retrofit curves in Figure 53, in units of degree-hours, represents a temperature increase after retrofit, during unheated hours.

In dwelling 8, this temperature increase is 2.2 degree hours. Given that the overall *M.I.T. increase* in dwelling 8 was 0.7°C, which over one day is 0.7 x 24 = 16.8 degree hours, the temperature increase attributed to only this 5 hours of night cooling represents 13% of the total *M.I.T. increase* of this dwelling. If the pre- and post-retrofit curves were even further extrapolated to, say, a duration of 8 hours (a typical time period over which this occupant could be expected to be in bed with the heating off), then the contribution of the whole night of cooling would represent 45% of the total *M.I.T. increase* of this dwelling.

This figure should be interpreted within its exploratory context, given that the large error on the *M.I.T. increase* (1.2°C) is compounded with the (unquantified) error on the process of determining and using the two *thermal time constants*. As such, all that will be concluded here is that night cooling alone can represent a significant proportion of the total *M.I.T. increase*. The implication of this is that there is a reasonable proportion of *M.I.T. Increase* for which occupant behaviour cannot be responsible, as the occupants are not even awake.

## 8.5 INTER-ROOM TEMPERATURE GRADIENT

The reader is reminded of the theory explained in Section 2.2.2.3, where it was proposed that the temperatures in rooms within a dwelling could be expected to be more similar following an intervention increasing the thermal efficiency of the building fabric.

This would be easiest to observe in unoccupied dwellings or a model. In real dwellings, where occupant behaviour may change as a result of or at the same time as the building fabric efficiency increase (as will be demonstrated in the next chapter), this might be more difficult to observe. To try to observe change in *inter-room temperature gradient* in the case study dwellings, only those dwellings without any change in the main heating system and with the same occupants both years are included here. For example, dwelling 9 is excluded since the occupant changed from primarily using secondary heating in one room to using central heating in all the rooms, which would be a different reason for *inter-room temperature gradient* to change.

Histograms such as the example from dwelling 2 in Figure 54 were plotted for each eligible dwelling:

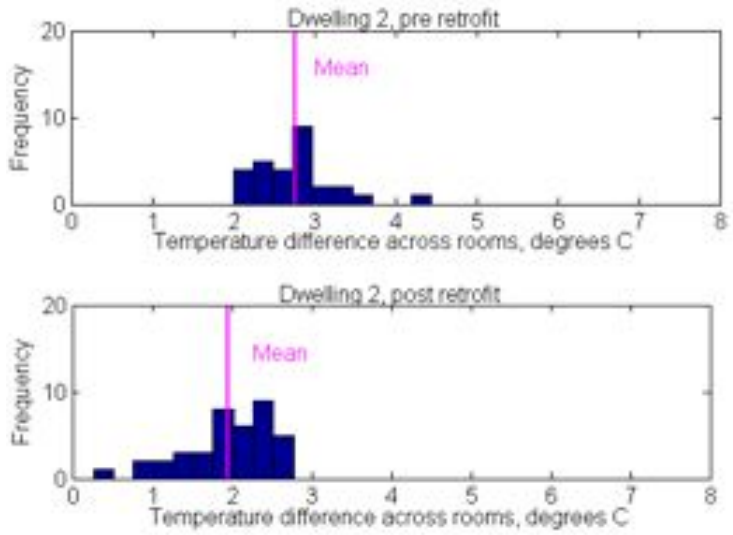



Figure 54: Example histogram of *inter-room temperature gradient*.

Across the eligible sample, the *inter-room temperature gradient* decreased in most dwellings. Table 15 shows the size of the change compared to the initial *inter-room temperature gradient* in each dwelling:

| Dwelling | Mean pre retrofit *inter-room temperature gradient*, degrees C | Mean change in *inter-room temperature gradient*, degrees C |
|---|---|---|
| 2 | 2.8 | -0.9 |
| 3 | 1.7 | 0.4 |
| 5 | 1.8 | 0.0 |
| 8 | 2.3 | -0.8 |
| 10 | 4.0 | -0.2 |
| 11 | 4.0 | -1.2 |
| 13 | 2.1 | -0.1 |
| Mean | 2.7 | -0.4 |

Table 15: Change in *inter-room temperature gradient* across the eligible part of the sample.

The changes in Table 15 are generally small compared to the pre retrofit *inter-room temperature gradient*. This might suggest that change in *inter-room temperature gradient* following building fabric retrofit is not an important phenomenon (although the changes are fairly consistently negative, so it may be important over a larger sample). However, before moving on to the next metric there are a few specific points of interest to note related to *inter-room temperature gradient*, concerning dwellings 10, 12, 2 and 1.

Firstly, it would appear that temperature changes due to an occupant no longer spending time in a room can outweigh temperature changes from building fabric upgrade. In dwelling 10, where the female occupant moved out between the monitoring periods, the temperature decrease in her former bedroom was larger than any other temperature change in the property over the two years. Similarly, the occupant of dwelling 13 changed which room she based herself in between the monitoring periods (from the kitchen to the living room). The temperature changes in the associated rooms are clearly visible in Figure 55: the blue and green lines swop places in terms of relative temperature.

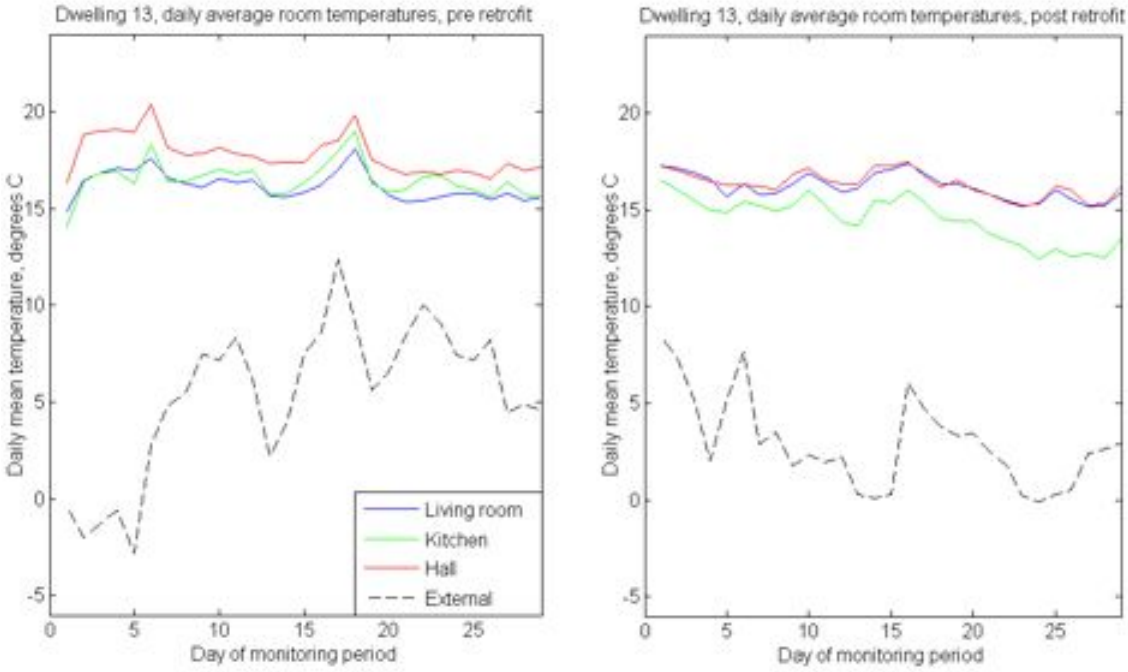



Figure 55: Temperatures of the rooms for which there are sensor data both years, dwelling 13.

Turning now to dwelling 2, Figure 56 shows a higher increase in temperature of the upstairs rooms (the bedrooms) than the downstairs ones:

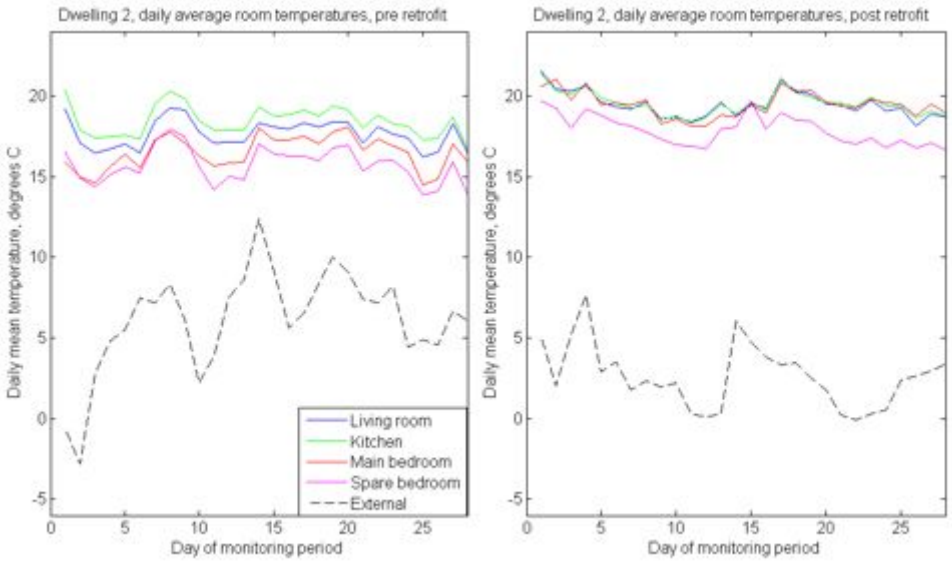



Figure 56: Temperatures of the rooms for which there are sensor data both years, dwelling 2.

The reason for the larger increase in the temperature of the bedrooms than other rooms is unknown. However, the general conclusion from this section is that other effects dwarf the effect of insulation when it comes to temperature gradient, and thus that the role of the physical mechanism introduced in Section 2.2.2.3 is probably a second order effect. However, a case study will be given later on in Section 9.4.4.2 in which inter-room temperature gradient itself is shown to be important in influencing occupant behaviour. This is an example of where a physical mechanism in itself does not make much of an impact on the internal environment, but it triggers an occupant response which does.

A final point to make, potentially of importance, is that contrary to BREDEM assumptions, the living room is not necessarily the warmest room in a given dwelling. In this small sample, there is in fact no pattern as to which rooms are warmest and coolest unless a household is known to use secondary heating in a given room.

Figure 57 illustrates this:

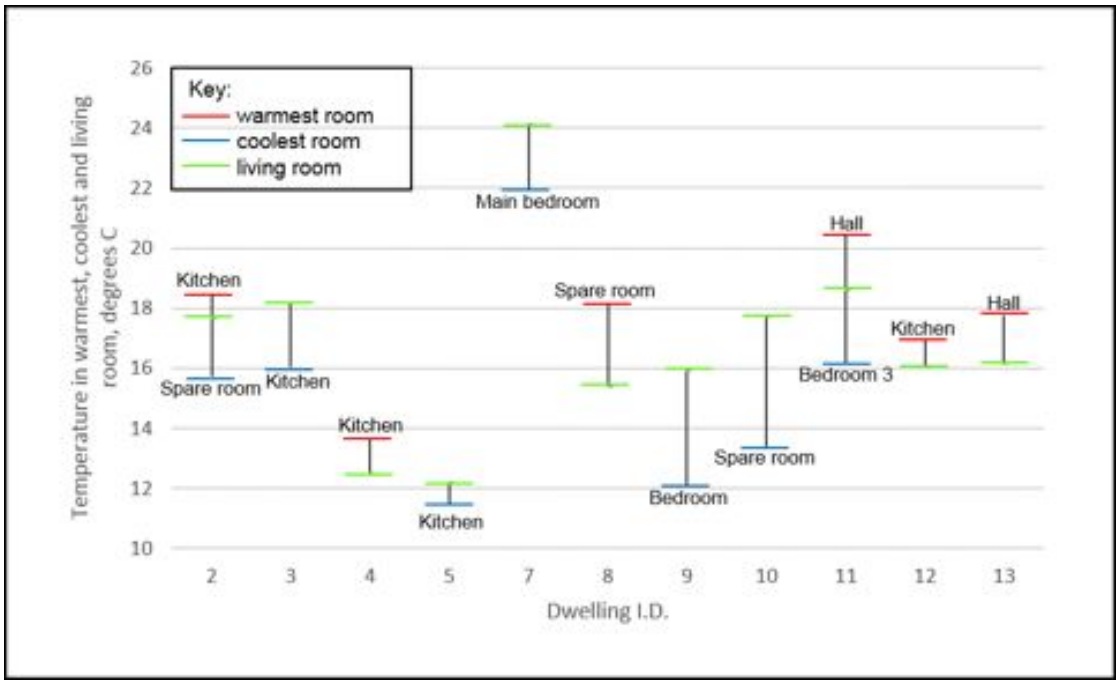



Figure 57: Warmest and coolest rooms across the sample pre retrofit; also showing the relative position of the living room.

## 8.6 M.I.T. VERSUS EXTERNAL TEMPERATURE

An important premise of this thesis is that values of measured variables, for example mean internal temperature and how it changes following retrofit, come about as a result of three interacting elements: occupant behaviour, heating systems and building fabric. Because of this, empirically observed values of such variables are likely to differ from modelled values, which originate from holding certain elements constant. One such variable which is assumed to be constant in SAP is number of *daily heated hours*. This section will challenge this assumption using evidence from the case study dwellings, and show the impact on mean internal temperature.

In Chapter 2, a possibility space of mean internal versus external temperature was mapped out, reproduced in Figure 58:

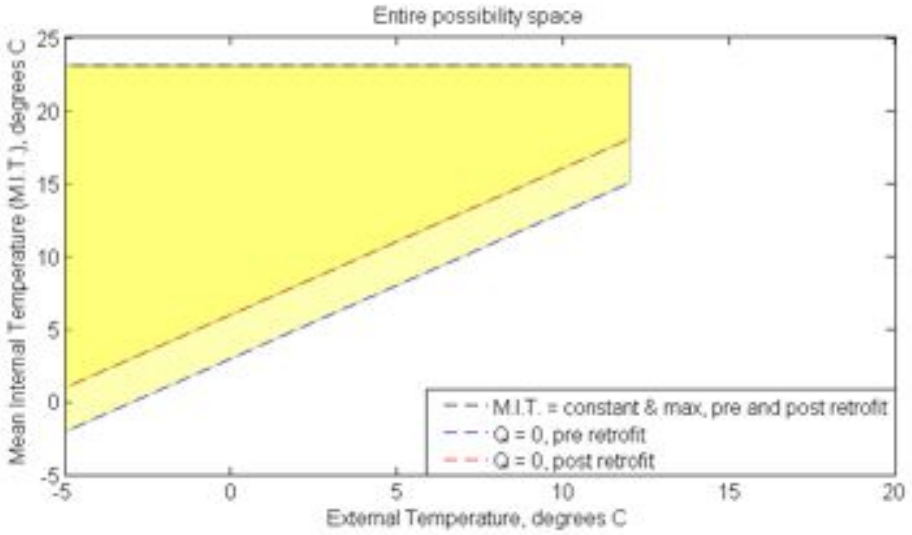



Figure 58: Bounded possibility space of internal versus external temperatures.

If occupants behaved according to the SAP assumption of constant *daily heated hours* throughout the heating season as shown in the left hand subplot of Figure 59 below, this would result in the internal versus external temperature profile on the right hand of the figure:

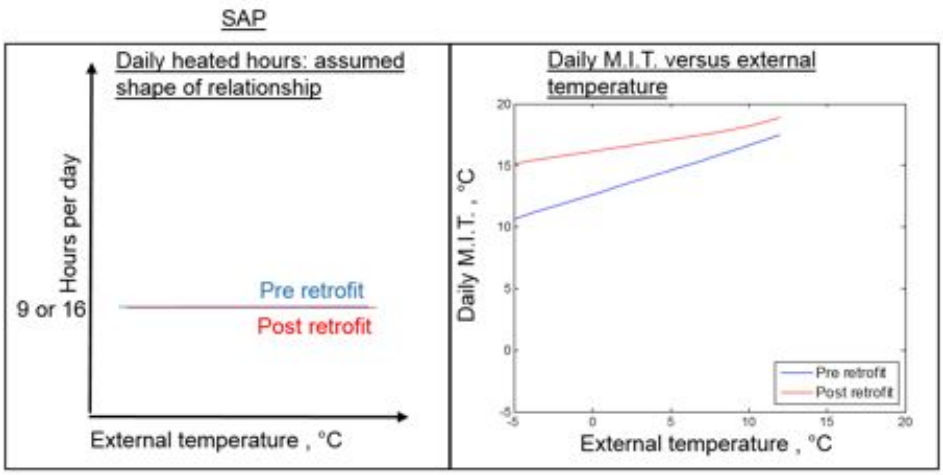



Figure 59: SAP assumptions for *daily heated hours* (left) and resulting *M.I.T.* (right).

The next three figures will show that the observed *M.I.T.* versus external temperature profiles within the case study sample not only span almost the entire possibility space, they are also associated with different types of *daily heated hours* profile.

The most common relationship between *daily heated hours* and external temperature is negative: that is, *daily heated hours* increased as external temperature decreased. Of the

part of the sample for which there is heating use and air temperature data (12 out of the 13 dwellings), two thirds of them manifested this behaviour. An example from dwelling 3 is as shown in Figure 60. The left hand subplot is the *daily heated hours*, and the right hand subplot is the resulting *M.I.T.* profile.

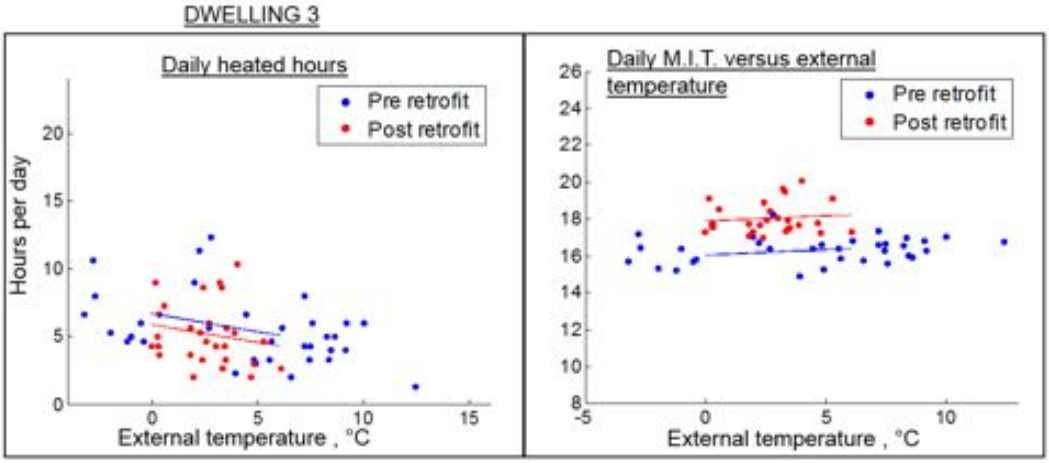



Figure 60: Dwelling 3, exploring the relationship between daily heated hours (left) and M.I.T (right) with external temperature.

The negative relationship between daily heated hours and external temperature seen across most of the sample (especially in the pre retrofit case - post retrofit the relationship is often flatter) contrasts with the SAP assumption of constant daily heated hours. In the next chapter, evidence is given to show that homes being heated for longer on colder days was a likely result of the fact that heating timing was carried out by manual heating control (see Section 7.9) as opposed to an automatic timer. Depending on the setting and/or use of the thermostat, this behaviour of changing number of daily heated hours according to external temperature can result in the *M.I.T.* versus external temperature profile being either similar to the SAP one in Figure 59, or flatter. The latter is the case for dwelling 3.

Figure 60 represents the most common shape of the daily heated hours versus external temperature profile, but is not the only shape. Two more examples will be given to show the extent of variation within the sample.

The occupant of dwelling 5 used an electric bar heater pre retrofit and a gas fire post retrofit as his main heating sources. These were both devices of constant power output. The left hand subplot of Figure 61 shows that there was no clear increase in hours of heating with decreasing external temperature. This combination of constant power

during heated hours and constant number of heated hours leads to the *M.I.T.* profile in the right hand subplot of Figure 61.

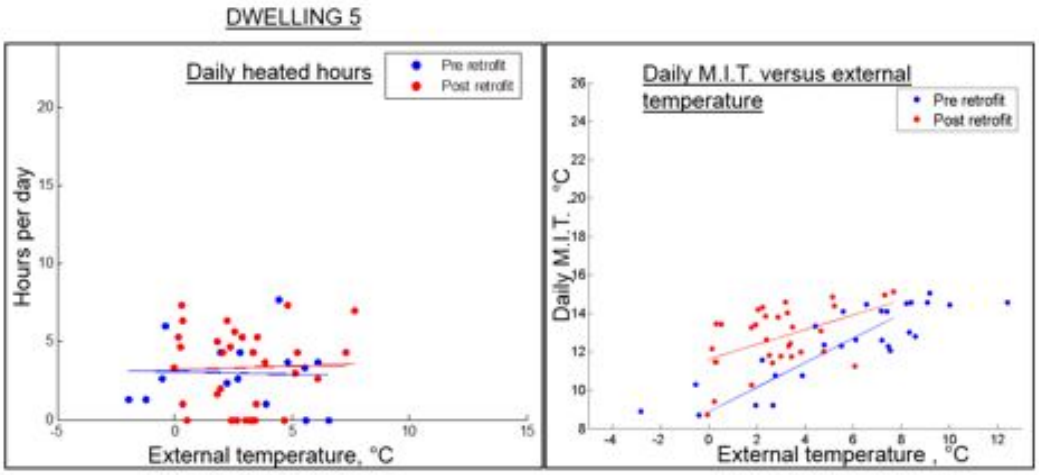



Figure 61: Dwelling 5, exploring the relationship between *daily heated hours* (left) and *M.I.T* (right) with external temperature.

Conversely, the pre retrofit occupants of dwelling 7 kept their heating on all the time, at a high *achieved demand temperature*, giving the M.I.T. profile shown in Figure 62 (the post retrofit occupants used heating in differently; only the pre retrofit case is shown here since this dwelling represents the upper extreme of heating behaviour):

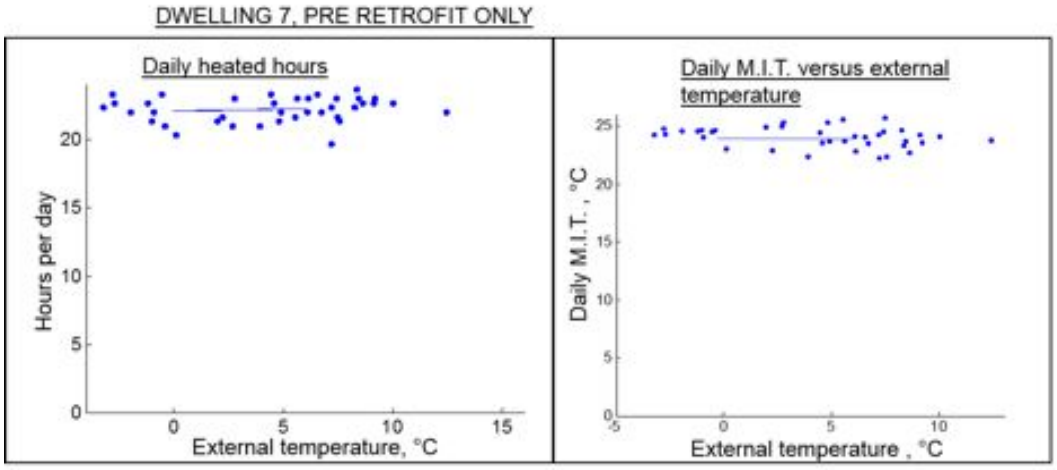



Figure 62: Dwelling 7, exploring the relationship between daily heated hours (left) and M.I.T (right) with external temperature.

The three types of *M.I.T.* profile, along with the SAP M.I.T. profile, are now superposed onto the possibility space, to yield Figure 63:

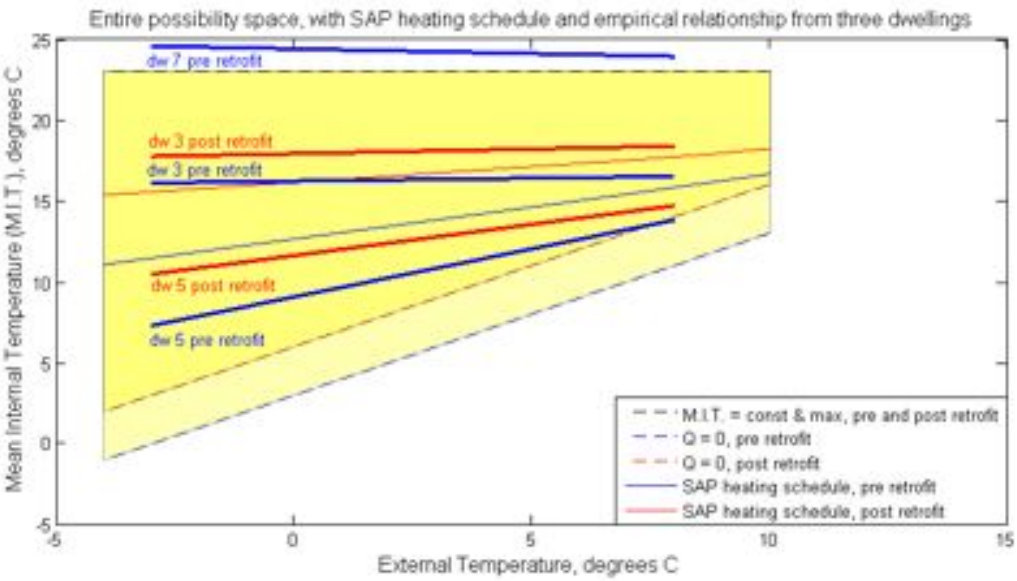



Figure 63: Possibility space of internal versus external temperatures with SAP and three dwellings.

From Figure 63, it can be observed that even from a small sample of 13 case study dwellings, the variation in *M.I.T.* profile spans most of the possibility space. In fact, dwelling 7 (pre retrofit) lies outside the preconceived possibility space. Furthermore, the most common profile occurs as a result of *daily heated hours* decreasing with increasing external temperature. Both of these observations will be returned to in Chapter 11.

## 8.7 SUMMARY

This chapter set out to answer Research Question 1: how internal temperature changes after retrofit, during heating and non-heating hours and throughout the dwelling. It was found that the *M.I.T.* increased in most dwellings following retrofit. This was mostly due to unheated hours becoming warmer, partly because unheated hours made up most of the time. *Daily heated hours* generally decreased, but *achieved demand temperature* was higher. There was not a pattern of which rooms warmed up more than others, or even which were warmer in the first place. There was however generally a negative relationship between *daily heated hours* and external temperature, indicating occupants switching the heating on and off as opposed to use of a timer.

In attempting to explain what happened after retrofit, it is clear that this type of analysis of monitored data has its limitations. For example, this data cannot explain why there is a negative relationship between *daily heated hours* and external temperature, or why *achieved demand temperature* increased following retrofit. The next chapter will overcome these limitations by the introduction of the qualitative data into the analysis. What this type of analysis has been able to suggest, however, is that normative models do not currently capture the complexity of real-world occupant behaviour.

# 9

# RESULTS 2: WHY MEAN INTERNAL TEMPERATURES CHANGE

## 9.1 INTRODUCTION

Having described in the previous chapter the quantitative characteristics of the *M.I.T.* in the case study dwellings before and after retrofit, the next part of the analysis will be devoted to why those outcomes occurred, in order to answer Research Question 2:

In social housing undergoing building fabric retrofit,

2) If internal temperature changes afterwards, why? What are the interactions between occupants, building fabric and heating systems which produce the temperature change?

Research Question 2 is answered in this chapter by means of a cross-case analysis. Before this is presented, two example case studies are given. This is so that the reader can gain an idea of the type of insight emerging from combining physical and social data streams within each case study. That is, the individual case study's role here is a way to understand interactions in detail before being able to undertake a cross-case comparison in which the bulk of the findings are drawn out. The individual case studies do not directly answer the research questions themselves but are a necessary step towards answering them.

## 9.2 PRESENTATION OF TWO EXAMPLE CASE STUDIES

### 9.2.1 *Format of the case studies*

The case studies, of which two are presented here and the rest can be found in Appendix A, are all written up in the same standard format. The order is as follows:

- A general introduction to the household, constructed primarily from what the occupant said during the interviews and occasionally supplemented with thoughts and impressions of the author (who was the interviewer). This is to give context to the rest of the analysis.

- A table of physical information about the dwelling.

- A summary of the occupant's comments on standard topics. These topics are more specifically related to heating and retrofit than the general introduction.

- Observations from the monitored data. By this point, given the above sections, there is some context to the graphs presented. However, sometimes a given graph will seem to contradict an aforementioned occupant statement, so this section is also used for triangulation purposes to note where interpretation of a graph requires even more care than usual. Up to this point the topics to be investigated are the same for each household.

- A section on further analysis, which is different for every household.

- A proposed causal mechanism for the observed change in mean internal temperature following retrofit. This begins each time with the building physics assumption that the dwelling internal temperature rose naturally upon being made more efficient, and goes on to propose what happened next.

- Where the evidence is less clear, discussion of the validity of the proposed mechanism.

- A discussion of interesting other themes which came up from the data for the houshold in question.

## 9.3 FIRST EXAMPLE CASE STUDY: DWELLING 1

### 9.3.1 *Context of the household*

The occupant of dwelling 1, a two-bedroomed ground floor flat, was a single mother from Rwanda with two British born primary school aged children. She was studying from home to become an accountant but at the time did not have much money. She was concerned about being able to find a job which would allow her to look after her children, since the only time she received help from their father was at weekends.

In the winter before the retrofit, cold was very much on her mind and seemed to affect many aspects of her life at home. There seemed to be several trade-offs involving cold. Firstly, she felt she had to heat her home adequately otherwise the children would suffer, but this cost a lot so compromised taking the children out. Secondly, she wanted to let in fresh air, but did not open the windows for long so as not to let in the cold. Since the radiators did not give out much heat, she had several strategies: top up the central heating with a fan heater, wear extra clothes, allow the children to spend time in her bedroom which was the warmest room (the children did not like being in their bedroom as it was too cold), or close off the living room from the rest of the flat. They enjoyed being together in the same room, talking and laughing together, so she did not mind them coming to play in her room. She had resigned herself to the fact that she lived in a cold flat, although she wanted to get someone to come and look at the radiators. She was really looking forward to the works making the house warmer, since the family spend a lot of time at home.

By the time of the post retrofit interview, her flat felt very different to her and she was delighted with the change. Although she had not previously complained about being in the same room as the children, she was now able to study in a different room to them whilst keeping the doors open to keep an eye on them. Heating still revolved around the children although they had not noticed the difference in warmth.

Although she felt that the RSL responded well to problems, no one throughout the two years had ever given her information on how to use a central heating system or its constituent components, and in that way she resented no longer having the night storage system present in a previous house, which allowed the house to be warm all day. One could wonder whether, due to her African background, she had in fact never lived in a property with a central heating and thermostat system before.

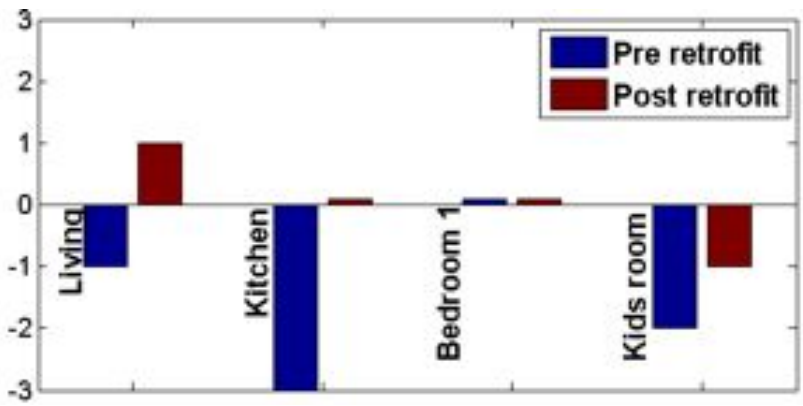
| | |
|---|---|
| Rooms present | Living, kitchen, bedrooms 1 and 2 (comprising of mother's bedroom and kids' bedroom) |
| Rooms with complete longitudinal air temperature dataset | Living. This was because the children moved all the sensors into the living room in the pre retrofit monitoring period. For this reason the M.I.T. and all calculations using it only take into account the living room. |
| Primary heating system | Gas central heating with T.R.V.s |
| Secondary heating system | Gas fire in the living room, portable electric fan heater normally in bedroom 1. Not monitored as nowhere to put the logger given that the heater was portable. |
| Location of thermostat | Hall |
| Retrofit measures undertaken | E.W.I. and double glazing |
| Zone 1 *achieved demand temperature* increase | 0.2°C |
| *Daily heated hours* increase | -6.5 hours |
| *M.I.T. increase* | 1.9°C |

Table 16: Physical characteristics of dwelling 1.

### 9.3.2 *Summary of occupant comments on standard topics*

Table 17: Dwelling 1, occupant responses to standard topics

| | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How heating was switched on/off | Press 'on' or 'off' at programmer | Press 'on' or 'off' at programmer |
| Heating timing | When the children were in | When the children were in. i.e. 2 hours in the morning, 15.30 to 19.00 in the evening. |
| Thermostat | Left at Max, i.e. >30 | Left at Max, i.e. >30 |
| Radiator valves | Not adjusted | Sometimes bedroom one was switched off if it became too hot |
| Secondary heating | An electric heater which was carried between the main bedroom and living room. It was put on either in addition to the central heating (CH) when the dwelling felt very cold, or instead of the CH, but it was very expensive to run. | An electric heater which was only used when the occupants come in after being out, to warm the living room up quickly |

| | | |
|---|---|---|
| Other related factors which changed apart from the retrofit | Work was undertaken on the radiators to make them hotter. The occupant was not sure what this work was. | |
| Temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Hopes/expectations of works (2012); opinion of what changed after the works (2013) | Did not exactly know the purpose but had been to someone else's house which had been insulated, and it was warm, so she was expecting the same. | It was both warmer and used less energy. |
| What constitutes energy saving | | Energy saving lights /switching off lights. |
| Perception of change (or lack of) in own heating behaviour following the retrofit | No longer had the heating on all day. No difference in window-opening behaviour. | |
| Perception of how long it takes to warm up and cool down, and difference after retrofit | Warm up – 30 mins but it was still not warm. Cool down – immediately. | Warm up – 10 minutes Cool down – about an hour. |

### 9.3.3 *Observations from monitored data*

Before starting this section, the reader is reminded of two facts about this particular property which differentiate it from the others in the sample. Firstly, it transpired that work had been carried out on the heating system at some point between the monitoring

periods as well as installation of insulation and double glazing. Secondly, the mean internal temperature is replaced by the living room temperature in the following analysis, since in the pre retrofit monitoring period the temperature loggers were all moved to the living room by the children.

Figure 64 demonstrates an increase in internal temperature following retrofit, despite a dramatic reduction in *daily heated hours* as shown in Figure 65:

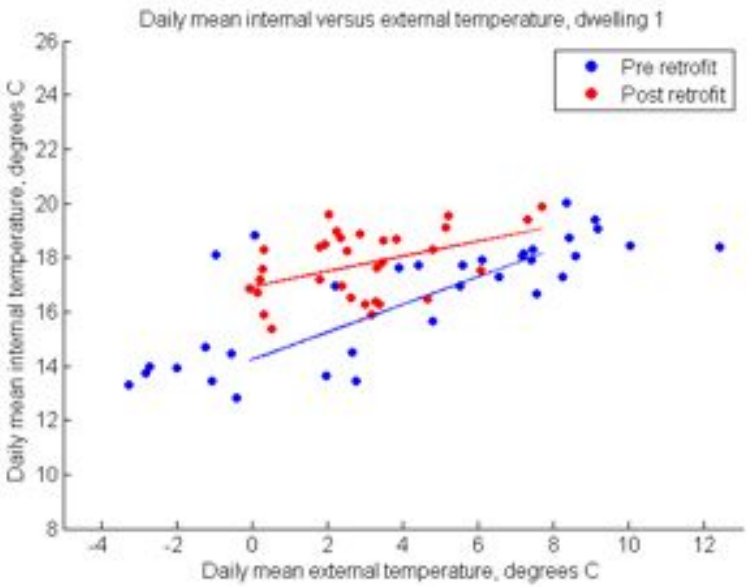



Figure 64: Dwelling 1, *mean internal temperature*.

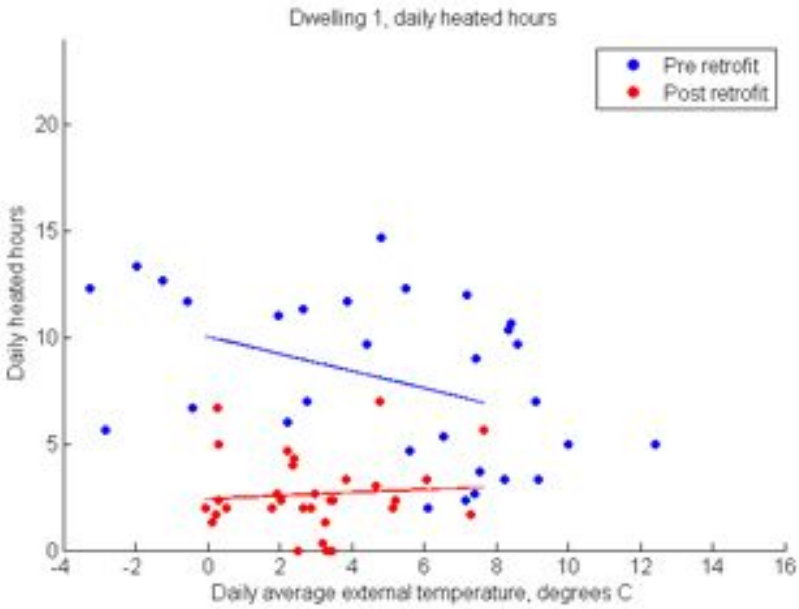



Figure 65: Dwelling 1, *daily heated hours* against external temperature.

This property exhibits a so-called 'double dividend' of shorter heating hours and a warmer dwelling. The reader is reminded once again that this is thought to be contributed to by an increase in the efficiency of the heating system, and also that the 'M.I.T.' here is in fact the living room temperature only.

Figure 66 shows that the increase in temperature of unheated hours was greater than that of heated hours.

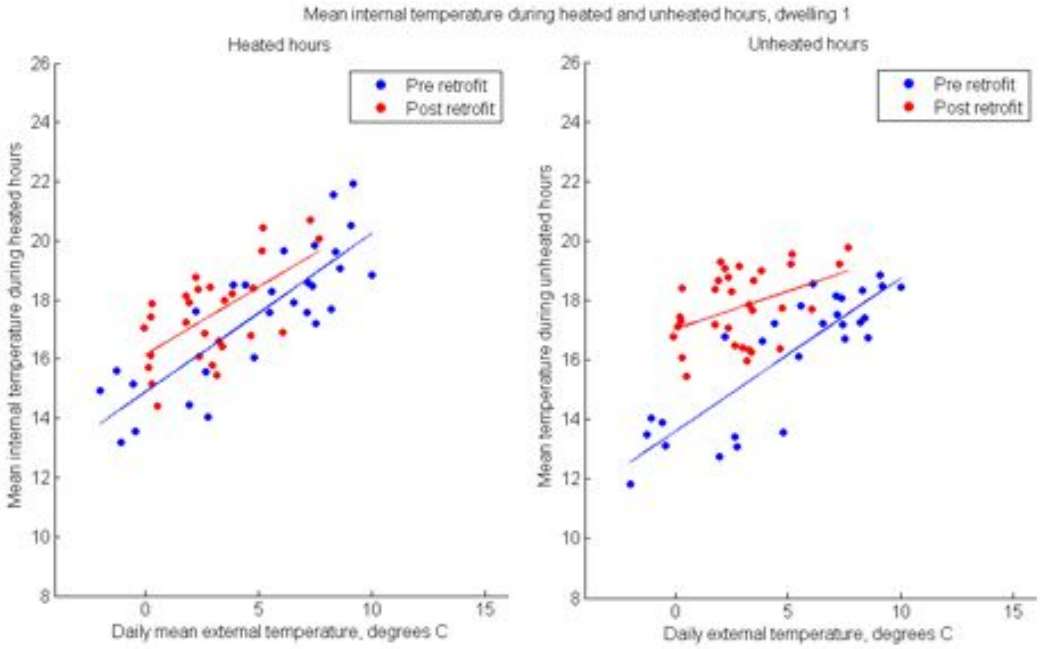



Figure 66: Dwelling 1 temperature during heated and unheated hours.

Figure 67 shows that the *M.I.T. increase* was made up mostly of unheated hours, but also of a significant proportion of previously heated hours which became unheated. As explained in Section 7.15.2.1, error is only shown on the total *M.I.T. increase* as the multi-stage calculation process on the attribution process to heated and unheated hours causes the error to increase; the reader is advised to interpret these results with caution.

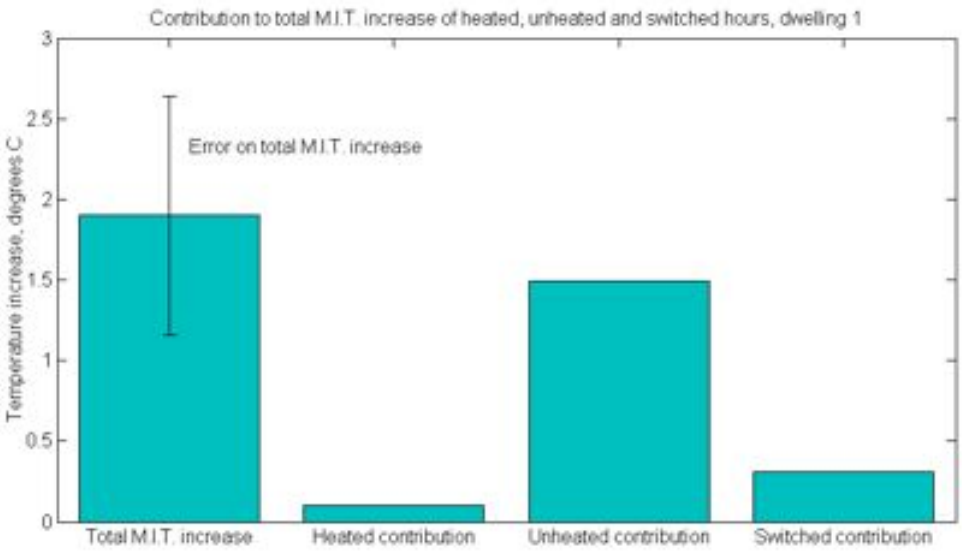



Figure 67: Dwelling 1, attribution of *M.I.T. increase* to different types of hour.

The existence of a positive switched contribution to *M.I.T. increase* in Figure 67 indicates that unheated hours post retrofit were warmer than heated hours pre retrofit.

After retrofit, heating was not being switched off at higher temperatures, but was sometimes coming *on* at higher temperatures (Figure 68). Part of this may be the result of night cooling occuring more slowly (Figure 69), but this is a qualitative inference only as the lines in Figure 69 are not straight and therefore a time constant cannot be extracted from their gradients.

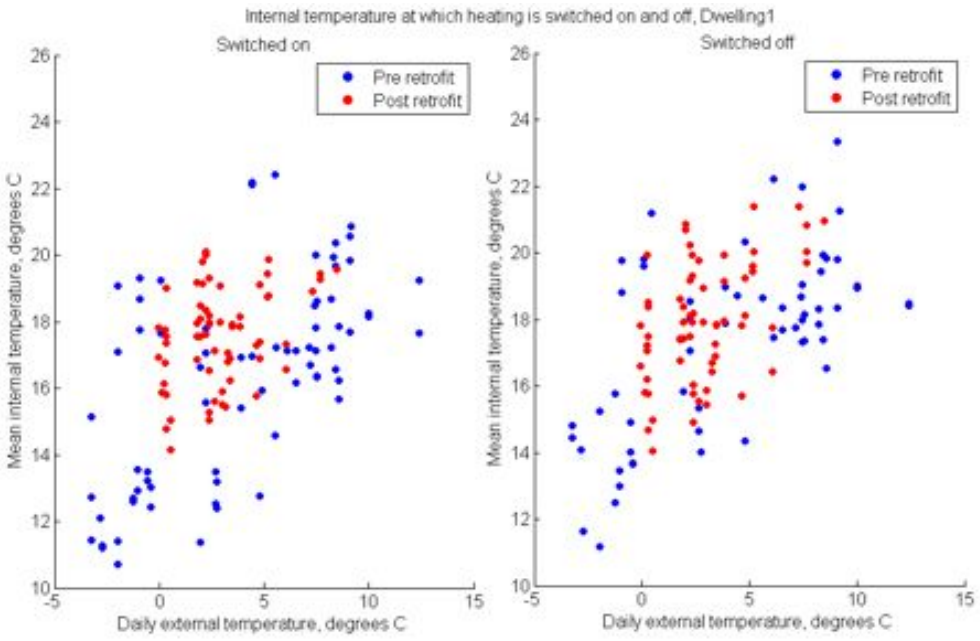



Figure 68: Dwelling 1, temperature at which heating switched on and off.

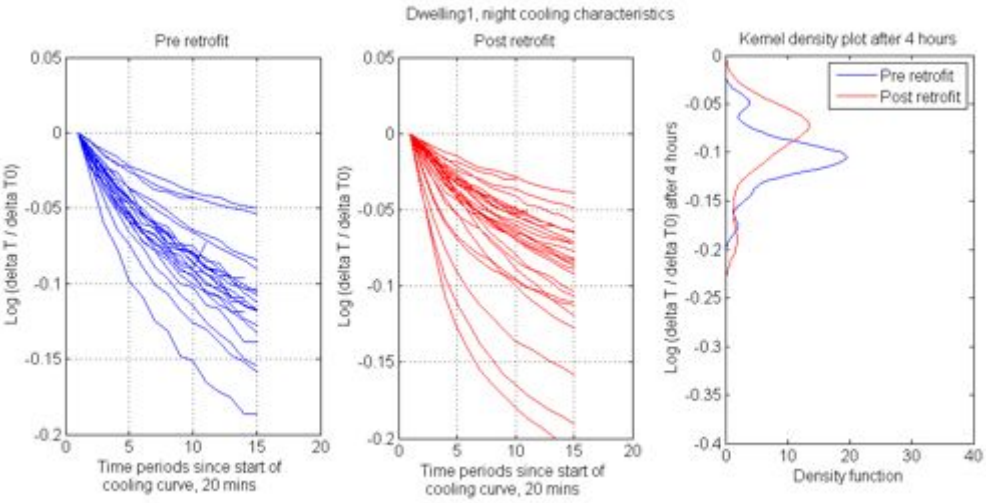



Figure 69: Dwelling 1, log plots of night cooling.

### 9.3.4 *Further analysis (mixed methodology)*

#### 9.3.4.1 *Heating revolved around the children*

It is useful to consider some of the occupant's statements about why she used heating, given that she had strong opinions on this without being prompted. She was insistent

that the heating pattern revolved around the children's occupancy, and made some comments implying that they were the reason the dwelling had to be warm:

*"I have to put [it on] or the children suffer"* (dwelling 1, pre retrofit).

However, before retrofit there was a lot of time when the heating was on whilst the children were not in. By the post retrofit monitoring period, this had changed so that the heating was no longer on very much during the daytime, nor when the children had gone to bed. She was now able to be warm enough herself throughout the day by just heating when the children were in, or even just part of this time. This change can be seen in Figure 70, which is a probability density plot of heating state (on or off) against time of day, as first introduced in Figure 8 (Section 3.3.3).

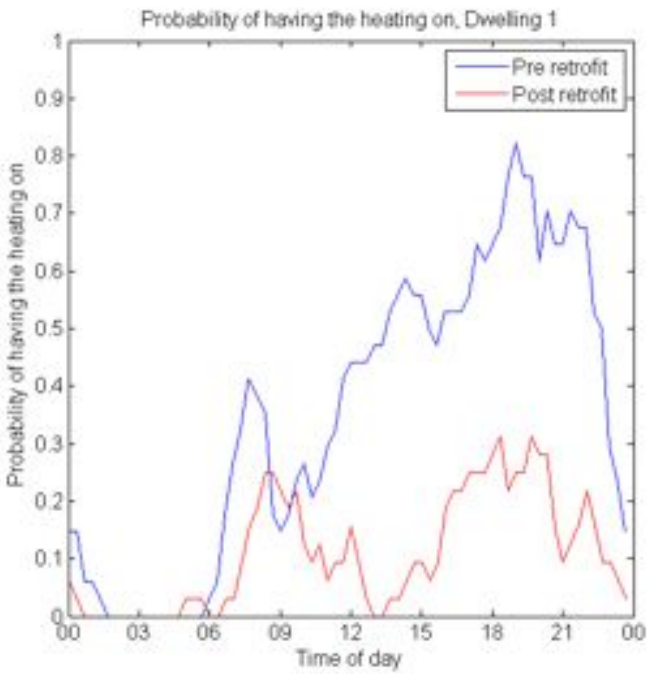



Figure 70: Probability the heating is on at different times of day, dwelling 1.

Furthermore, by plotting the times of switching heating on and off against time of day, it is possible to discern to what extent the occupant's statements about the children being the reason for using heating could be seen in the monitored data, and whether there was a change following retrofit. This is shown in Figures 71 and 72.

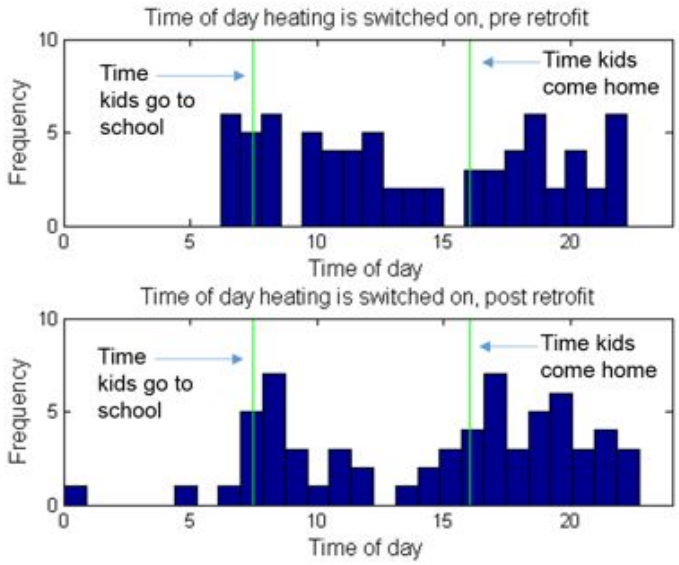



Figure 71: Dwelling 1, time the heating is switched on.

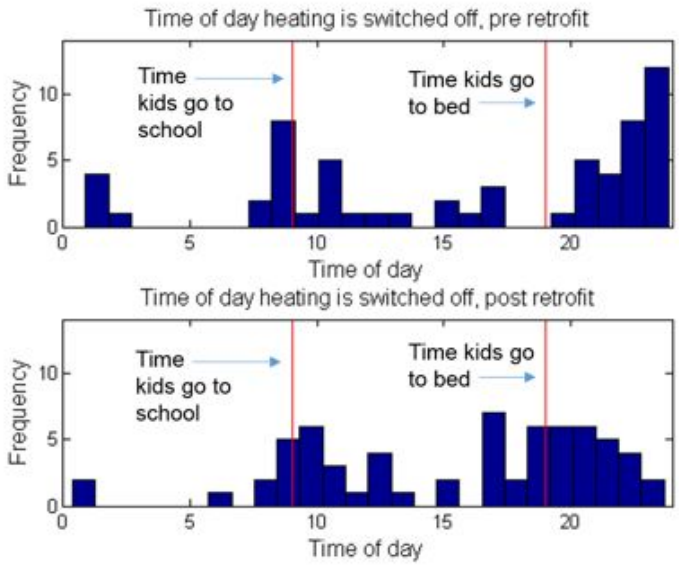



Figure 72: Dwelling 1, time the heating is switched off.

Figures 71 and 72 indicate that prior to retrofit, heating could be turned on or off at almost any time during waking hours, but that post retrofit it followed the occupancy

of the children more strongly. It seems that although the 'heating needs' in this dwelling consist of both herself and her children, before retrofit she had to use the heating to fulfil both needs, whereas after retrofit she could operate the heating around the children and there would be enough residual heat left in the house to meet her needs too.

#### 9.3.4.2 *Heating system*

During both the pre and post retrofit monitoring periods, the occupant had the thermostat set on maximum and did not alter it, so after retrofit the heating system did not do anything differently itself in terms of control. The evidence for this is Figure 73 and the accompanying example quote which is one of several demostrating between them that the thermostat was never altered.


Figure 73: Dwelling 1 thermostat.

*Occupant: It's not working, I don't use. [...]*
*Interviewer: "Do you know even what it is?"*
*Occupant: "No."* (Dwelling 1, post retrofit)

However some work, separate from the retrofit, was done on the heating system which seemed to increase its heat output. Before the retrofit the radiators did not appear to be very hot:

*Occupant. "They are not really hot. I am trying to talk to them about how they are..."*

*Interviewer: "How long does the flat take [to warm up]?"*

*Occupant: "It take, like, 30 minutes. Cos I'm trying to not cover the heater, you can see. But it's still not enough."* (dwelling 1, pre retrofit)

The impression of insufficient delivered heat was likely to be a result of both inefficiency in the heating system and the high heat loss of the dwelling fabric - the heating system could not cope.

One year later, the occupant reported an intervention to the heating system which had increased the effectiveness with which they delivered heat:

*"No, they didn't change the system, but there was something there, you could sit by the radiator but it was never warm. But now since they changed it you can even feel".* (dwelling 1, post retrofit)

Given that the thermostat was set at maximum, this apparent increase in heating system efficiency could have increased the temperature during heated hours. However, this only occurred to a small extent as the occupant reduced the mean heating period length as well as the *daily heated hours*. It is therefore likely that the reason she was leaving the heating on for longer pre retrofit was to try and deliver enough heat into the dwelling.

### 9.3.5 *Proposed causal mechanism*

In this section, the information presented so far is drawn together in an attempt to deduce what occurred after the dwelling fabric was upgraded, in terms of occupant behaviour, the building fabric, the setting of the heating system and the reaction of each of these elements to a change in another.

The proposed causal mechanism following retrofit is given in Figure 74. The likelihood of this being the correct explanation is then discussed in Section 9.3.5.1.

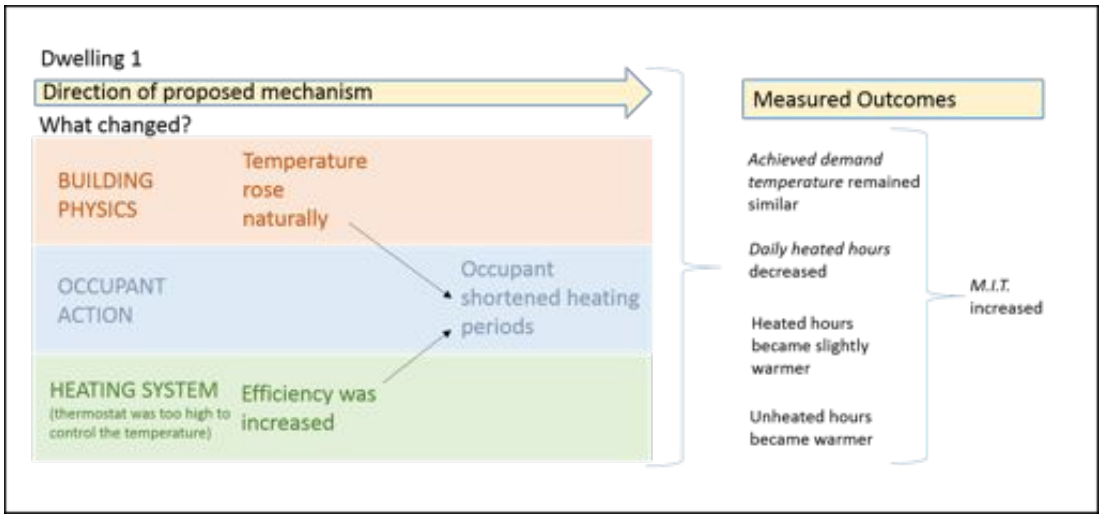



Figure 74: Dwelling 1, proposed causal mechanism leading to observed outcomes.

#### 9.3.5.1 *Validity*

The weak point of this proposed causal mechanism is knowing exactly why the occupant shortened the heating hours, which it is very evident that she did. Asking more direct questions about triggers for switching off the heating might have helped ascertain her perspective on this. However the monitoring data might shed light here: it is extremely interesting that she switched off the heating at about the same internal temperature pre and post retrofit (or perhaps even lower after retrofit). This perhaps suggests the existence of a comfort temperature, at which demand for heat is satisfied. The temperature in this dwelling was then not controlled by the thermostat but a 'human comfort stat' (a concept named by Tadj Oreszczyn, 2013).

### 9.3.6 *Other interactions*

#### 9.3.6.1 *Use of space*

The self-reported use of space of this household changed. This will now be described. Please note that there is no occupancy sensor data for this dwelling, due to a combination of the children removing the sensors in the pre retrofit monitoring period and their mother not wishing them to be installed in the later monitoring period.

Before retrofit, the children used to come into their mother's room to play as it was the warmest room. She had not minded this since they enjoyed being all together. This has been previously documented in the literature in Gilbertson et al. (2006), where in fact the mother felt lonely following the installation of central heating as her teenage children spent more time apart from her in their bedrooms. However in this case study there was not a sense of loss following the retrofit: the occupant was able to work in her room and leave the children in the living room, with the doors between the two spaces left open so that she could keep an eye on them. In this way, use of space and zoning of spaces both changed.

To further investigate the above, it would have been interesting to see how much the temperature gradient between the living room and bedroom had changed. However there was no temperature gradient data from this dwelling, nor occupancy sensor data. Thus, in this case the self-reported data has to be relied upon by itself.

### 9.3.7 *Conclusion to Case Study 1*

This dwelling underwent a *M.I.T. increase* of 1.9°C ± 1.5°C. This occurred with only slight increase in *achieved demand temperature* and a reduction in *daily heated hours* (of 6.2 hours) This is sometimes known as 'double dividend' - the occupant can experience a warmer home with less heating. This dwelling is different from the others in that as well as the physical works, it transpired during the post retrofit interview that the efficiency of the heating system had been increased.

Looking more closely at the *M.I.T. increase*, not only did most of it occur in unheated hours, 16% occured in hours which were previously heated becoming unheated (Figure 67). This means that unheated hours post retrofit were warmer than heated hours prior to retrofit. The significance of this phenomenon is that even though the occupant had dramatically reduced her heating hours, there was still an increase in mean internal temperature, for which it could be argued that the occupant was not responsible (as the only way for it not to occur would perhaps be to eliminate heating altogether, or nearly so).

Although the occupant did not comment to a large extent about cutting down on heating use, it was not the thermostat which led to the large reduction but her own behaviour. It can be seen in Figures 71 and 72 that her heating pattern pre-retrofit involved heating when the children were in and when she was in, whilst after retrofit she heated just when the children were in. It appears that there was enough residual heat from the latter to heat herself when the children were not in. Although this is a simplified version of events, it shows there existed a minimum level of heating below which this occupant would not be prepared to compromise: it had to be warm when the children are in.

The occupant carried out the role of the thermostat - a 'human comfort stat' - by switching off the heating at the same temperature after retrofit as before. She did not know the 'proper' way of using a heating system, yet was aware of when enough heat had been delivered to satisfy her demand. Although this indicates that energy savings following retrofit are possible without heating systems being operated in the way they were designed, it could be argued that this is not a guaranteed outcome across all dwellings, since in most of the case study dwellings in which the temperature was controlled without the thermostat there was an increase in temperature during heated hours.

An additional point to highlight from this case study is that the heating system had been unable to deliver enough heat to offset the pre retrofit heat loss. Most modelling

assumes that the heating can achieve the desired heat output; this was achieved in the end in this dwelling after both the insulation and work carried out on the heating system.

## 9.4 SECOND EXAMPLE CASE STUDY: DWELLING 2

### 9.4.1 *Context of the household*

Dwelling 2 was a three-bedroomed terraced house occupied by a middle-aged cohabiting couple and their grown-up son. At the time of the pre retrofit monitoring period all of them were unemployed, having mostly been part of industries which moved away from the Midlands; by the post retrofit monitoring period the woman had found some part-time work. In this latter period, the woman was not fully aware of what her son was up to; he would come in and out. Her granddaughter was present twice a week too – so all in all different family members were in the house at different times. However, she alone was the registered tenant, so the spare room tax was about to hit her hard. She was fiercely determined to stay, even though she disliked how cold and dingy the house was, as she felt it was hers and she had the right to a family house.

Pre retrofit, illness and low temperatures seemed to be affecting the woman's health in a vicious cycle: she had Chronic Obstructive Pulmonary Disease (C.O.P.D.) and could not work, so she had to spend more time at home, and although the doctor had told her to keep the temperature at 18°C, she could not afford to do this, so could not recover. She had been in and out hospital during the pre retrofit winter.

This dwelling had extreme mould and damp. Although one way to alleviate it would be to ventilate the property adequately, when it came to whether to open the trickle vents there was conflict between the aims of obtaining fresh air and retaining warmth.

There were several ways in which, even though the occupants felt that the house was very cold, other priorities came before temperature. For example, they had been advised to close the living room door so that they could be warm in that room, but they chose to replace the door with an archway. Another example involved their use of space – if the occupants wanted to watch two different TV channels, the man would go upstairs to the colder bedroom. A third example was that they felt the spare room was the warmest room but had not used it since their daughter, whose room it used to be, moved out.

Into this context came the insulation – the man had been expectant that it would clear up the damp. However the effect of the works seemed to be to emphasise the temperature difference between their room and the rest of the house, and to make the damp in the bathroom worse than it had ever been.

For the woman, the effect of the insulation meant that she operated the thermostat differently so that not as much gas was used any more. She had her own mental model of how the heating system operated, and it worked for her.

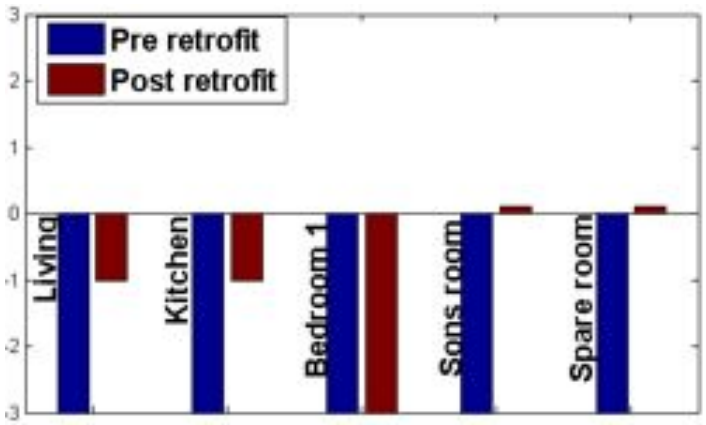
| | |
|---|---|
| Rooms present | Living, kitchen, bedrooms 1 to 3 (comprising of main bedroom, sons's bedroom, spare bedroom respectively) |
| Rooms with complete longitudinal air temperature dataset | Living, kitchen, bedroom 1, bedroom 3. |
| Primary heating system | Gas central heating with T.R.V.s |
| Secondary heating system | Gas fire in the living room, replaced by an electric fire after retrofit (chosen by RSL not occupants). |
| Location of thermostat | Upstairs landing |
| Retrofit measures undertaken | E.W.I. |
| Zone 1 *achieved demand temperature* increase | 3.2°C |
| *Daily heated hours* increase | 0.6 hours |
| *M.I.T. increase* | 2.6°C |

Table 18: Summary physical information about dwelling 2.

### 9.4.2 *Summary of occupant comments on standard topics*

Table 19: Dwelling 2, occupant responses to standard topics

| **Theme** | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How was heating switched on/off | Press 'on' or 'off' at programmer. | Press 'on' or 'off' at programmer. |
| Heating timing | Would never have it on a timer – that would cost too much.<br>- Morning<br>- 6pm, or before they went to bed at 10pm | Sometimes in the morning, always in the evening, especially before they go to bed. |
| Thermostat | The man reported that it just stays where it is. | The woman reported that before the retrofit it was at 30 but following the insulation, she set it at 25 or 22 depending on how cold it was outside, since 30 felt stuffy. |
| Radiator valves | All rooms heated on maximum setting, except the kitchen which in warmer weather was turned down to 3/5. | All on maximum setting, except the kitchen which in warmer weather was turned down to 3/5. |

| | | |
|---|---|---|
| Secondary heating | The gas fire in the living room did not make a difference, unless the kitchen door was closed and the fire kept on for half an hour. | |
| Other related factors which changed apart from the retrofit | The gas fire in the living room was replaced by an electric one against the occupants' will; the new one was very expensive to run. The woman worked part-time by the time of the post retrofit interview. | |
| Occupants' opinion of temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Hopes/expectations of works (pre); opinion of what changed after the works (post) | They hoped to be warmer and less damp. The man had been to someone else's house where the occupants had been able to be warmer at the same time as having the heating on less. | The house kept the heat in better, but the damp was worse, and their bedroom was still cold and did not retain heat. |
| What constitutes energy saving | They were "too poor to be energy efficient".<br>External wall insulation was similar to putting a jacket on the house, so surely that would help keep the heat in. | |
| Perception of change (or lack of) in own heating behaviour | None apart from the thermostat setting (which was turned down, as post insulation the air felt stuffy). | |
| Perception of how long the dwelling took to warm up and cool down | Warm up – 30 minutes. Cool down – pretty much immediately. | Warm up – 10 minutes Cool down – about an hour. |

### 9.4.3 *Observations from monitored data*

Figures 75 and 76 show an increase in *M.I.T* and a possible slight increase in *daily heated hours* respectively.

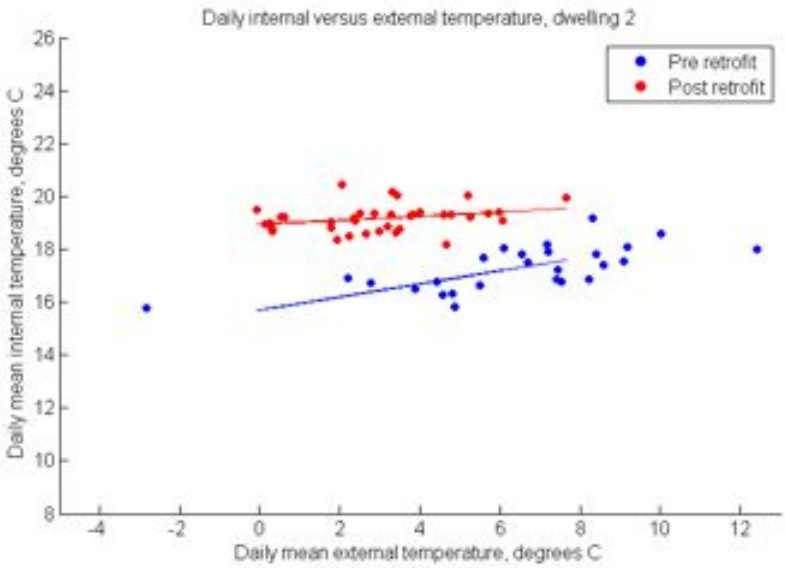



Figure 75: Dwelling 2, *mean internal temperature* versus external temperature.

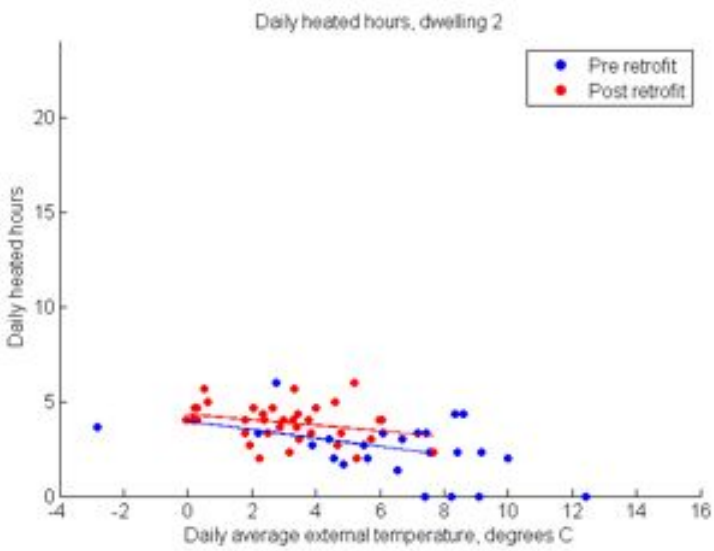



Figure 76: Dwelling 2, *daily heated hours* versus external temperature.

It is instructive to look more closely into heating use by considering when heating is likely to be on. Figure 77 demonstrates that pre retrofit there were often two heating

periods, and post retrofit the first of these was less likely to occur and the second more likely and possibly longer.

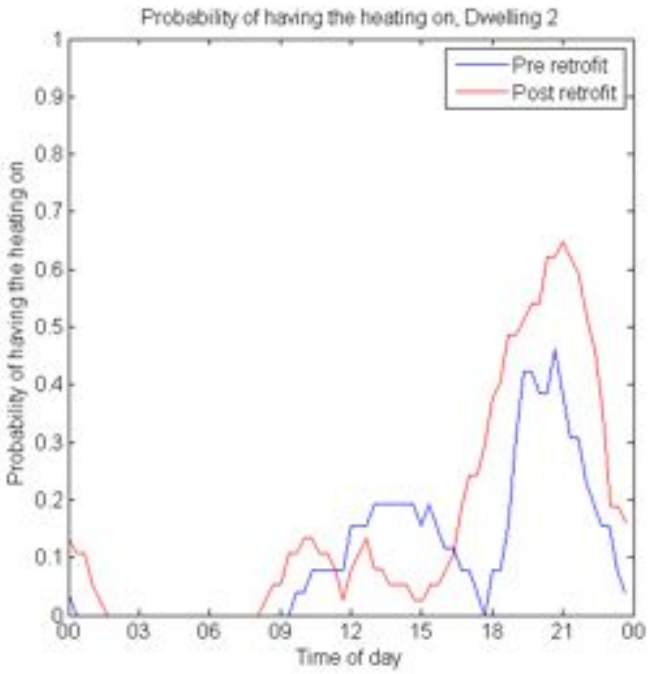



Figure 77: Dwelling 2, probability the heating is on at different times of day.

Given the observation from Table 18 that *achieved demand temperature* increased following retrofit[1], it is useful to consider the temperature profiles during heating periods in more detail. The degree of stabilisation of temperature during heating periods, as introduced in Section 7.9.1, is shown in Figure 78. Prior to retrofit, the temperature during heating periods almost never stabilised. Given that the average length of a pre retrofit heating period was 2 hours, this suggests the combination of high heat loss of the dwelling combined with inadequate power of the heating system. After retrofit, it was more common for the temperature to stabilise. This is probably partly because the average length of heating period was greater (2.3 hours), and partly due to the reduced heat loss enabling the heating system to warm the dwelling up within the timeframe of the heating period.

1 It may seem strange that the *M.I.T.* increased less than the *achieved demand temperature*. This is thought to be because the latter is calculated in zone 1 - the living area - which in this dwelling was one of the rooms with the largest temperature increase following retrofit.

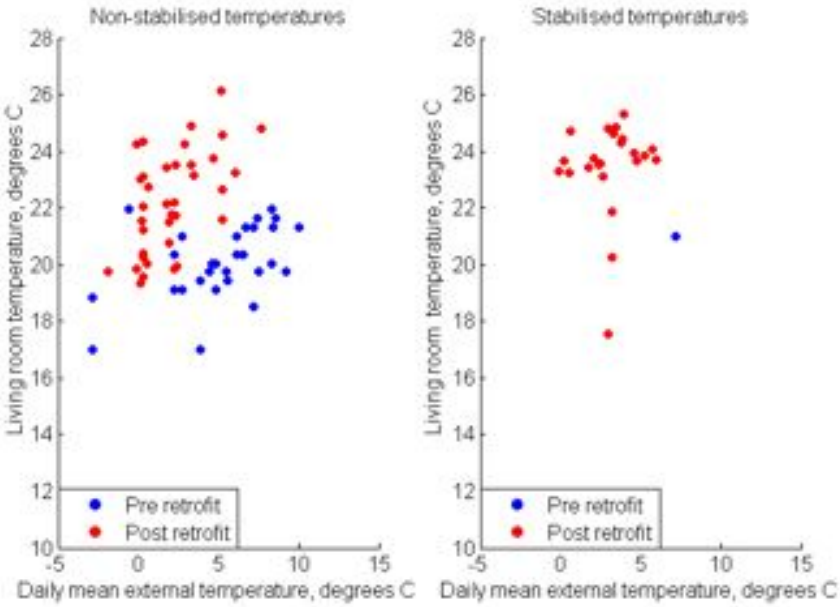



Figure 78: Dwelling 2, stabilised and non-stabilised temperatures.

Figure 79 shows that both heated periods and unheated periods increased in temperature. According to the procedure described in Section 7.8, most of the *M.I.T. increase* occured during unheated hours (82%), with 14% occuring in heated hours and 4% in hours switched to heated. This is shown in Figure 80.

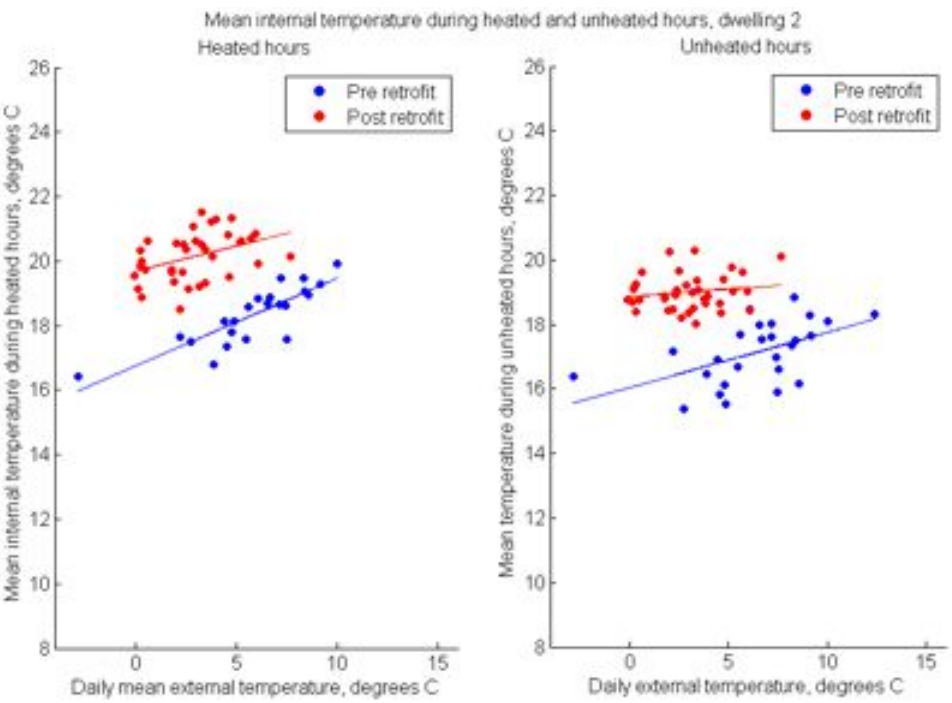



Figure 79: Dwelling 2, mean internal temperature during heated and unheated hours.

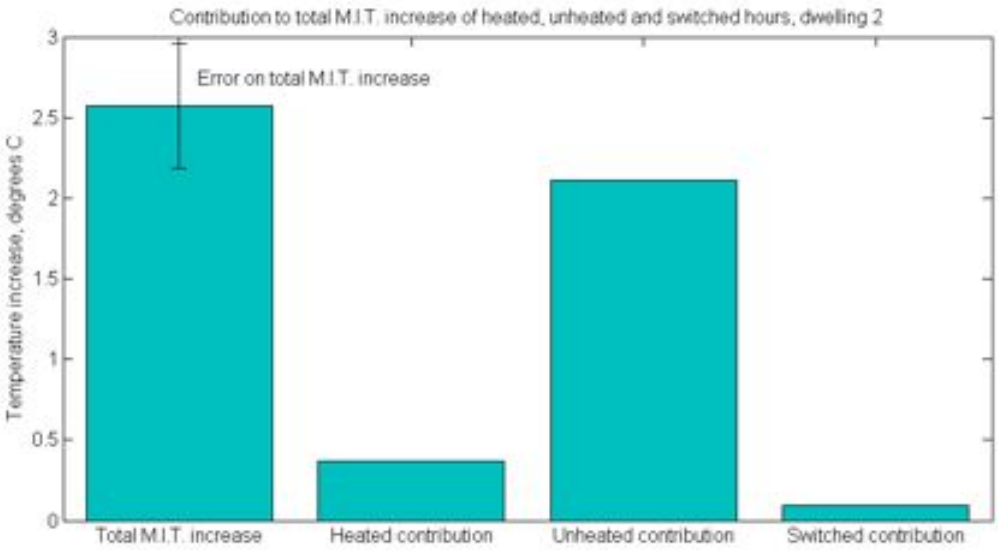



Figure 80: Dwelling 2, attibution of *M.I.T. increase* to heated and unheated hours.

The *inter-room temperature gradient* in the dwelling reduced after the insulation was applied - see Figure 81 and Figure 82. Some rooms - notably the main bedroom - warmed more than others. This may indicate that the heating system was not balanced.

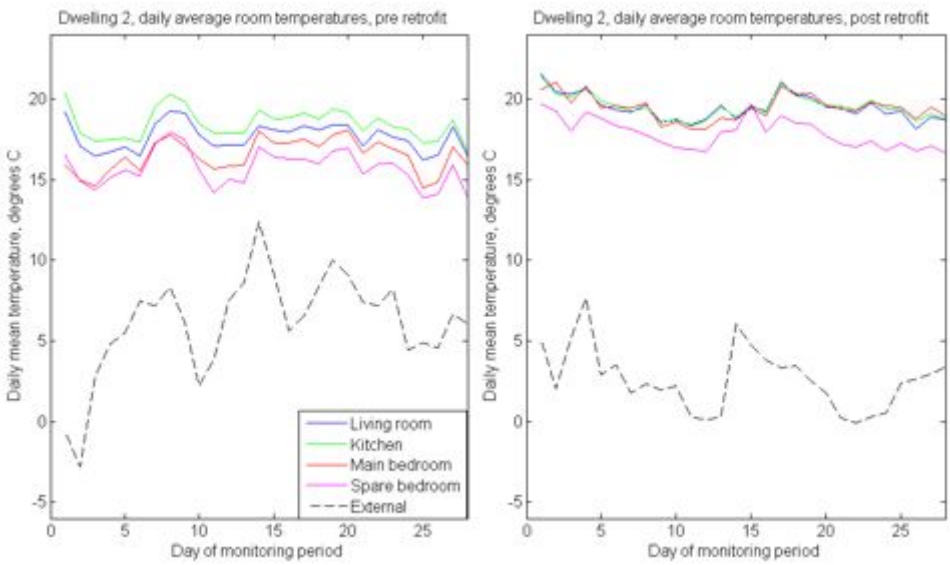



Figure 81: Dwelling 2, temperatures of rooms across the monitoring period.

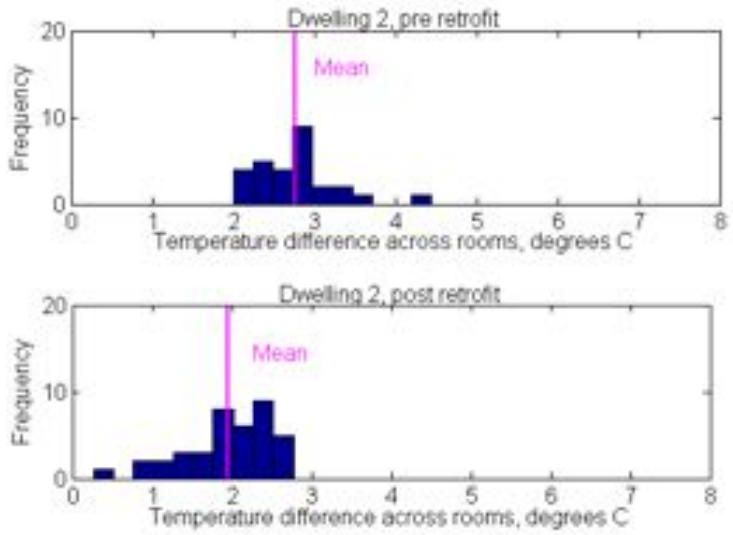



Figure 82: Dwelling 2, histogram of temperature difference between rooms.

However, the occupants' comments in the post retrofit interview that the main bedroom was colder than the other rooms (see Table 19) require further investigation as to why that would feel the case, given that in Figure 81 it appeared, post retrofit, to have caught up in temperature with the living rooms and kitchen (see Section 9.4.6).

### 9.4.4 *Further analysis (mixed methodology)*

#### 9.4.4.1 *Thermostat*

Two factors appeared to influence the thermostat setting in this dwelling: the insulation and the outside temperature. After retrofit, the female occupant described how she had changed the thermostat setting since the insulation, and also on warmer days outside:

*"I used to have it on 30, now we have it on like 23, 25, you know. When it's really cold like today I normally turn it to 25 again. I haven't had it on 30 since we had the insulation."/ "When it's warm outside you don't need it as much, do you..."* (female occupant, post retrofit)

She had observed that turning down the thermostat reduced the use of gas:

*"I've turned the dial down a little bit, so it doesn't burn as much, and probably that's why the gas doesn't seem to go down as quick."*

The phenomenon of increasing the thermostat setting as the external temperature decreases fits within the 'valve theory' of heating control from Kempton (1986) introduced in Section 3.3.3: the occupant was trying to make the system work harder to make up for the cold temperature outside. From this behaviour the inference could be made that the dwelling was not reaching a comfortable temperature on cold days, and therefore almost certainly that the system was on at full power. As for why the occupant decreased the thermostat setting after insulating a property:

*"I don't think you need it on 30 now because I think it stays in more."*

This second component of the occupant's mental model of the thermosts also fits within valve theory: she turned down the rate of delivery of heat after retrofit, as it was not lost so rapidly.

Before attempting to attribute the observed *M.I.T. increase* to different causes, it would be useful to know whether the dwelling was actually under thermostatic control before and after retrofit, as opposed to the heating system working at full power. That is, of the mental model of thermostatic control held by the occupant, did any aspects of it make a differerence to the actual temperature of the dwelling or was the thermostat always too high to have any control over the temperature? The occupant's view that the *"gas doesn't seem to go down as quick"* after turning the thermostat down would suggest that the dwelling had transitioned from a state of never being under thermostatic control to being under thermostatic control to some extent. This is confirmed by Figure 83 which shows that before retrofit, the thermostat setting was never reached. However, after retrofit the temperature did reach the lower thermostat setting. Although the thermostat may have been set at the higher setting at the time, this is still evidence that the dwelling could achieve at least the lower of the thermostat settings following retrofit.

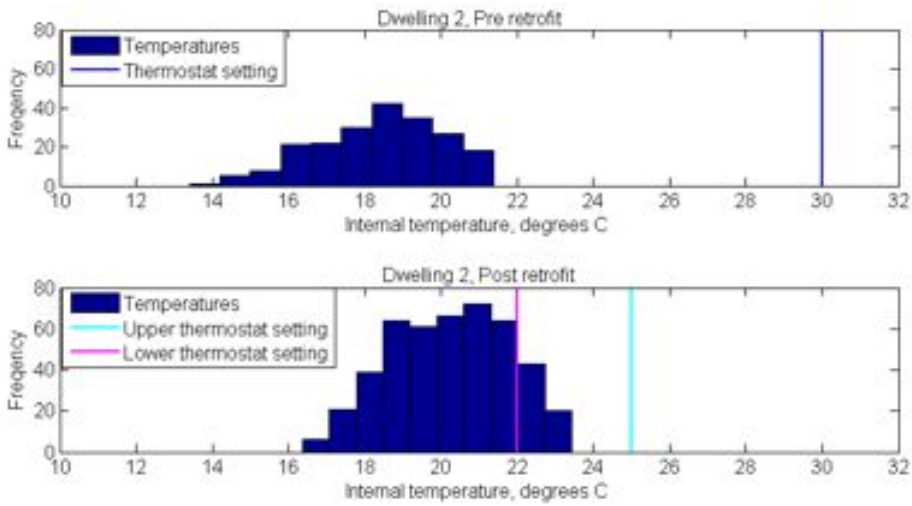



Figure 83: Internal temperatures during heated hours, compared to thermostat settings.

#### 9.4.4.2 *Effect of instantaneous temperature gradient on heating use*

It was shown in Figure 77 that in this dwelling heated hours redistributed towards the evening following retrofit. At first glance, this would correspond with the interviews, with the emphasis after retrofit being put on how cold the main bedroom was, and thus the need to switch the heating on before bed every day.

*Man: "You gotta turn the heating on before you go up there, it's cold. It's our room that seems the coldest out of the lot, it always has done. That's nothing to do with the rendering and that!"* (post retrofit)

*Woman: "I think the coldest room in the house is our bedroom. I must be honest, I've got to say this, when we have the heating on, and the stuff's been done, the insulation you know, and we go to bed, even though you can feel a drop, if the heating's been on a few hours before bed, you can get undressed in the bedroom without going like that ('aargh'), but before we couldn't. . . .but it's still very cold."* (post retrofit)

Figure 81 in Section 9.4.3 showed that the main bedroom was, when averaged over a day, not colder than the other rooms post retrofit. However, Figure 84 just averages over the time period 18.00-23.00, and shows that the main bedroom was cooler than the other rooms. To check, Figure 85 shows the rest of the time (that is, 23.20-17.40), and indeed

the main bedroom was warmer then, which resulted in the mean bedroom temperature over the day being approximately the same as those of the living room and kitchen.

Please note that Figure 85 is plotted using dashed lines instead of solid ones to indicate that the timeseries is not continuous.

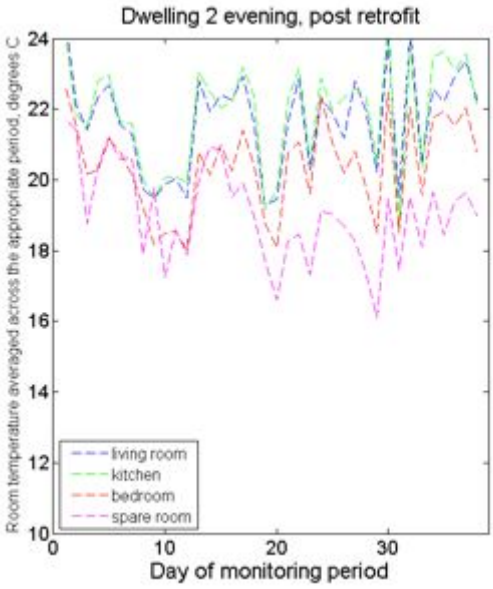



Figure 84: Dwelling 2 evening mean room temperatures

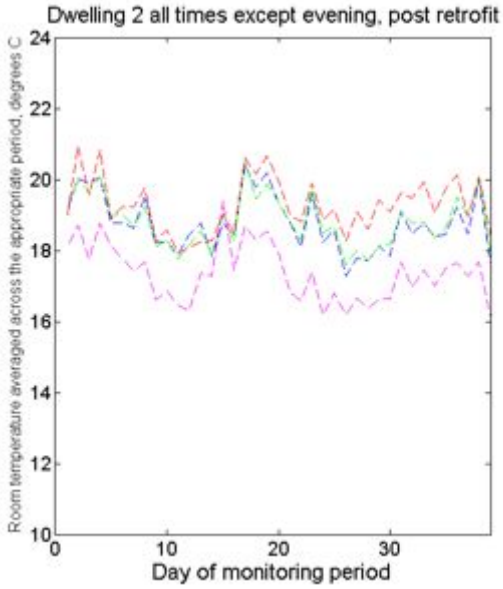



Figure 85: Dwelling 2 non-evening mean room temperatures.

This is an interesting finding - it seems to be the evening temperature of the bedroom, not the mean daily temperature, which brought about the need to switch on the heating. The reason for the this temperature gradient in time is unknown, but it highlights two important points. Firstly, it emphasises the importance of not just taking daily average temperatures into account but those around the start of the occupation period of the room. A similar finding was noted in DECC (2013b), in which it transpired that occupants wanted their bedroom to be warm when they went to bed but cool once they were in bed. Secondly, it is an indication that inter-room temperature gradient matters - if a room to be used is perceived to be colder than others, it might be perceived as 'cold' in its own right, and the whole-house heating might be switched on to remedy this.

### 9.4.5 *Proposed causal mechanism leading to the observed outcome*

Given the above analysis, the proposed causal mechanism following retrofit is given in Figure 86. The likelihood of this being the correct explanation is then discussed in Section 9.4.5.1.

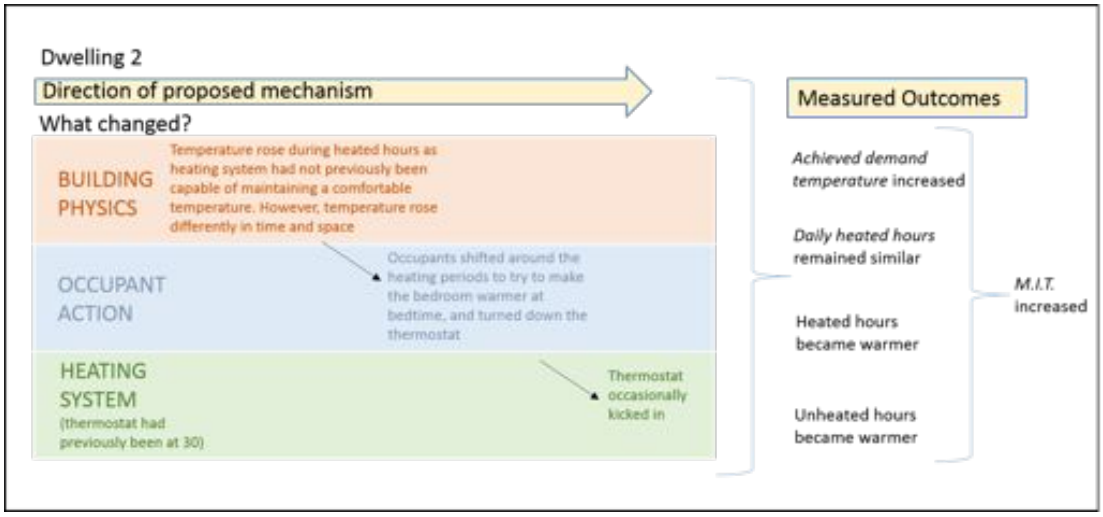



Figure 86: Dwelling 2, proposed causal mechanism leading to observed outcomes.

#### 9.4.5.1 *Validity*

This is a relatively complicated proposed mechanism because it involves several components at once: a mental model of a thermostat, and spatio-temporal dynamics of heat in a dwelling along with the occupants' perception of it. However, just because it is complicated does not mean it is less 'true' - conversely, it is likely that something has been missed.

### 9.4.6 *Other interactions*

#### 9.4.6.1 *Occupant health, and whether it improved following the retrofit*

At the time of the pre retrofit monitoring period the female occupant was in a state of poor health, suffering from C.O.P.D. and asthma. The former is normally caused by smoking, and is aggravated by cold especially if smoking continues, which was the case here. Osman et al. (2008) found:

*"Maintaining the warmth guideline of 21°C in living areas for at least 9 h per day was associated with better health status for C.O.P.D. patients. Patients who were continuing smokers were more vulnerable to reduction in warmth."*

The occupants had been advised to keep the temperature of her bedroom at 18ºC by the doctor, but felt unable to do this due to cost:

*Male occupant: "And they've said she has to have the room at a certain temperature of the house, so that she won't feel the cold on her chest, but you'd have to be putting 15 pound a day on your gas meter to get that"*

*Interviewer: "So they say 'do it', and you say 'we just can't'?"*

*Male occupant: "Yeah, we can't afford to do it."* (pre retrofit)

Turning now to relative humidity, there is not a well-established causal link between R.H. and C.O.P.D. However, asthma can be exacerbated by allergens present where there are dustmites and airborne moulds (Pope et al. (1993)). In this dwelling the R.H. adjusted for external conditions (calculated according to the procedure described in Section 7.13) decreased from 76% to 67%. This should reduce the occurrence of mould to some extent as not only was there less moisture in the air but most of the internal surfaces on external walls would have been warmer after retrofit. Note, however, that if mould is not cleared post retrofit it may carry on growing.

Furthermore, in Section 3.2.2 the link R.H., house dustmites and asthma was introduced. To adequately control house dustmites requires R.H. to be reduced below 60%. Under this criterion, in this dwelling the R.H. was still too high after retroft.

### 9.4.7 *Conclusion to Case Study 2*

This was one of the dwellings in which *M.I.T. increase* was largest, at 2.6ºC (± 0.8ºC). There was a similar temperature increase in heated hours and unheated hours, although the latter made up a larger proportion of total hours and as such most of the *M.I.T. increase* can be attributed to unheated hours (82%).

Concerning heated hours becoming warmer it appears that the heating system could not warm the dwelling in the time allowed by the occupants during pre retrofit heating periods. This changed, as a result of the insulation and also the occupants slightly lengthening their heating periods.

Temperatures in some rooms increased more than others: the living room warmed more than the kitchen, and the bedroom warmed more than the living room. The occupants did want a warmer bedroom and did acknowledge that the insulation had made the bedroom warmer but (perhaps given that it was cooler than other living areas when they wanted to use it) they still did not feel it was warm enough.

The proposed mechanism behind the observed *M.I.T. increase* is relatively complex as it combines an occupant mental model of how a heating system works with the reaction of the building fabric and heating system, and then with the occupants' reaction to that in terms of their actual needs. That is, it is proposed that one effect of the insulation was that the occupant turned down the thermostat (Section 9.4.4.1). This meant that instead of the setpoint temperature never being reached, it was reached during some heating periods, so the occupant noticed a saving in gas expenditure. Simultaneously, the bedroom was the coolest room around bedtime (for an unknown reason - potentially related to the balancing of the heating system, room heat loss and other factors), and this was noticed by the occupants who started being unable to go to bed without having the heating on for a few hours first (unlike the year before). Thus, the number of heated hours was not reduced but their timing was rearranged.

For health reasons, the female occupant had been advised to keep her bedroom at 18°C, but had felt unable to pay for enough heating to achieve that before retrofit. The insulation helped to raise the bedroom temperature above the lower limit specified by the doctor. Relative humidity had also decreased by 9% which would have reduced the risk of mould but not the growth of house dustmites, of which the latter could aggravate the occupant's asthma. The occupants reported that the damp had got worse; if mould had not been cleaned after retrofit it may have carried on growing.

## 9.5 SUMMARY OF INTERACTIONS BETWEEN OCCUPANTS, HEATING SYSTEMS AND BUILDING FABRIC

The case studies presented above are two examples of the thirteen separate analyses carried out, of which the remainder can be found in Appendix A. The rest of this chapter will use cross-case analysis to examine three key variables and how they changed following retrofit: *daily heated hours*, *achieved demand temperature* and use of secondary heating. Where the previous chapter reported these results quantitatively, this chapter will attempt to explain qualitatively why these changes occurred.

As part of each case study, a mechanism was proposed to explain what happened after the fabric of the building was upgraded, containing the three potentially interacting elements: the building fabric, occupant reaction and the heating system. These mechanisms will now all be presented together, to provide context for the discussion which follows. In each diagram, only *change* in any of the three components is shown. This is to distil what actually changed after retrofit. Arrows link the elements, showing one element responding to another. Only dwellings in which the occupants and main heating system remained the same over the study are included here.

The diagrams below are ordered by M.I.T. increase; from highest to lowest.

### 9.5.1 *Presentation of mechanisms diagrams*

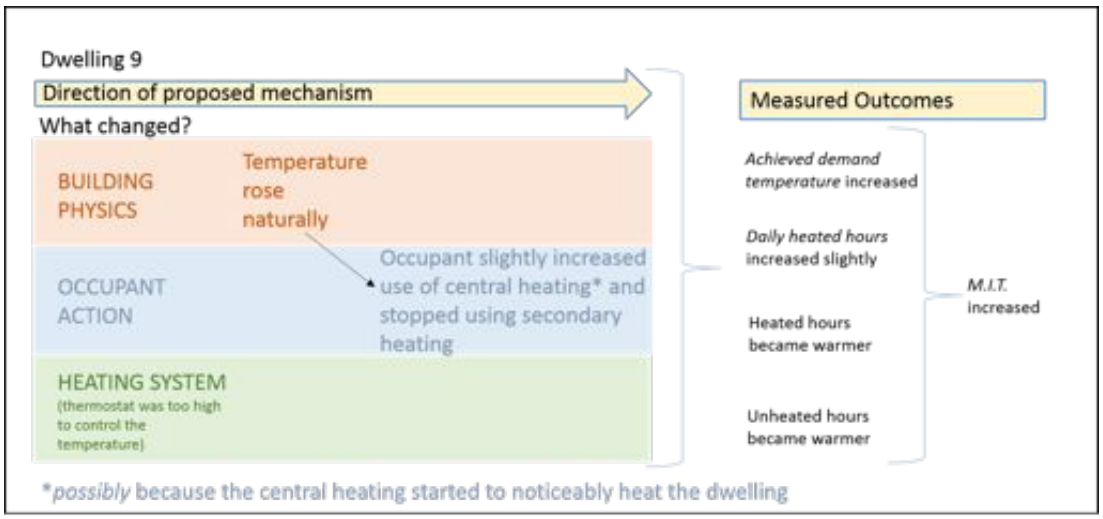



Figure 87: Dwelling 9: what changed following retrofit?

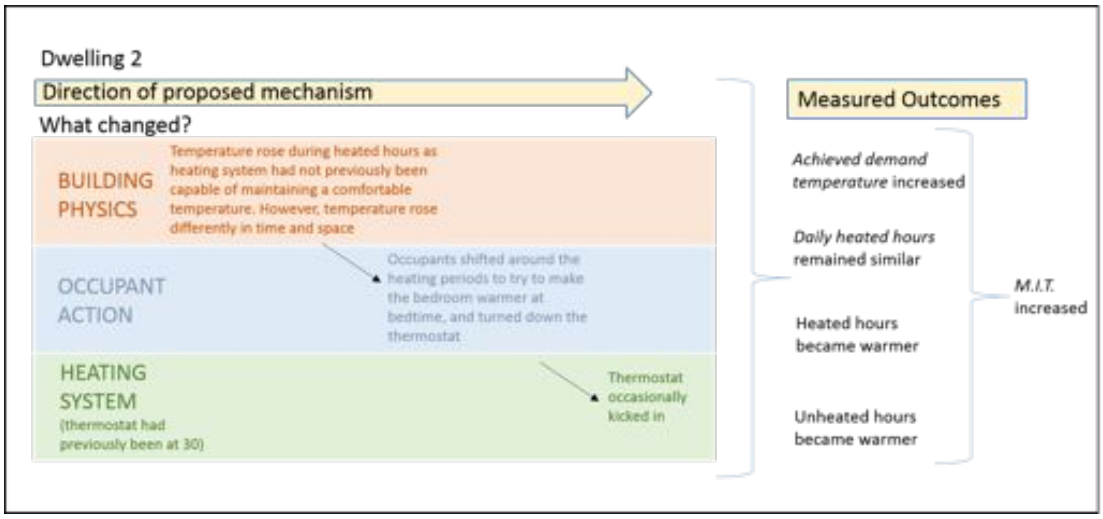



Figure 88: Dwelling 2: what changed following retrofit?

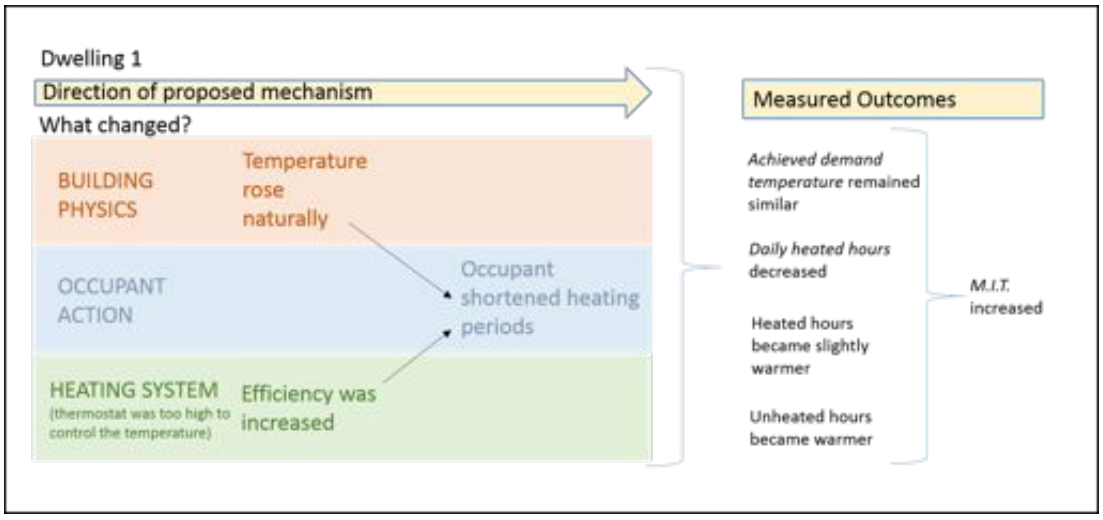



Figure 89: Dwelling 1: what changed following retrofit?

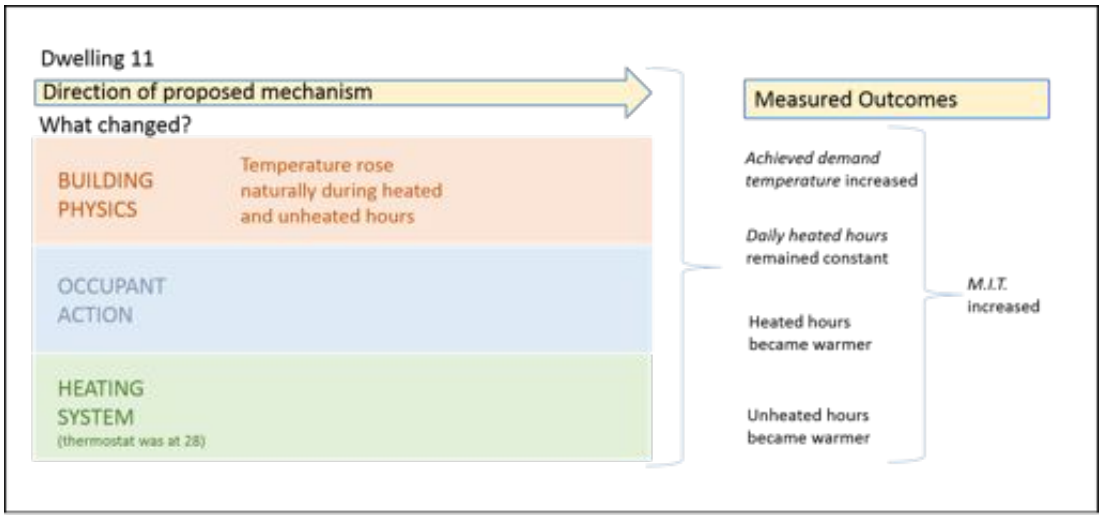



Figure 90: Dwelling 11: what changed following retrofit?

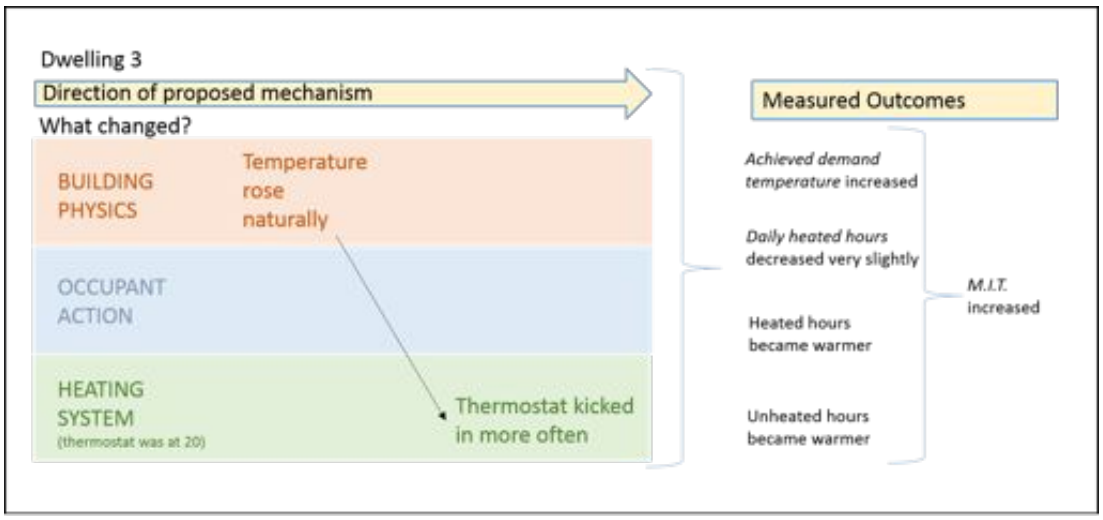



Figure 91: Dwelling 3: what changed following retrofit?

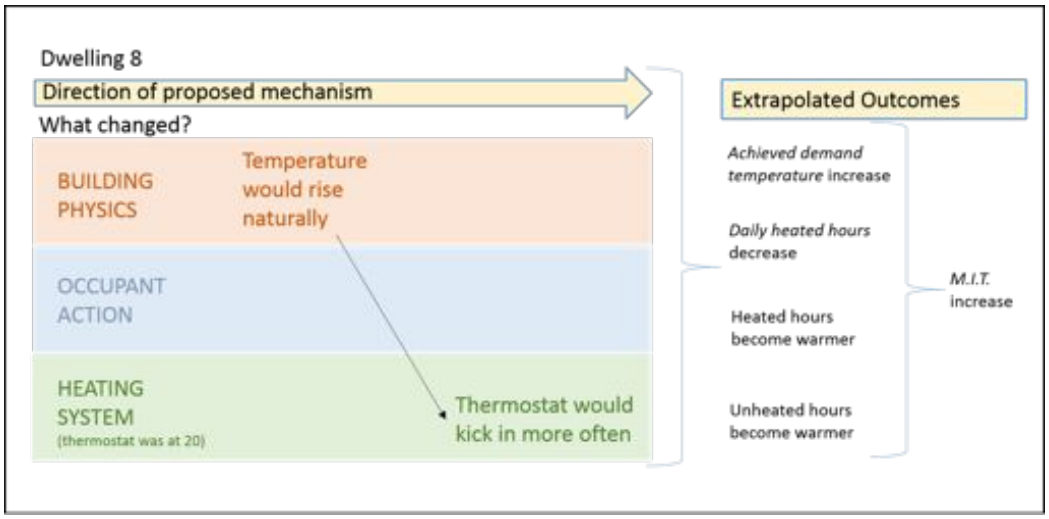



Figure 92: Dwelling 8: what changed following retrofit?

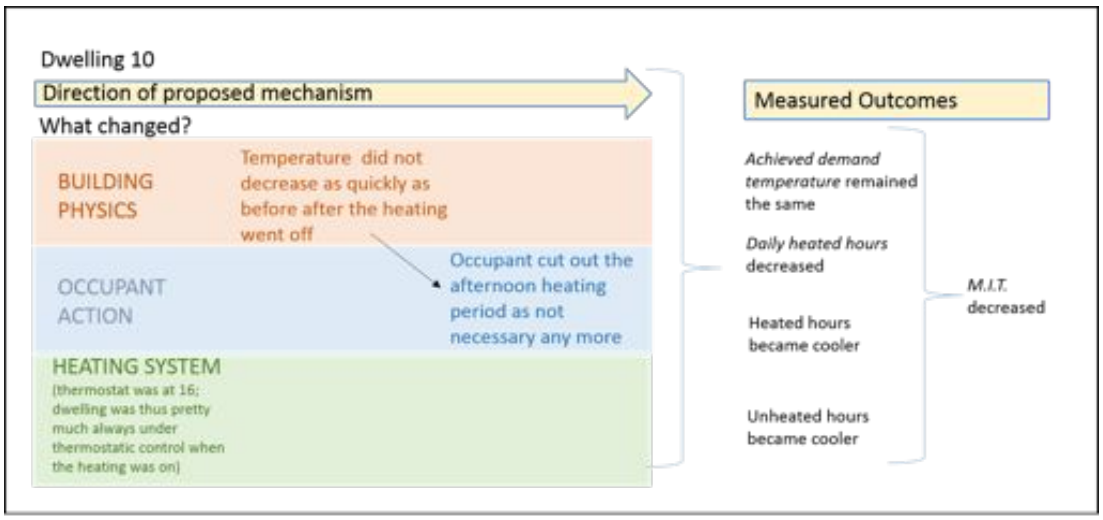



Figure 93: Dwelling 10: what changed following retrofit?

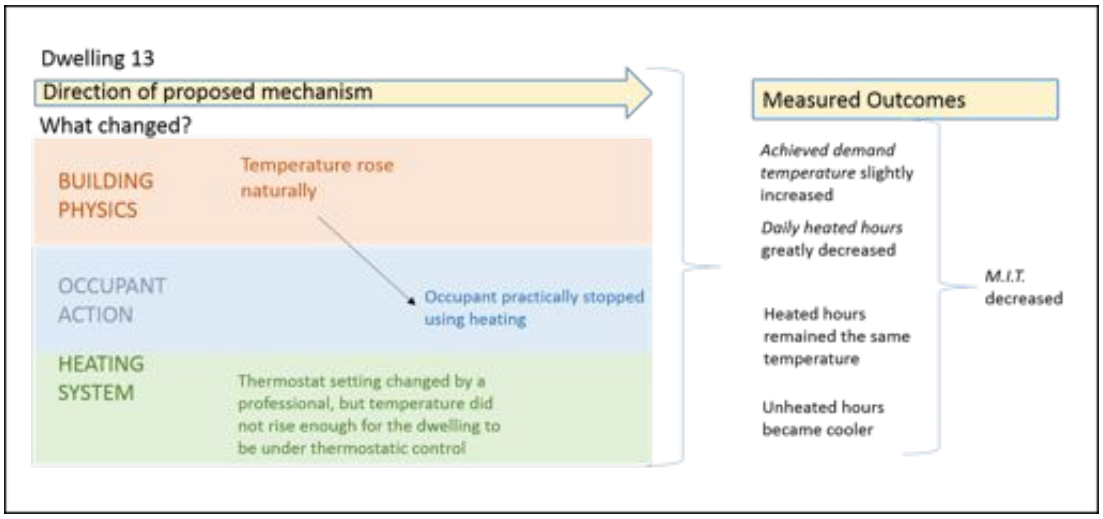



Figure 94: Dwelling 13: what changed following retrofit?

## 9.6 USING THE MECHANISMS TO EXPLAIN CHANGE IN KEY VARIABLES

In the previous chapter, Table 13 and Figure 50 were presented concerning change in *achieved demand temperature* and *daily heated hours* following retrofit. It was observed that in general (i.e. across the sample) *achieved demand temperature* increased and *daily heated hours* reduced following retrofit. Using the mechanisms presented above these quantitative findings can be examined more deeply as to how they came about. To provide useful context for this analysis, two important cross-case observations can be stated as follows:

1. Underheating was prevalent in the sample, both before and after retrofit, as demonstrated by Table 13 showing that *daily heated hours* and *achieved demand temperature* pre and post retrofit were generally below normative assumptions.

2. As has already been noted in Chapters 7 and 8, it emerged through the interviews and observation of thermostats that occupants predominantly used manual heating control - often without the internal temperature becoming high enough to reach the thermostat setting - and also through use of secondary heating.

Given these general observations, the following two sections will address change in *daily heated hours* and *achieved demand temperature* following retrofit.

### 9.6.1 *Why did daily heated hours change following retrofit?*

In this sample, the main way in which the occupants interacted with their central heating system was through the 'on/off' button on the programmer (a minority of households used the thermostat as an equivalent 'on/off' switch by turning it to zero and back up again). Interaction normally took place either when the occupants felt too cold/warm enough, or when they perceived that their dependents needed heat (Section 10.6). Heating periods were often short (Table 11) and thus the temperature was still rising by the time the heating was switched off. In this way, dwelling internal temperature was controlled not by temperature controls such as the thermostat, but by the amount of time the heating was left on.

Within this context, the case studies can be grouped according to what happened to daily heated hours following retrofit: that is, how the occupants adjusted their heating hours in response to the building warming naturally (natural temperature increase, as defined in Section 2.2.2). The categories are as follows:

1. Natural temperature increase from the building, entailing considerable shortening of heating hours by occupants (dwellings 1 and 13);

2. Natural temperature increase from the building, followed by slight shortening of heating hours by occupants (dwellings 8 and 10);

3. Natural temperature increase from the building, little or no change in occupant hours of heating (dwellings 3 and 11);

4. Natural temperature increase from the building, enhanced by lengthening of heating hours by occupants (dwellings 2 and 9);

The above categories are explored below.

#### 9.6.1.1 *Category 1: Natural temperature increase from the building, entailing considerable shortening of heating hours by occupants (dwellings 1 and 13)*

Two dwellings fell into this category. In dwelling 13, the occupants' reduction of *daily heated hours* led to a decrease in internal temperature which was larger than the natural temperature increase, so the *M.I.T.* slightly decreased overall. Since this is a surprising outcome, it requires more attention, and will be treated separately in Section 9.6.4.

In dwelling 1, the same behaviour led to an increase in *M.I.T.* instead of a decrease, since the radiators were made more efficient as well as the building fabric. As was explained more fully in Section 9.3 earlier in this chapter, the occupant switched the heating off at a similar range of temperatures post retrofit to pre retrofit (of which the upper bound was 21-22°C). This may suggest that shortening of heating period and *daily heated hours* post retrofit could be linked to satisfaction of demand for temperature.

#### 9.6.1.2 *Category 2: Natural temperature increase from the building, followed by slight shortening of heating hours by occupants (dwellings 8 and 10)*

The occupants in this category made slight changes to their heating behaviour following retrofit. The occupant of dwelling 10 knew exactly how his behaviour had changed: by elimination of his previous afternoon heating period; whereas the occupant of dwelling 8 had not realised she was using less heating until the post retrofit interview. Furthermore, she did not seem to have had her thermal comfort demands completely satisfied by the retrofit:

*Occupant: "I have found a difference when the heating's on, you know, so there is a slight difference."*

*Interviewer: "Did you say just when the heating's on?"*

*Occupant: "Yeah, it's quite chilly other times, first thing in the morning, especially if I don't have the heating on, so at that time it's a bit chilly. But nothing that I can't, sort of, live with."* (dwelling 8, post retrofit)

#### 9.6.1.3 *Category 3: Natural temperature increase from the building, little or no change in occupant hours of heating (dwellings 3 and 11)*

The occupant of dwelling 11 did not feel that the insulation had made a reduction to the energy bill greater than the increase in energy prices over the same period:

*Interviewer: "You've not been that impressed?"*

*Occupant: "No. We put on £20-30 [per week] last year, and we're still using the same."* (post retrofit)

In contrast, in dwelling 3 the occupant did feel that the insulation had made a difference to the internal temperature, but had made little or no reduction to the *daily heated*

*hours*. Before jumping to a conclusion that this represents rebound behaviour due to insulation alone, an extra detail should be taken into account: the fact that changing energy suppliers between the monitoring periods had led to a reduction in his monthly energy payment.

#### 9.6.1.4 *Category 4: Natural temperature increase from the building, enhanced by lengthening of daily heated hours by occupants (dwellings 2 and 9)*

In both of the dwellings in this category there was both a lack of thermostatic control and an increase in *daily heated hours*. The latter is proposed to occur for different reasons: in dwelling 2, to ensure that the bedroom was warm enough at bedtime (Section 9.4.4.2); in dwelling 9, possibly because after retrofit the occupant could finally feel the effect of the heating system so started using it more (Section A.7.4.1). In dwelling 9, secondary heating also came into the mechanism - the aforementioned increase in central heating use was accompanied by a decrease in secondary heating use. The topic of secondary heating is treated separately in Section 9.6.3 below.

To summarise, occupant heating responses to retrofit varied across the sample from acting to counteract the building's physical response to acting to enhance it. To use the people-energy-buildings framework (Section 1.10), the building reacted first to the retrofit, the occupants reacted to the building, and this was translated to an observed *M.I.T.* change via the particular settings of the heating system.

### 9.6.2 *Why did achieved demand temperature change following retrofit?*

The *achieved demand temperature* increased after retrofit in dwellings 2, 3, 4, 5, 8, 9, 11 and 12; that is, most of the sample. Dwellings 4 and 12 will be excluded from this analysis as they were inhabited by different occupants in the post retrofit monitoring period. The *achieved demand temperature* remained approximately constant after retrofit in dwellings 1, 10 and 13. These two categories of outcome will be addressed below.

#### 9.6.2.1 *Increase in achieved demand temperature*

Despite *achieved demand temperature* increasing in most dwellings, there were no cases in which the occupants increased the thermostat setting following retrofit. As has been

previously stated, in this sample 'temperature controls' were not the main way in which temperature was *actually* controlled; the latter was determined by length of heating period. The occupants also did not report altering the settings on their boiler (i.e. the temperature of the heat delivered to the radiators); nor did they change the settings of the T.R.V.s except in two circumstances[2].

Given this, any observed increase in *achieved demand temperature* is proposed to be due to the increased ability of the insulated building fabric to retain heat. In order to be able to test this hypothesis - i.e. to observe in the data that a given dwelling really could reach a higher temperature after retrofit - dwellings must be found in which the occupants had the heating on long enough pre retrofit to generate pre retrofit *stabilised demand temperature* data, so that it can be shown that this was the maximum temperature attainable before the energy efficiency measures. This condition is fulfilled in dwellings 3, 5 and 11 - about half of the sample under examination.

It is perhaps then possible to make the extrapolation to all the dwellings - after retrofit, the increased thermal efficiency of the building fabric allowed a higher temperature to be achieved during the heating period.

#### 9.6.2.2 *No increase in achieved demand temperature*

Where normative models such as SAP are used to predict the effect of building fabric retrofit on energy use, modelled demand temperature (defined in Section 2.3.2) is assumed to remain constant after retrofit, due to the effect of the thermostat. In dwelling 10, in which the thermostat was set at 16°C and in which this temperature was achieved during the heating period, the thermostat prevented an increase in *achieved demand temperature.*

Another mechanism through which *achieved demand temperature* can remain constant after retrofit occurred in dwellings 1 and 13. Here, the heating period was shortened after retrofit to such an extent that the *achieved demand temperature* could not increase. In both of these dwellings, the thermostat setting was too high for the dwelling to be under thermostatic control; as such, the occupants and not the thermostat determined the *achieved demand temperature.*

2 The occupants of dwelling 8 and dwelling 3 kept the spare bedroom T.R.V. on low; the former occupant turned it back up when the room was inhabited. Three of the case study households believed that the same amount of energy was used whether none or some of the TRVs were switched off.

### 9.6.3 *How did use of secondary heating change following retrofit?*

From the qualitative data, four main uses of secondary heating emerged. A visualisation of this, and how it changed after retrofit, is presented in Figure 95, accompanied by the following notes:

- The numbers represent the dwellings.
- Where qualitative data exists for a dwelling with the same occupants pre and post retrofit, an arrow is shown to demonstrate how their use of secondary heating did or did not change post retrofit.
- Central heating is abbreviated by C.H.
- Some but not all relationships in Figure 95 can be triangulated with monitored data since secondary heat sources were only monitored if the occupant reported using them more than 'occasionally'.[3]

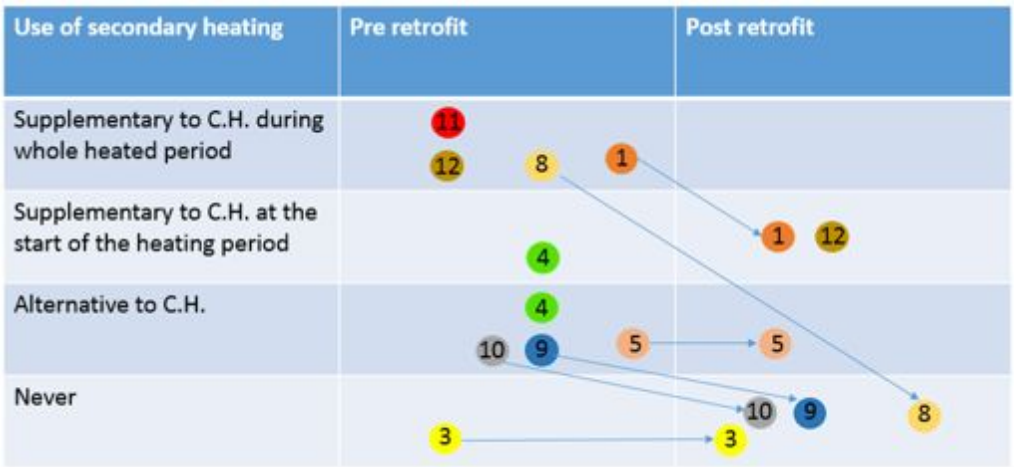



Figure 95: Cross-case visualisation of self-reported use of secondary heating.

Although the categories in Figure 95 were not predefined prior to the interview and analysis, they are similar to those found in the EFUS study described in Section 3.3.5 in the Literature chapter. One difference is that the use-type 'Supplementary to central heating' in the EFUS study has been subdivided in this thesis into 'Supplemetary to central heating (C.H.) during the whole heated period' and 'Supplementary to C.H. at

3 This was so as not to appear to distrust the occupant: if the occupant had reported not using a particular heat source and the interviewer had then put a sensor on it, the occupant might feel as if the interviewer did not trust them. Some occupants were quite adament that particular heat sources did not need to be monitored.

the start of the heating period'. This is because, even after retrofit, some occupants found that they were not comfortable as they were waiting for the central heating to warm the space they were in after returning home:

Occupant: *"Sometimes I'll use [the electric fan heater], because sometime we come back and then it's so cold, we switch that [on], since this room, to catch up the warm, it take ages.." [...] "...and once the house is warm enough we switch off that [electric heater], then we can continue with the central heating."* (dwelling 1, post retrofit)

Figure 95 will now be used to draw out some general observations.

#### 9.6.3.1 *Cross-case insights into use of secondary heating before and after retrofit*

Three points will be made here:

1. Before the insulation, some of the tenants felt that at times they needed to use secondary heating on top of the central heating. This indicates that the main heating system was not able to warm the dwelling up to a comfortable temperature. After retrofit, no occupants reported using secondary heating in this way. Thus, one effect of the building fabric efficiency upgrade was to allow the heating system to heat the building to the desired temperature without the use of additional heat sources.

2. However, occupant thermal comfort was not satisfied post retrofit throughout the whole heating period. In some cases the central heating took a long time to warm up the building, and this is where secondary heating was then used by occupants to speed up the provision of warmth.

3. Two households used secondary heating instead of central heating prior to retrofit. In one case (dwelling 9) this appeared to be because in the pre retrofit dwelling the secondary heating seemed more effective at providing warmth than the central heating. The effectiveness of the central heating in the insulated dwelling, however, was such that the occupant had not had to use the secondary heating at all.

The last point above is illustrated by the following quotation:

*Occupant:"I realised that... I might put the heating in my house, but as long as a neighbour doesn't use the central heating, it means that it's not gonna help much, my heating which I produce here, goes to other flats which are also freezing."*

*Interviewer: "...where would you put [the living room] now [on the comfort scale]?"*

*Occupant: "I pick two of them here. Comfortable, and comfortable but a bit on the warm, because what I normally do, like right now, is just put the central heating on, just about 10 minutes ago I put it on, and it's already warm enough that I can take off my jacket. So if it goes for the next one hour, two hours, then that's when I say comfortable but a bit on the warm side."* (dwelling 9, post retrofit, referring to pre retrofit)

Figures 96 and 97 illustrate this switch of heat source using an example week of quantitative data for both the pre and post retrofit monitoring periods:

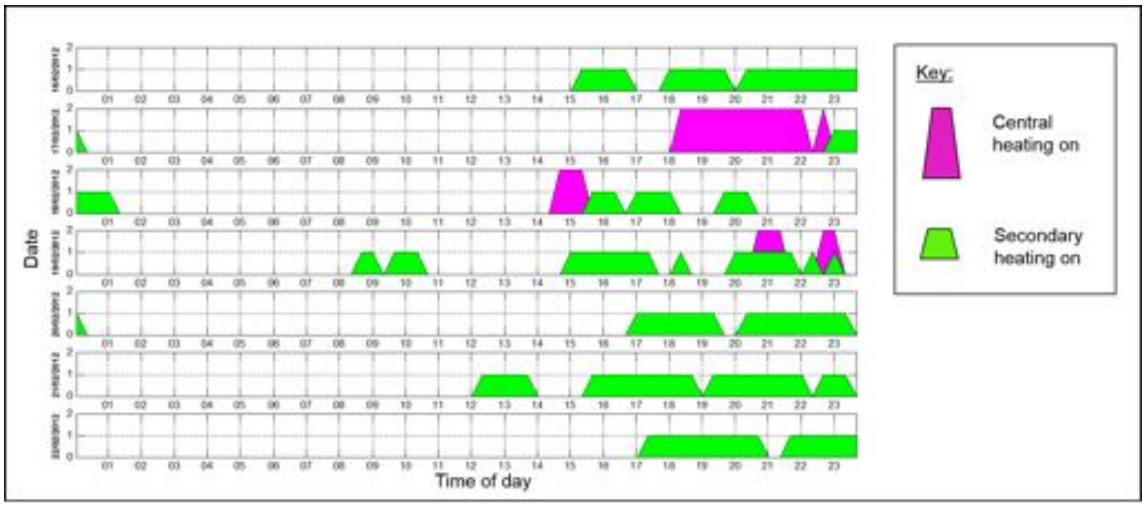



Figure 96: Dwelling 9 pre retrofit typical week: using secondary heating instead of central heating.

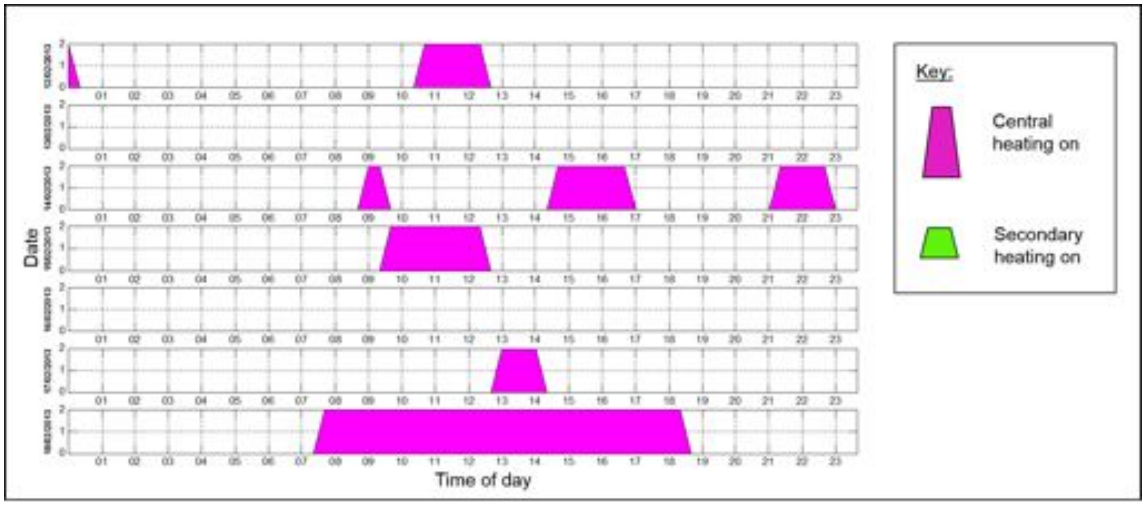



Figure 97: Dwelling 9 post retrofit typical week: using central heating.

This parallels the observed effect of installation of central heating described in Section 3.5.1, whereby there is a step-change in an occupant's heating behaviour, switching from heating one rooms to heating all rooms.

### 9.6.4 *Why did the M.I.T. decrease in two dwellings?*

In Section 8.2 the *M.I.T. increases* following retrofit were presented for all the dwellings. One noteworthy result was the slight decrease in internal temperatures in two dwellings: 10 and 13. In dwelling 10, the standardised *mean internal temperature* fell after retrofit by 0.8°C (±0.5°C), although as is explored in its individual case study (in Section A.8), this is largely influenced by one room which became unoccupied. In dwelling 13, the standardised *mean internal temperature* fell after retrofit (by 0.9°C ±1.0°C); it can be seen that the error is larger in this latter dwelling.

These dwellings have a few aspects in common. Firstly, the occupants were struggling for money at the time of the post retrofit monitoring period. Both occupants of dwelling 13 had suffered a recent income cut, and the occupant of dwelling 10 had been faced with a recent expenditure increase as his children were both in difficult financial situations and were regularly borrowing from him.

Secondly, from the interview data, both occupants were expecting the 'double dividend' of lower heating costs and a warmer home:

*Interviewer: "What are you expecting will happen when you have the works done?"*

*"Lower heating costs. That's what I'm aiming for. And obviously, come next winter, a warmer home. Again, less heating needed to get it to the temperature that makes it comfortable."* (dwelling 10, pre retrofit)

*Occupant, dwelling 13: "That it'll get warmer. We won't have to suffer in the winter. And it'll cut down on the heating as well."* (dwelling 13, pre retrofit)

The above quotes correspond with the self-reported comfort scale data: both occupants report that most rooms are not warm enough before retrofit (Tables 34 and 40) implying a degree of underheating. This is important to point out, as it it then shown not to be the case that the occupants were satisfied with the temperature before retrofit so cut down on the heating to create that same temperature after retrofit.

Thirdly, the occupants of both dwellings reduced their daily heated hours. This reduction was of a similar nature in both dwellings in that it consisted of near-elimination of ad-hoc heating that occurred as and when the occupants felt the need. For dwelling 10:

*"With the walls being done, I put the heating on for an hour in the morning and that takes the nip off the air, and that sees me right through the day. So long as the temperature doesn't drop below zero too early, it's good enough for me."* (dwelling 10, post retrofit)

For dwelling 13:

*Interviewer: "Why would you heat this room?"*

*Occupant: "Sometimes my hands go really cold, when I'm watching the telly, and then I can't get myself warm, so I go and put the heating on for about half an hour."* (dwelling 13, post retrofit)

Fourthly, neither dwelling 10 and dwelling 13 increased their achieved temperature during the heating period after retrofit. Dwelling 10 was under thermostatic control at a low temperature (16ºC), and after retrofit the occupant of dwelling 13 turned the heating off quite shortly after turning it on, thus limiting the potential for high internal temperature.

Fifthly, both occupants felt that their dwelling became warmer after the retrofit. To try to understand the cause of this, several temperature-related variables other than mean internal temperature were examined, since occupants do not exactly perceive the latter.

The first alternative metric was the temperature of the room in which the occupant spent most of their time, averaged over the times they were normally there. For dwelling 10, this was the living room during all waking hours, and for dwelling 13, it was the kitchen before retrofit and the living room afterwards (for reasons unrelated to the retrofit), during all waking hours. These datasets can be plotted to ascertain whether the temperatures increased following retrofit; this is shown in Figures 98 and 99:

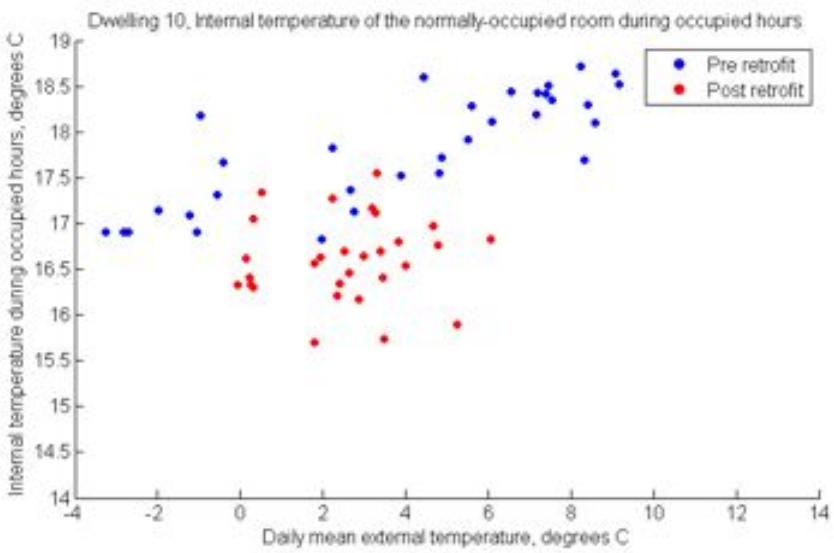



Figure 98: Dwelling 10, mean internal temperature of the living room during normally-occupied hours.

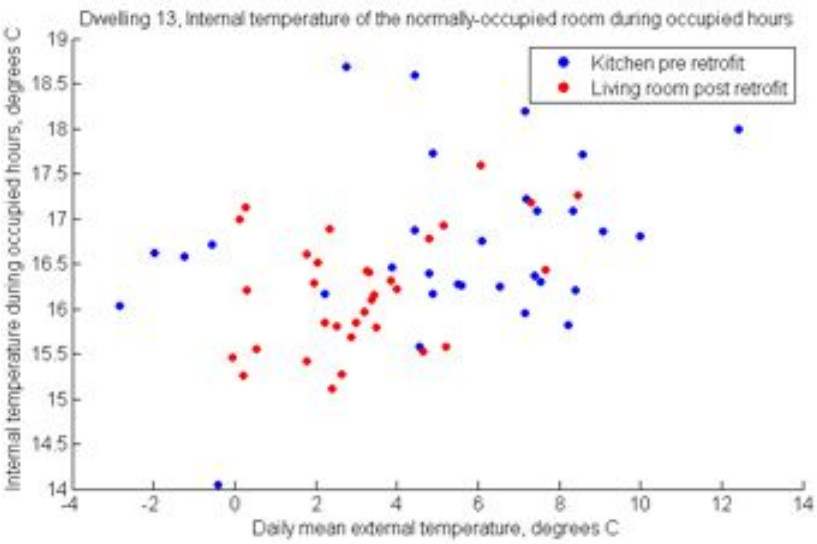



Figure 99: Dwelling 13, mean internal temperature of the normally-occupied room during normally-occupied hours.

Figure 98 shows that in fact the occupied rooms decreased in temperature after the retrofit. Therefore this particular alternative to the *mean internal temperature* metric did not explain why the occupants felt warmer after retrofit.

Another possible reason that the occupants felt warmer after retrofit could relate to the *minimum* temperature in the spaces instead of the *mean* temperatures. For example, the occupant of dwelling 10 was pleased after retrofit that, "*All winter, that temperature gauge hasn't read less than 13 degrees.*".

To explore this, visualisations of the range of temperature within each dwelling have been made using the following method: the daily maximum and daily minimum temperatures were plotted against their respective external temperatures, and lines fitted through each. The area in between the maximum and minimum line was shaded, to give simplified shapes as in Figures 100 and 101:

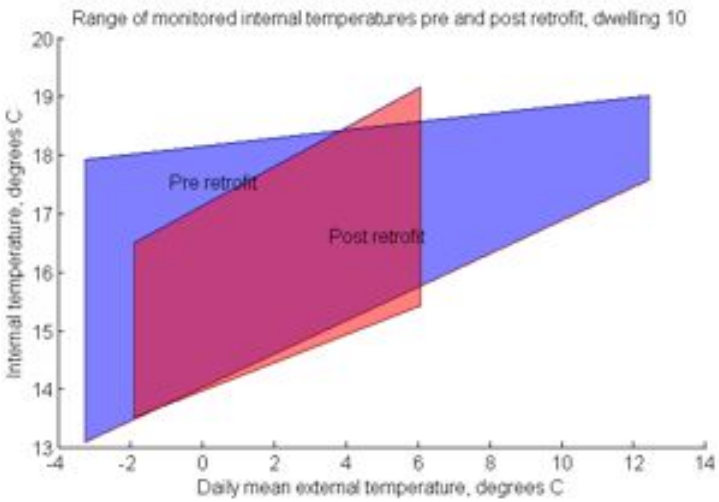



Figure 100: Dwelling 10, range of internal temperatures.

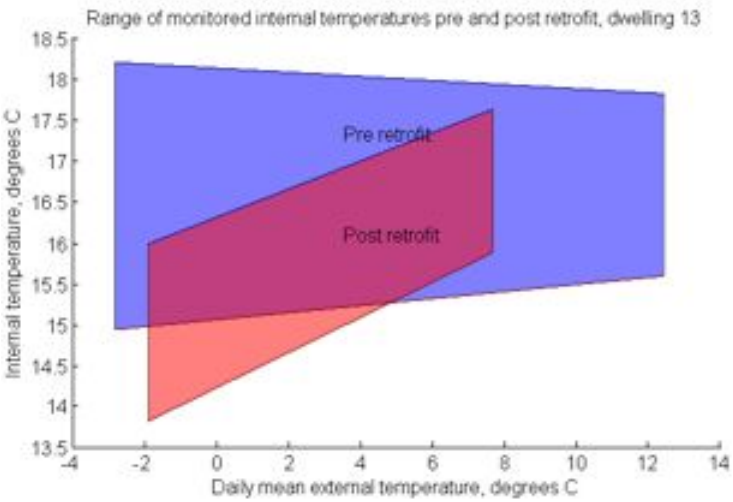



Figure 101: Dwelling 13, range of internal temperatures.

In Figure 101, minimum mean internal temperatures in fact decreased following retrofit, so the above hypothesis can be shown to be false. In the case of dwelling 10, this is less clear, since the external temperature did not reach as low in the post retrofit monitoring period as in the pre retrofit one, so the minimum internal temperatures are greater after than before. This is an example of a framing issue within the physical data (see

Section 7.15.4.1), which if not noted could affect the conclusions reached. In any case, a reason has not been found from the empirical data as to why the occupants felt that their dwellings were warmer following retrofit. It could be that other thermal comfort variables not measured in this study, such as radiant temperature, were involved.

In conclusion, there are several similarities between the households whose mean internal temperature after retrofit decreased or at least did not increase, the most notable one in the author's opinion being that the result did not come about because of a previous satisfaction with the temperature. However it has not yet been discovered why these occupants both reported feeling warmer.

## 9.7 CONCLUSION

In this chapter, explanation for observed changes in *M.I.T*, *daily heated hours* and *achieved demand temperature* were proposed by combining monitored data with interview data for each dwelling. It was shown that understanding the way occupants use heating is a crucial starting point when trying to discern what happened after retrofit and why. In this sample, the starting point was usually manual control of timing often combined with a lack of thermostatic control. Increasing the efficiency of the building fabric then led to an occupant reaction of decrease in *daily heated hours* and a building physics reaction of increase in *achieved demand temperature*.

There is one final set of results to be presented before all the findings are drawn together. This is the set of other interactions between occupants, building fabric and heating systems, not necessarily related to retrofit, which emerged from the data. The next chapter will highlight those considered to be the most useful.

# 10

# RESULTS 3: OTHER INTERACTIONS UNCOVERED BY THE INVESTIGATION

## 10.1 INTRODUCTION

This chapter arose as a result of two related factors. Firstly, a great deal of insight was gained through analysis combining physical and social data, not all of which falls into the remit of the research questions which solely concern change in internal temperatures. Secondly, it was realised that to understand change in *M.I.T.*, one has to understand *M.I.T.* in the first place. Some useful information on the way *M.I.T.* came about in the case study dwellings emerged from the empirical work.

As with the previous chapters, qualitative, quantitative or both types of findings will be presented as appropriate.

## 10.2 OCCUPANT HEATING CONTROL

As has been mentioned in the preceding results chapters, occupants in the sample generally interacted with the central heating system using manual heating control. This was shown to have implications for how heating use changed after retrofit (see Section 9.6.1). In this section the reasons why manual heating timing was the preferred mode of control are explored.

Firstly, an overview of the heating behaviour of the occupants in the sample will be described. 12 out of 13 of the case study households turned the heating on and off manually, either using the programmer or by turning the thermostat up from and back

down to zero. For those who had some understanding of how the thermostat or programmer worked, there was a general skepticism to devices which regulate either the time of heating or in some cases the temperature, through a view that such devices are not suited to their lifestyle or are unable to predict their preferences. Three examples are shown below:

*"Timers are for people with children"* (dwelling 4, pre retrofit)

*"There's too much variation in our day to use a timer"* (dwelling 12, post retrofit)

*"I don't put on automatic. I just switch it on in the kitchen. There's a button. I don't want it to predict, to think it's OK, I just want to feel it's warm enough for myself to switch it off."* (dwelling 9, post retrofit)

Other occupants in the sample did not know what the thermostat was supposed to do, stating that it was broken (when in fact it was set too high for the internal temperature to reach the setpoint):

*Occupant: "It's not working, I don't use. [...]"*

*Interviewer: "Do you know even what it is?"*

*Occupant: "No."* (dwelling 1, pre retrofit)

It is interesting to consider how households used thermostats across the sample. Within the ten households present both years of the study, plus the six households who were part for the study during one of the monitoring periods., the following thermostat behaviours were documented:

- Six households used the thermostat in the conventional way, i.e. to regulate temperature. They had chosen the setpoint themselves (dwellings 3, 6, 10, 4 post retrofit, 7 post retrofit, 12 post retrofit).
- Four households had the thermostat set so high that the temperature never reached the setpoint. They did not know that the function of a thermostat is to regulate temperature (dwellings 1,4,9,11).
- One occupant had a mental model of the thermostat which led her to turn it down after the retrofit and thus sometimes brought the property under thermostatic control (dwelling 2).
- One occupant knew the function of a thermostat but heated with secondary heating that was therefore not controlled by the thermostat (dwelling 5).

- One occupant had been informed of the function of a thermostat between the monitoring periods and so by the second one had turned it to a reasonable setting (dwelling 13).
- In two properties the thermostat appeared to be genuinely broken from what the author could discern (dwelling 7 pre retrofit, 12 pre retrofit).

In short, either occupant preference or difference in mental models of how heating systems work led to heating behaviour very different from the SAP normative assumption of fixed hours of heating and fixed modelled demand temperature. This could be important when predicting the energy effects of retrofit. Where SAP would assume no change in modelled demand temperature and no change in modelled daily heated hours following retrofit, in this sample, the general pattern was an increase in *achieved demand temperature* and reduction in *daily heated hours*. It is not immediately obvious what the energy effect of this difference from the normative assumptions would be: that is, whether actual energy savings are higher or lower than predicted. The next chapter discusses this further.

## 10.3 AWARENESS OF ENERGY SERVICE COST REDUCTION

This section discusses the extent to which occupants were aware of their homes being cheaper to heat following retrofit, and whether this led any of them to increase their heating use.

### 10.3.1 *What facilitated awareness?*

Awareness of energy savings following retrofit appeared to be associated with method of paying for gas. It was clear that occupants paying for their gas via prepayment meters were immediately aware of the effects of the retrofit, as opposed to those who paid by other means. Two example quotes from those with prepayment meters are given below:

"*I've turned the dial [thermostat] down a little bit, so it doesn't burn as much, and probably that's why the gas doesn't seem to go down as quick*" (dwelling 2, post retrofit)

"*Sometimes I check, to find out, let's say I've gone 2-3 weeks, [...], and when I go to check, my usage, I can see, it's still there, I can still go for another week*" (dwelling 9, post retrofit).

In contrast, the occupant of dwelling 8 who paid quarterly bills had not noticed the bill decrease until she was asked to compare past bills during the interview. The occupant of dwelling 3, who paid by direct debit, did not appear to have been informed that his direct debit could be decreased after the retrofit, although he had switched supplier to get a better deal so it had decreased anyway.

It is interesting to consider whether incentivising people to interact with some kind of energy meter at regular intervals reduces their energy use. However, other researchers are currently addressing this topic much better than the author could, with much more data, from a psychological perspective (e.g. Hargreaves et al. (2013)). The discussion will therefore move on to a possible implication of awareness of energy service cost reduction: rebound.

### 10.3.2 *Rebound*

Rebound was introduced in Section 1.9 as a decrease in the price of an energy service causing an increase in demand for that service. In the context of occupants who realised that they were saving money on fuel after retrofit, rebound would manifest itself as occupants reinvesting the money either into more fuel (direct rebound) or into energy consuming services (indirect rebound). This phenomenon is normally studied using economic methods and quantitative research. Here, insights will be gained from the qualitative data.

The phenomenon of rebound was introduced to the occupants in the post retrofit interview, so that they could give an opinion as to whether this mechanism described their behaviour. Most of those who knew that their home was cheaper to heat after retrofit denied reinvesting the money in heating. This was for different reasons: either there was something else relatively pressing to spend it on, or something less pressing but still useful to spend it on, or they preferred to save up. Below is an example of each.

*[Interviewer's question was in slightly different words each time but roughly as follows:] Interviewer: "So the money you said you saved on heating since last year, do you use it for more heating or for something else, or not?"*

*"No, it doesn't work that way. Always the budget is always important. Right now my energy bill has come down, which mean those extras have to come to important things as well [...] the rent is going up. And things like water bills."* (dwelling 9, post retrofit)

*"No, you don't [use it for heating]. I've found myself buying little things for myself that I never used to be able to buy, I can't really put my finger on them, little bits and pieces of my computer and that, that I wouldn't have been able to buy before. But I've never really consciously thought, "I'm getting this because I'm saving money on the heating now"* (dwelling 10, post retrofit)

*"I don't spend it on...I try and save about maybe 100 or 150 a month so that covers my direct debits as well, and still leaves me with a bit in my pocket."* (dwelling 3, post retrofit)

The small sample size associated with this study means that no statement can be made regarding the rejection of microeconomic theory from this evidence alone. The discussion above is purely an indication that the way in which occupants think about retrofit is not well described by microeconomic theory.

## 10.4 LEVEL OF KNOWLEDGE OR ENTHUSIASM OF THE OCCUPANT ABOUT THE RETROFIT

Hypotheses can be found in the literature concerning the effect of perceived understanding of energy efficiency measures on actual energy saving. For example, Caird et al. (2012) found a correlation between the extent to which households whose dwellings had been retrofitted with heat pumps felt they understood their systems, and the actual system efficiencies attained. However, this relationship is often observed where there is a new technology installed which the occupants have to actively operate. Concerning building fabric efficiency improvements, it is less the case that occupants have to understand and use new equipment, and more the case that they can potentially use existing equipment (their heating system) at different settings (in time, space and temperature). There has been to date no equivalent study to Caird et al. (2012) which instead measures level of perceived understanding of *building fabric* improvements and resulting energy savings. From the case study data, two points will be made about the relationship between prior knowledge of what retrofit is supposed to do, expectation of what will happen, and the actual result.

Firstly, in this study there appears to be very little (qualitative) relationship between knowledge or expectation of the effect of the efficiency measures, and heating behaviour after they were installed. For example, some occupants seemed fairly sure that the retrofit would enable a warmer home to be maintained with less heating use than before, but either it did not happen in their home (dwelling 11) or they did not think about it until the interview (dwelling 8). The one dwelling in which the aforementioned link

is potentially demonstrable concerned one of the occupants of dwelling 2. Her mental model of the thermostat as a valve and her belief that the building would retain more heat after retrofit led her to turn down the thermostat (Section 9.4.4.1).

Secondly, although initially disengaged occupants can end up not reducing their heating use (dwelling 11), they can also end up delighted with the energy efficiency measures despite only partially changed heating behaviour (dwelling 9). The latter example, discussed extensively in Section A.7.6.2 in the appendices, shows that final satisfaction does not always require prior enthusiasm. However, there is evidence that lack of prior enthusiasm was not entirely the fault of the occupants but a communication failure between the RSL and the tenants. For the author, one of the most striking statements in the whole set of interview data was as follows:

*"Let's just hope that it's going to work. Because we don't know how they did their tests to find out whether this is the right project to do, for the benefit of the people."* (dwelling 9, pre retrofit)

In Chapter 4, it was hypothesised through the modelling exercise that deep fabric retrofit can ensure energy saving irrespective of occupant behaviour. It would seem sensible not to have to ask occupants to change their behaviour to ensure energy saving, instead letting the building do this for them. In other words, it would beneficial if energy savings could be guaranteed without relying on effective engagement. However, quotes such as the one above bring up a social justice element to the discussion. Irrespective of how much behaviour matters to the outcome of retrofit, and irrespective of what the occupants choose to do with information they are given, they should be clearly informed about why the particular energy efficiency measures were selected and how it will benefit them.

## 10.5 NEW OCCUPANTS AND NEW COMFORT STANDARDS

The modelling work in Chapter 4 introduced the topic of retrofitted dwellings undergoing a change of occupant, and the effects this could have on energy savings following retrofit. The idea was proposed that if the new occupants had much higher comfort preferences than the previous ones, then shallow retrofit could allow significant energy use increase, whereas deep retrofit would not.

However, this argument presumed that comfort preference (temperature demand in time and space) is constant for a given household, and therefore its value does not change as a household moves between dwellings. This may not be the case. One piece

of evidence indicating that temperature demand is not fixed is the relationship between level of underheating and SAP rating (Section 3.4); this suggests that occupants might vary their accepted comfort levels depending on the efficiency of the building fabric. It is therefore possible that occupants who previously lived in inefficient dwellings could maintain a higher *M.I.T.* than previously when they move into more efficient ones. This could be termed *inter-dwelling M.I.T. increase*, as opposed to *M.I.T. increase* which refers to one dwelling pre and post intervention.

The hypothesis of *inter-dwelling M.I.T. increase* occurring when occupants move into a more efficient dwelling cannot be tested quantitatively, as monitored data from the new occupants' previous dwellings is not available. However, some qualitative insights can be presented from dwellings 4 and 12.

As can be found in the write up of case study 4 (Section A.2), the occupant reported setting the thermostat at the same temperature in the new flat as the old one. However, he perceived the new flat to be warmer. Therefore any *inter-dwelling M.I.T. increase* would either take place in unheated hours, or as a result of length of heating period, or due to the building achieving the thermostat setting.

Conversely, the occupants of dwelling 12 had been impressed by the warmth of the new flat, and had put the thermostat to 28°C-30°C due to the presence of their new baby. These temperatures perhaps may not have been possible in less well-insulated dwellings. Therefore, there could have been a degree of *inter-dwelling M.I.T. increase* simply because this was possible.

The third household which changed (dwelling 7) had not received an energy bill at the time of the interview so had possibly not reached the stage of settling down with a pattern of heating behaviour. It is therefore not reasonable to comment further on changes in comfort preference following moving into the case study estate.

In summary, further research is required on how people's comfort standards change as they move between dwellings of different efficiencies, but in the very small sample in this study there was an occupant who did not change his thermostat setting, a family who did, and a household in which this cannot be discerned.

## 10.6 INFLUENCE OF CHILDREN ON HEATING AND ZONING

*"I have to put [the heating on] or the children suffer."* (Dwelling 1, pre retrofit)

Children were a large and conscious influence on the pre and post retrofit heating behaviour of the occupants. Parents across the sample had similar views to the above quote from a mother of two; in many cases they spoke as if the children were the main reason they used the heating at all, or as if heating revolved around the children. The households including children fell into two groups: those with children living in the dwelling full-time, and those whose children came to stay at certain times (usually at the weekend). Both situations contain useful insights and will be explored here, followed by a discussion about the influence of children on use of space and heating zoning, and finally implications for energy saving.

#### 10.6.0.1 *Children present part-time: influence of presence of children on heating use*

In dwellings 2, 3, 8 and 9, children came either to visit for the day or to stay. In all cases except dwelling 2, the occupants mentioned dramatic changes in their heating patterns during the period of the children's presence. A clear example of this is dwelling 3, whose occupant's son came to visit on Sundays. According to the occupant, *"Sunday is about the main day that I use the heating"* (dwelling 3, post retrofit). Figure 102, futher explored in case study 3 in the appendices (Section A.1), illustrates the difference in shape of the heating profiles on Sundays compared to the rest of the week. It can be seen that the heating is indeed on for much of the day on Sundays, compared to just the evening (and perhaps the morning) on other days.

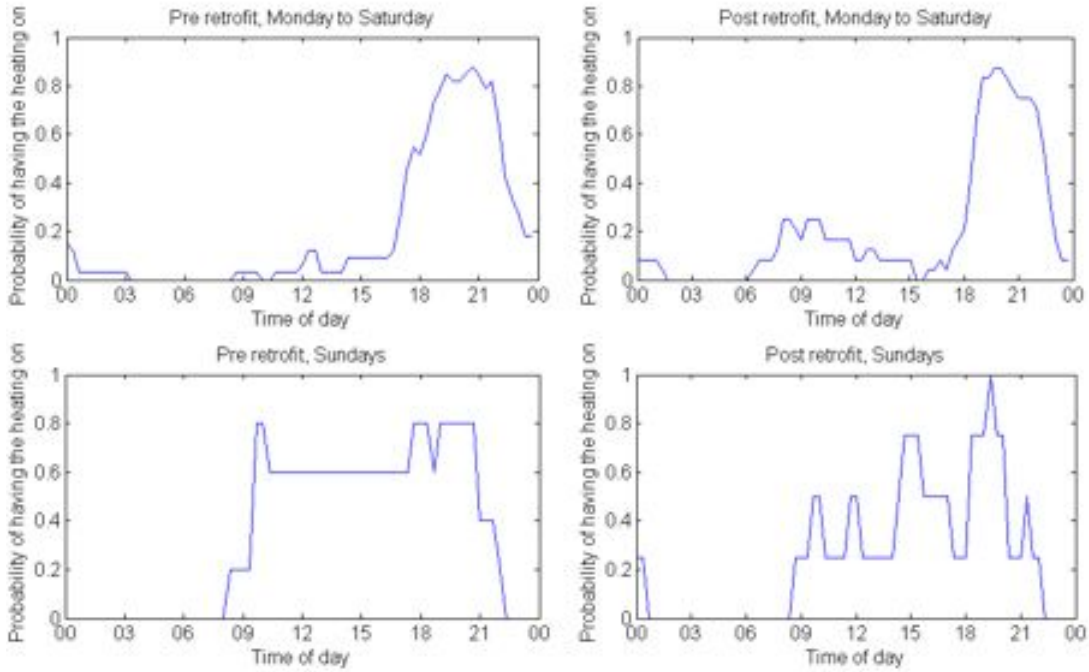



Figure 102: Dwelling 3, probability that the heating is on at different times of day, grouped by Sundays and other days.

It would be interesting to know whether Sunday really was the 'main day' of heating use - what proportion of heated hours occured on a Sunday alone? When the area under each curve in Figure 102 is multiplied by the proportion of days in the week it represented, the result is that before retrofit, $\frac{1}{5}$ of the heated hours occured on a Sunday; after retrofit, it was $\frac{1}{6}$. Although heating use was normally greater when the child was present, it did not represent the majority of heated hours during the week, even if it felt that way to the occupant. In other words, this occupant used the heating for himself more than for his child over a week, but was conscious of the extra he felt he should use when his child was present. It is notable that this 'child' was actually 13 years old; the increased use of heating appears not to be limited to small children, and thus could occur for many years throughout the life of a household.

#### 10.6.0.2 *Children present full-time: influence of presence of children on heating use*

The households who had (or used to have) children living with them permanently (dwellings 1, 10, 11, 12 after retrofit only) all spontaneously brought up the topic of the influence of the children on their heating use. The occupants of dwellings 10 and 12 mentioned that they maintained higher thermostat settings due to the presence of

children. In the case of dwelling 12, in which a baby was present, the thermostat was set at 28-30°C. This logic was reversed in dwelling 10: instead of the presence of a child necessitating a higher thermostat setting, the child's presence brought in child benefit allowance, which allowed the occupant to increase the thermostat setting:

*"Last year, I had a bit more money coming in – I had my youngest daughter here so had more money, and she was a baby so the heating would've been on and it'd have been on the warmer side, so... last winter the digital thermometer was around the 19, 20 degree mark – this winter I haven't set it above 16."* (Dwelling 10, pre retrofit)

The occupants of dwellings 1 and 11 did not refer to the thermostat but described how heating timing revolving around the children. In dwelling 1, in both the monitored data and the interview data, the time the heating was on was closely matched to when the children were in (especially after retrofit). Section 9.3.4.1 presented this in more detail. In dwelling 11, again in both the monitored data and the interview data, the heating was switched on up to four hours before the children came home from school to ensure the dwelling was warm enough for them (although this timing was partly due to the occupant's own schedule of putting the heating on before going for a nap).

#### 10.6.0.3 *Influence of presence of children on door opening behaviour*

Three examples will be described in which door opening within a dwelling was influenced by the competing factors of cold and the presence of children. Following retrofit, the former factor was no longer an issue in some cases.

The first example is dwelling 1, in which the constraint of shutting the doors due to cold was removed after the retrofit. Before the retrofit the occupant would let her children come and spend time in her bedroom, as it was warmer there than in their own room:

*Interviewer: "Do you think [some rooms being warmer than others] affects which rooms you use?"*

*Occupant: "Mmm, because it affects my children. All of the time they come in and sleep with me, and you think OK maybe their room is very cold, and try to use like a double duvet to cover them, it's very hard."* (Dwelling 1, pre retrofit)

During slightly less cold periods, when the children were playing in the living room, their mother stayed in there with them and closed the doors. However, by the time of the post retrofit monitoring period this had changed. Since the doors could then be left

open, without fear of losing all the heat from the living room, the children were able to play in there whilst their mother did her work in her bedroom:

*"I'm just leaving [the door] open, and see what they're doing."* (Dwelling 1, post retrofit)

The second example, dwelling 9, is different from the first in that even before retrofit the occupant felt it necessary to open up the whole dwelling to the child, which required heating it:

*Interviewer: "How much is [your energy bill] in relation to your income?..."*

*Occupant: "To be honest, very, very, difficult. Because you have to keep the entire house warm when you have children. If you want to barricade here, that's where the problem comes if you have small kids, because they need the freedom to run around the house. So you have to keep the entire house warm, for her movements."* (Dwelling 9, pre retrofit)

After retrofit, this behaviour was reported to be the same but less costly for the occupant.

The third example, dwelling 11, is similar to the second in that even before retrofit the opening up of spaces was regarded by the occupant as more important than conserving heat. However, this time the occupant had no choice regarding the zoning strategy, as it was the children who kept the doors open. Their mother discussed this in the pre retrofit interview:

*Interviewer: "Do you keep [internal doors] open or closed?*

*Occupant: "We try to keep them closed, but it is difficult with children!"*

*Interviewer: "Why do you try to keep them closed?"*

*Occupant: "Just to keep in the heat."*

*Interviewer: "The kids come and open them again. Kids don't close doors, do they?"*

*Occupant: "They don't. No matter how many times you tell them!"* (Dwelling 11, pre retrofit)

The extent of this phenomenon of children constantly moving around can be observed in the monitored occupancy data. Figures 103 and 104 both present data from the living room door sensor. As explained in Section 7.14, the unit of analysis is *hourly ocucpancy events*: the number of times per hour the sensor logged an occupant going in or out of the room. It is plotted as a histogram over the day, referred to in this thesis as a daily occupancy profile. It can be seen from Figures 103 and 104 that in both years, at the

time when the children are home from school and still awake (16:00-20:00), the number of occupancy events per hour can exceed 30. There is then almost no point trying to keep the heat in the living room.

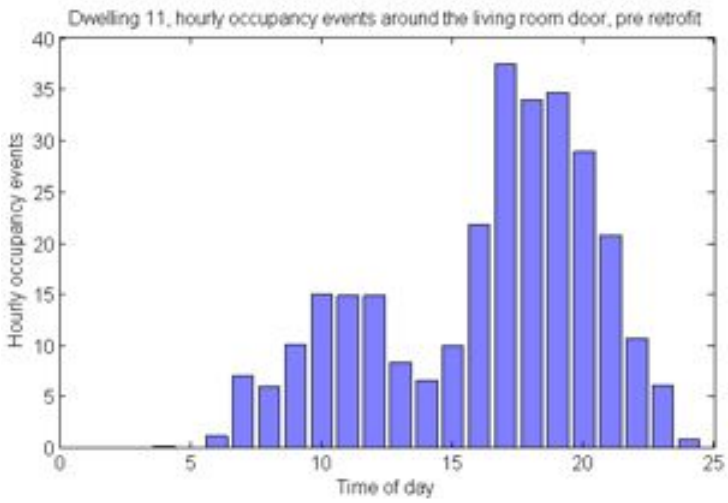



Figure 103: Dwelling 11, illustrating occupancy events per hour around the living room door-frame, pre retrofit.

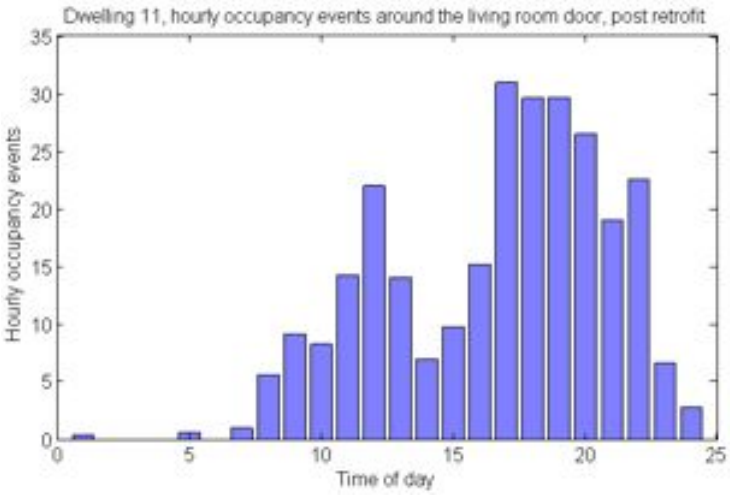



Figure 104: Dwelling 11, illustrating occupancy events per hour around the living room door-frame, post retrofit.

In summary, and to draw some implications from the above, children play a major part in the determination of heating schedule, temperature and the interior zoning of the dwelling. This often plays out not so much from what level of comfort the children desire themselves, but through their parents' decisions of what is needed. Alternatively, considering the zoning of the dwelling, the parents may wish to close off certain spaces but the children open them up anyway. Relating this back to the literature, babies have

been reported as an important driver of heating decisions in DECC (2013b). However, in this thesis the age range was found to extend much further. Occupants with teenage sons and daughters reported using more heating for their children than they would for themselves.

This seems to place limits on possible temperature demand reduction in time and space. If internal doors are kept open, the resulting heat flow means that a dwelling's spatial layout becomes more like one zone in the households with children, and the whole space is heated. When considering what advice could be given to such households to save energy, the parents might agree that they would like to reduce the temperature or hours of heating use, but the priority is not themselves, it is the children. At this point the conclusion from Chapter 4 is relevant again: it would seem desirable to carry out fabric retrofit to such an extent that the (often higher) comfort preferences present in households with children can be met without high energy use.

## 10.7 conflict between fresh air and warmth

The next theme to be discussed concerns the apparent incompatibility of a warm home with a well ventilated one from the point of view of the occupants.

Some occupants appeared to have understood the purpose of trickle vents in terms of reducing moisture or providing fresh air, for example:

*"In my house they're all open. Cos I'm scared of those things, like you know, the... damp, like, the moulds."* (dwelling 1, post retrofit)

Other occupants understood the purpose of trickle vents, but saw them as conflicting with another priority, which was retaining heat. The most critical example of this was in dwelling 2, which was very mouldy and inhabited by an occupant who suffered from asthma. She knew she should keep the trickle vents open to mitigate this but her partner prioritised warmth:

*Woman to her partner: "Jenny's right, you've closed the vents in our bedroom again, you can't do that, that's why the windows are all mouldy!"*

*Partner: "I'd prefer a bit of mould than to feel [cold]"*

*Woman: "Well I don't, cos it ain't good for my chest!"*

*[Pause]*

*Partner: "So why do they put 'em there, then, if you're not allowed to close them..."* (dwelling 2, post retrofit)

A further group of occupants either did not know what trickle vents were at all, or in one case the occupant was aware of their existence but did not understand their purpose in providing background ventilation as opposed to the function of windows for purge ventilation. This resulted in windows being opened occasionally instead of trickle vents being left open continually, as the latter resulted in uncomfortable draughts (the relevant interview section and a more full discussion can be found in Section A.11.6.1).

A similar set of compromises occurred concerning window opening in winter. The occupant of dwelling 11 used air fresheners so that she did not have to open the windows. Even after retrofit, opening windows was not an option for some occupants unless the outside temperature was not too cold.

*Interviewer: "Do you open the windows in winter?"*

*Occupant's son: "I have done, yeah."*

*Interviewer: "In what situations?"*

*Occupant's son: "Just to get some air in here, when it hasn't been overly cold."*

*Interviewer: "If it's really cold outside, would you open them?"*

*Occupant's son: "No!"* (Dwelling 13, post retrofit)

The only example of an occupant mentioning a change in window opening behaviour after retrofit was in dwelling 9:

*"I do open this [bedroom] one in winter, which would have been very strange before, because every night when I'm going to sleep I open the window in my room [..] before you couldn't open a window!"* (dwelling 9, post retrofit)

The latter example could have negative consequences for energy consumption, but could be considered a positive outcome in that the occupant felt he had gained freedom to open the window.

Turning now to the monitored data, it is possible to observe the total effect of the physical retrofit and occupant behaviour on relative humidity (R.H.). This is important,

as the conflict described above could entail the R.H. being maintained at levels high enough to contribute to the types of health problems described in Section 3.2.2.

To compare R.H. pre and post retrofit in a given dwelling, the latter is adjusted to pre retrofit external conditions (R.H. and temperature) according to Equation 29 in Section 7.13. This is a necessary step because the post retrofit external R.H. was lower than that pre retrofit, so without performing this adjustment it is not possible to say whether all of the observed decrease in post retrofit R.H. was simply due to different external conditions or whether the retrofit changed the internal conditions. Figure 105 shows the pre retrofit R.H., and adjusted and unadjusted post retrofit R.H., compared to the critical levels above which house dustmites and mould are likely to grow as noted in Section 3.2.2:

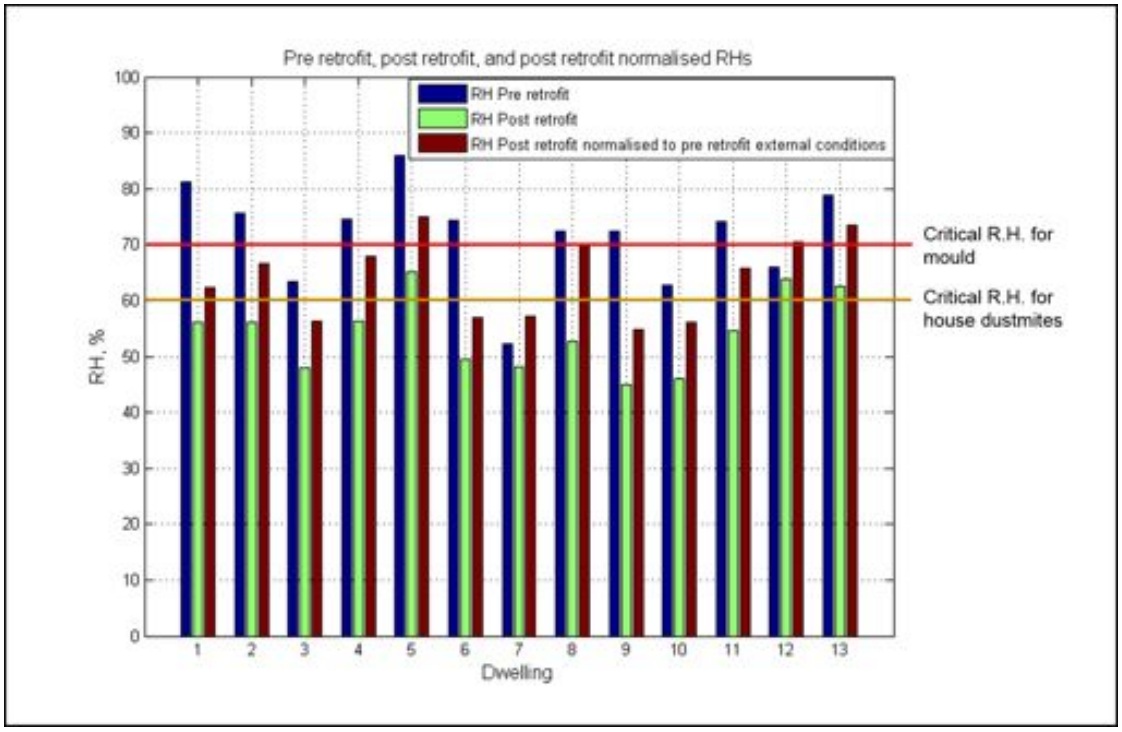



Figure 105: Change in R.H. following retrofit.

Figure 105 shows that the R.H. decreased after retrofit in 11 out of 13 dwellings. The two dwellings that demonstrated an increase in R.H. were those inhabited by new occupants. This is a positive result, but is not in itself the important metric: it is the absolute R.H. which matters to occupant health. In fact, in almost $\frac{2}{3}$ of the dwellings the post retrofit R.H. is still above 60%. There is still a substantial risk of dustmites and some risk of mould. However, given that the retrofit was not deliberately designed to lower internal R.H., this incidental decrease is a positive outcome.

Figure 105 also shows the importance of taking external conditions into account: without performing this adjustment, the reduction in R.H. after retrofit is overestimated.

A second finding can be highlighted from this analysis. During the derivation of Equation 29 in Section 7.13, the vapour pressure generated within the dwelling, $VP_{gen}$, was calculated for each household pre and post retrofit. This quantity is a function of both occupant behaviour and the ventilation rate of the dwelling. Both could change following retrofit: the ventilation rate might decrease especially in the properties in which double glazing was installed. Occupant behaviour could also have changed, although occupants did not seem to think they had changed their window opening behaviour (except the occupant of dwelling 9).

Figure shows the change in $VP_{gen}$between the monitoring periods:

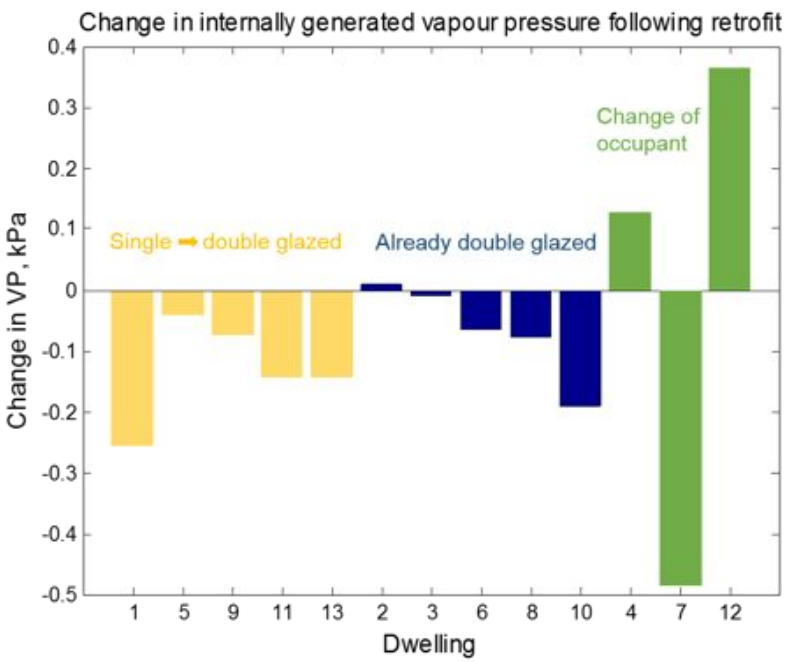



Figure 106: Change in $VP_{gen}$ following retrofit.

Figure 106 shows that, despite some of the dwellings being fitted with double glazing, in most dwellings the generated vapour pressure either stayed about the same or decreased. The sample size is not large enough to determine whether the addition of double glazing made a difference to the generated vapour pressure. Figure 106 seems to suggest that occupant behaviour changed such that generated vapour pressure decreased following retrofit. Only in one dwelling (9) did an occupant report opening windows more following retrofit; it is possible that others did so without realising. In general, the result in Figure 106 was not what the author had hypothesised.

The three dwellings which had different occupants in the second year are separated out on Figure 106. It can be seen that in two of these the largest effects on $VP_{gen}$ are observed. Although the sample sizes are small, it appears that a change of occupant is more important than the installation of double glazing to change in $VP_{gen}$. However, further work is required in this area as the sample sizes in this study are too small to show any result conclusively.

## 10.8 USE OF SPACE

Due to the occupancy sensors not working as well as had been hoped, the monitored data obtained was not real-time data of which rooms were being used, but data on frequency of changing room. Therefore it is not possible to answer questions originally proposed by the author at the start of the PhD (documented in Section 12.5), concerning when the heating was on compared to when occupants were present in a given room. However, the data actually obtained yield four main observations of interest which will be described here. The following discussion begins with an investigation into frequency of changing room, then the relationship between occupancy and heating, and ends on the potential for change of use of space following retrofit in the case study dwellings.

### 10.8.1 *Frequency of changing room across the sample*

Current dynamic domestic energy models (such as EnergyPlus) assume that occupants stay in a room for at least an hour at a time. The data from the study in this thesis, however, shows much higher frequency change. As was highlighted in Section 10.6.0.3, the occupants of dwelling 11 move around such that someone goes into or out of the living room up to 30-40 times per hour at certain times of day. The mean number of events per hour, at the hour of the day in which this was highest, is shown across the sample in Figure 107; it spans from 4 to 37.

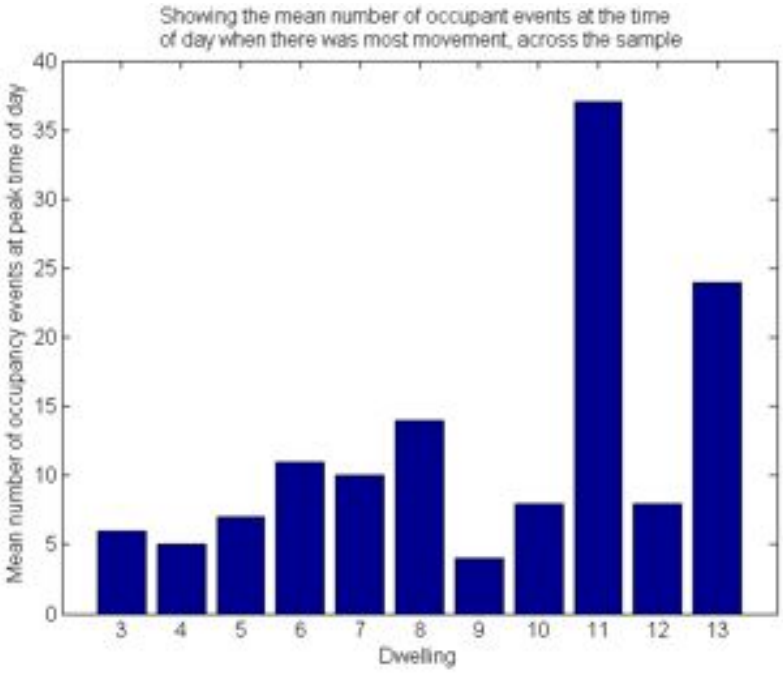



Figure 107: Mean occupancy events per hour, at the hour in which this was greatest, across the sample.

This is not the same metric as total room changes per hour, since Figure 107 only represents one key doorway representing movement around the dwelling, but is a minimum bound for hourly room changes. The author did not especially have a preconceived idea of how often people change rooms, but was surprised at how high the numbers in Figure 107 were. If people move around more than is currently assumed in dynamic energy models then there may be implications here for the usefulness of zoned heating systems. This is firstly because if doors are either left open or frequently opened then heat may flow around the building more than is currently assumed, and secondly because it may be that the frequency at which occupants enter and leave a room is higher than a heating system can keep up with.

On this latter point, Scott et al. (2011) claimed to have implemented a heating system which used machine learning algorithms to predict when each space would be occupied, preheated that space, and only kept it warm for the time during which the space was occupied. However no mention is made in the study of how often occupants changed room (or in fact whether they wanted each room they occupied to be heated - but this is a different matter), and whether the heating system could keep up, given an inevitable degree of inertia.

An attempt will now be made to compare the frequency of room change observed in the case study sample to that in other studies. In Chapter 7, a study by Gillott et al. (2009)

was briefly introduced to illustrate the use of RFID sensors worn by occupants to monitor their whereabouts. Figure 108 is reproduced here from Spataru and Gillott (2011) with the first author's permission. Each discrete value on the vertical axis represents a different room, the horizontal axis is time of day, each colour represents a different occupant, and each subplot represents a different day of the week.

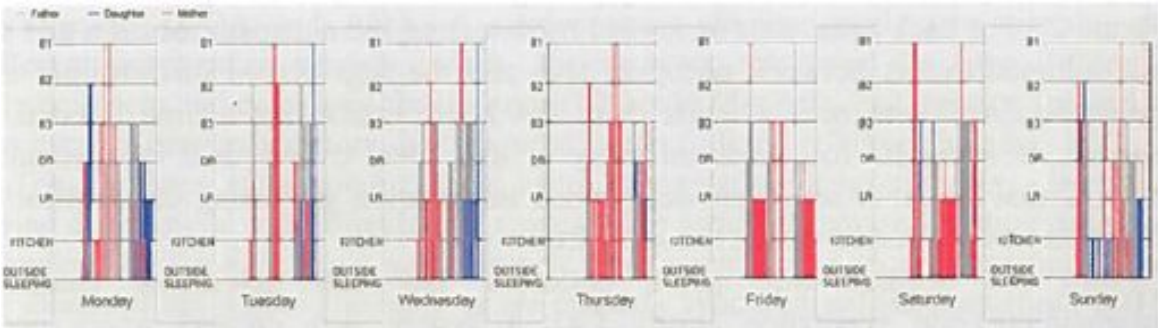



Figure 108: Which rooms used against time of day, aggregated, from Spataru and Gillott (2011).

Using the above data, the authors calculated these occupants changed room 4-7 times per hour (Catalina Spataru 2013, pers. comm.). However the sample size was even smaller than that in this thesis. Further work of the same type has not been carried out with this data.

In short, high-resolution temporal and spatial dimensions of occupancy within dwellings remain relatively unknown.

### 10.8.2 *Frequency of changing rooms across the day*

The metric *hourly occupancy events* was introduced in Section 7.14, and first used in Section 10.6 on a plot called a daily occupancy profile in order to show the effect of children on the potential for keeping internal doors closed in dwelling 11. This metric and type of plot will now be used to examine use of space more widely than just the data from that dwelling.

From examining the occupancy data it was observed that most daily occupancy profiles fell into one of three categories: those which rose then fell gradually throughout the day, those with two relatively even peaks (in the morning and early evening), and those whose evening peak was higher than the morning peak. An example of each is shown in Figures 109 to 111 respectively. This time the histograms are given in the form of box

plots, so that the extent of variation as well as the mean *hourly occupancy events* can be observed.

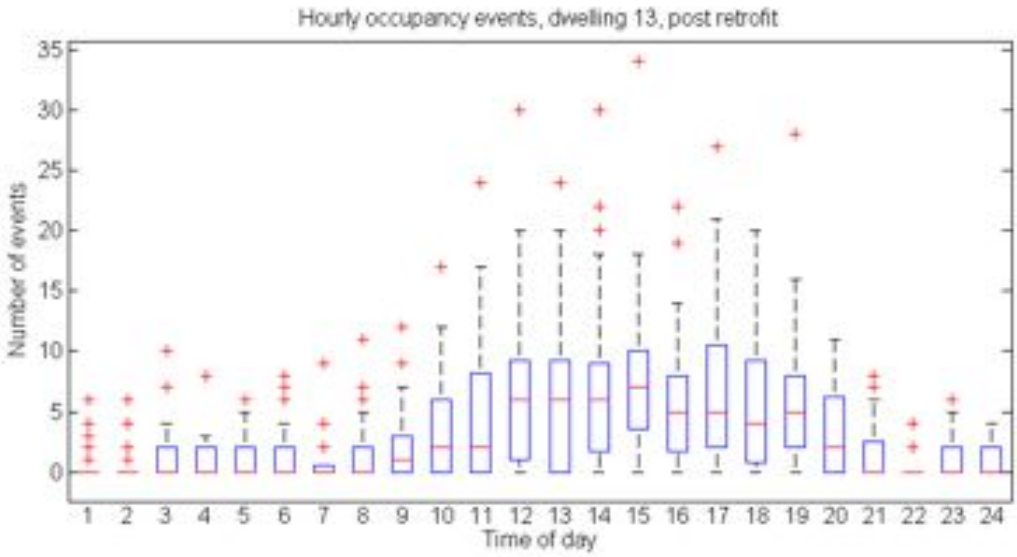



Figure 109: Dwelling 13, box plot histogram of daily occupancy profile (post retrofit).

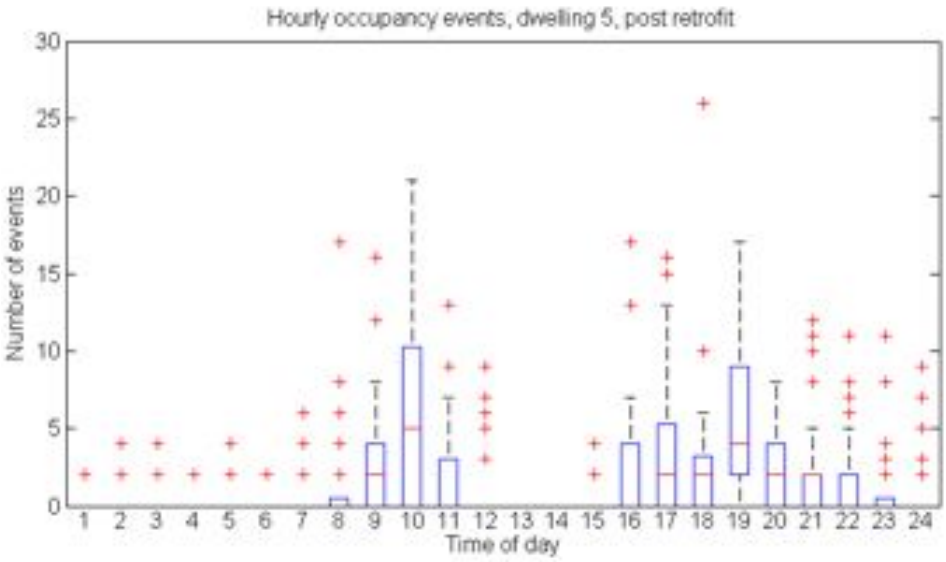



Figure 110: Dwelling 5, box plot histogram of daily occupancy profile (post retrofit).

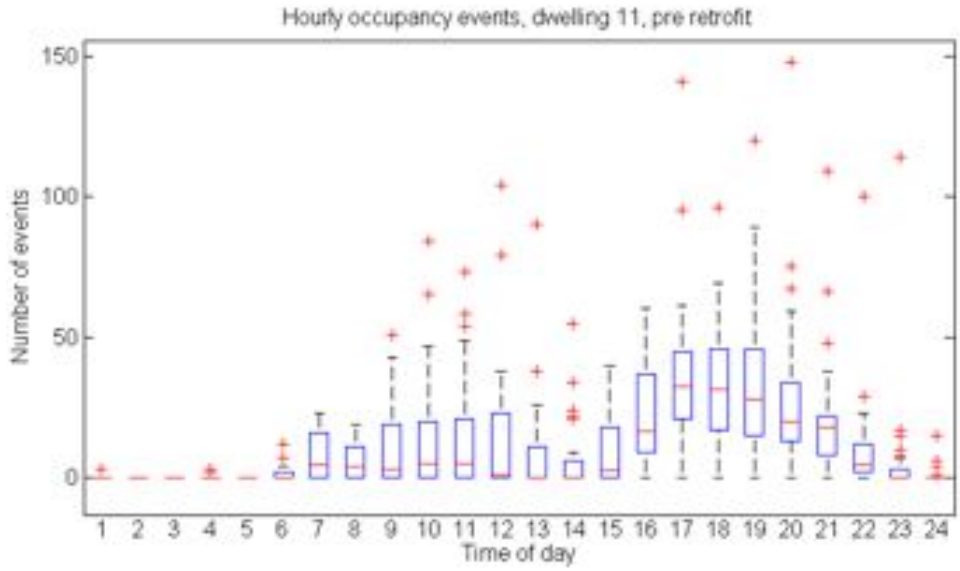



Figure 111: Dwelling 11, box plot histogram of daily occupancy profile (pre retrofit).

The first example profile (Figure 109), featuring one gentle peak centred around the afternoon, is typical of occupants who are relatively housebound; in the case studies normally because they have mobility difficulties. The second (Figure 110) is typical of those who either work, or do not work but instead go out every day. In this type of profile there is a morning period of activity, then the occupants go out, then they come back and there is another period of activity, then they settle down in the evening. The third type of profile (Figure 111), featuring a period of more movement in the evening than during the other peak in the morning, is proposed to be more common in households with children but this cannot be verified since the sample size is too small.

### 10.8.3 *Observations about the relationship between occupancy and heating use*

Several interesting features can be observed from combining a daily occupancy plot with other types of monitored data. Figure 112 shows a daily occupancy plot onto which are superposed the probability that the heating is on and the dwelling *mean internal temperature* across the day. In about a third of households, probability of heating increases during the evening as *hourly occupancy events* decreases. Dwelling 12 was chosen to illustrate this, in Figure 112:

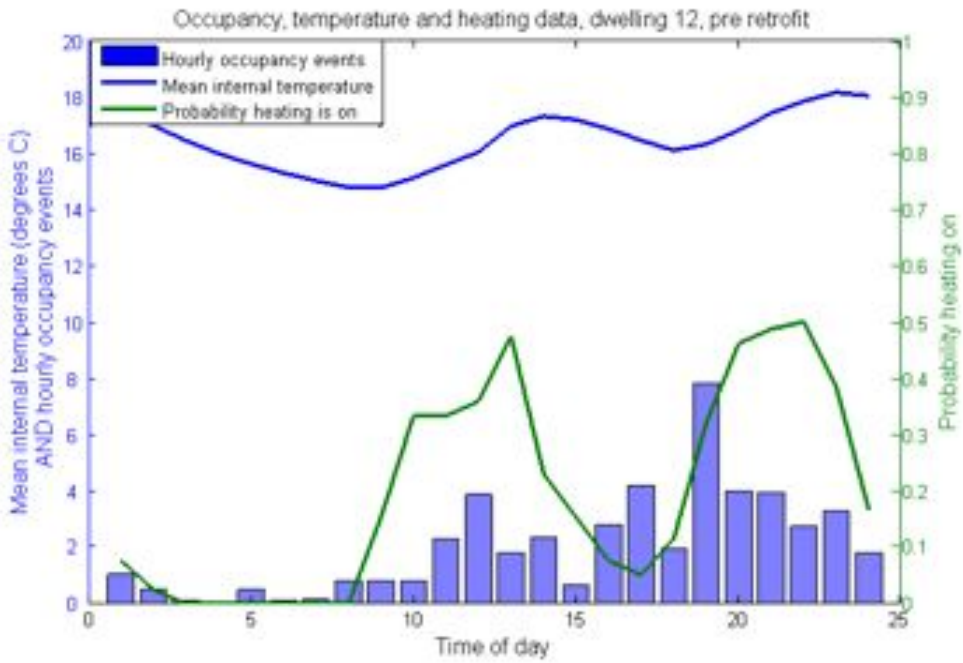



Figure 112: Dwelling 12, pre retrofit: Showing the relationship between heating, occupancy and internal temperature.

From the interview data, during this period occupants are generally settling down into one room (usually the living room), to watch television or read. This was also found in the interviews carried out in DECC (2013b).

It is reasonable that a decrease in *hourly occupancy events* occurs at the same time as an increase in *mean internal temperature*, as lower metabolic rate requires more ambient heat for thermal comfort to be maintained (Section 3.2.1). If, as is normally the case, this temperature rise comes about by central heating, it seems that whole-house heating is used when the occupant is presumably settling down in one room. This may or may not be a waste of heat. For example, if an occupant settled down for the evening in the living room - as the occupant of dwelling 12 to which Figure 112 refers claimed to do - he would be heating not only himself but also the kitchen, the bedroom and the hall. Some of this heat may turn out to be 'useful' later on, for example when he went to bed he may have appreciated his bedroom being warmer than it would have been if the heating had not been on. Equally, the heat delivered to rooms which are not the living room might be considered as non-useful heat. The field of energy and buildings does not yet have a unanimous definition of what is 'useful' heat and what is not.

### 10.8.4 *What is the potential for change in use of space after retrofit in the case study dwellings?*

At the start of the study, it was theorised that a change in use of space after retrofit could both exist and be observed. This was partly based on previous qualitative studies (see Section 3.5.1), normally under two premises. The first is that occupants use and heat only one room before retrofit. The second is that they expand their use of space into other rooms after retrofit, due to a combination of the rooms being naturally warmer (theorised in Section 2.2.2.3) and cheaper to heat.

After the first monitoring period, the author realised that few of the occupants had the opportunity to significantly change their use of space. Furhtermore, few had the opportunity to spatially expand their use of heating.

Concerning expansion in use of space, few of the case study dwellings contained unused rooms. Of those which contained a spare room, in some cases the occupants were already using it for something (see for example case study 8 in the appendices, whose occupant liked to *"potter"* around).

Concerning spatial expansion in use of heating, all the households already heated all of the rooms before retrofit, apart from dwellings 8 and 3 who both had a spare room and had turned the T.R.V. to a low setting (dwelling 8) or switched the heating off in that room (dwelling 3).

The two households who did report changing their use of space after retrofit (see Section 10.8 above), in one case to spend more time in his bedroom and in the other case to *"wander around"* the house more, did not change their spatial heating behaviour as all the rooms were already being centrally heated. This is evidence that a change in use of space can occur after retrofit without an increase in heating (in other words, these two outcomes can be uncoupled).

Shortly after the post retrofit monitoring period the 'spare room tax' came in (April 2013). Many of the tenants who were under-occupying their properties talked in the interviews about potentially having to move out. If the probability of social housing tenants having a spare room decreases, this further decreases the potential for their use of space to expand.

It is therefore concluded that in social housing, the idea of expansion of use of space resulting in spatial expansion of use of heating is unlikely. The main reason for this is that people already heat all the rooms (which is the default behaviour for a dwelling

in which there is central heating); a subsidiary reason is that most of them do not have that much unused space (any more).

Perhaps it is not surprising that only a small amount of empirical evidence was found for expansion of use of space and heating in this study. One piece of social theory and one piece of physical theory will be used to suggest why.

In terms of social theory, DECC (2013b), reviewed in Section 3.5.1, distinguished between occupants in larger dwellings who perceived their dwelling as a conglomeration of spaces, and those in smaller dwellings who thought of it as one space. Therefore, the theory of expansion of use of space and heating post retrofit may be more likely in larger (under-occupied) houses with unheated rooms.

In terms of physical theory: if expansion of use of space occurred following fabric retrofit, then one proposed mechanism would involve reduction of *inter-room temperature gradient* (Section 2.2.2.3). The previous chapter described how the latter is probably a second-order effect in the case study dwellings: *inter-room temperature gradient* only slightly reduced in most dwellings, and it was shown that other factors apart from the retrofit change this more. It is then likely that the temperature gradient effect of retrofit did not drive change in use of space in the case study dwellings.

## 10.9 CONCLUSION

This chapter demonstrated the type of insight which can be obtained by the combination of physical and social data from an in-depth study. Reflection on the benefits and disadvantages of this type of research design are given in the the Conclusion chapter. Before this, the Discussion chapter will bring together the findings from across the three results chapters and interpret them in the light of the theory and literature introduced at the start of the thesis.

# 11

# DISCUSSION

## 11.1 INTRODUCTION

The previous three chapters presented detailed findings from the two research questions, restated below:

In social housing undergoing building fabric retrofit,

1. How does internal temperature change afterwards, during heating and non-heating hours and throughout the dwelling?

2. If internal temperature changes afterwards, why? What are the interactions between occupants, building fabric and heating systems which produce the temperature change?

However, the empirical study carried out to answer the questions has provided insight not only into how *mean internal temperature* changes following retrofit, but how it is determined in the first place. Understanding this can offer some implications as to how retrofit could be carried out in this type of dwelling to achieve better outcomes, both in terms of occupants' thermal needs and in terms of energy use.

Therefore, in this chapter insight about *mean internal temperature* will be used as a way to frame or understand the findings of how it changed after retrofit. The flow of the chapter is as follows:

1. How *M.I.T.* is determined in the case study dwellings;

2. How this led to a change in *M.I.T.* and heating behaviour following retrofit;

3. Tentative implications of the above for how building fabric retrofit of social housing is carried out.

These three sections will draw together the results chapters with the theory, literature and modelling chapters at the start of the thesis.

## 11.2 NEW INSIGHTS ON HOW MEAN INTERNAL TEMPERATURE IS DETERMINED

### 11.2.1 *Current and new models of mean internal temperature*

In Chapter 2, the influences to M.I.T under the BREDEM modelling paradigm were visualised in a diagram. This is reproduced in Figure 113 with the addition of an arrow from M.I.T. representing the energy and cost consequences (although M.I.T. is not the only factor affecting energy use and cost in the BREDEM paradigm; the full set of relationships is not shown here to simplify the diagram):

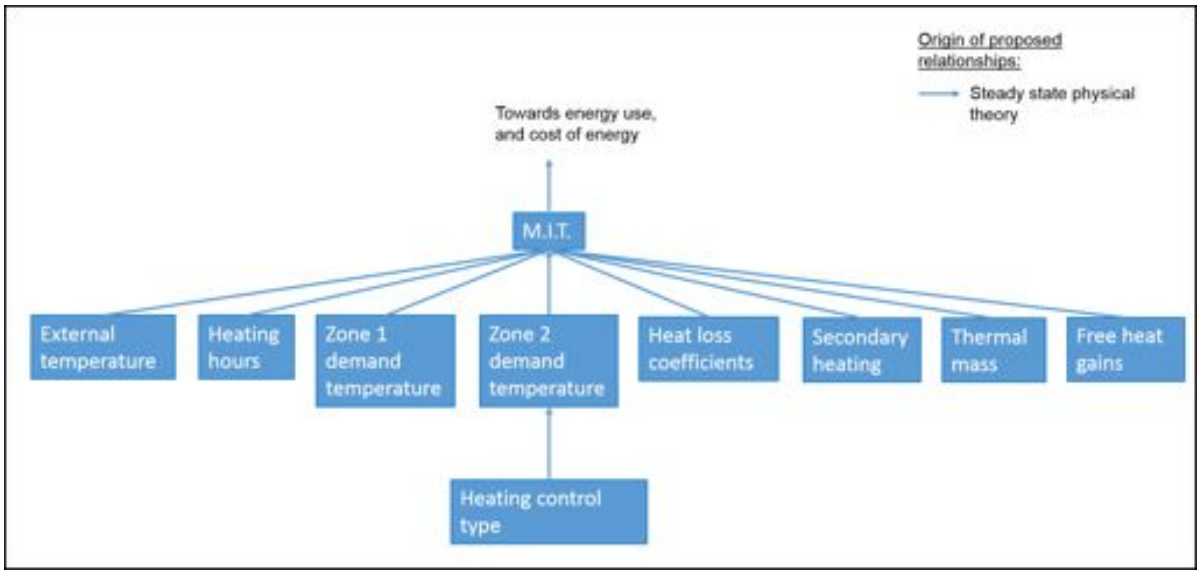



Figure 113: Influence diagram for M.I.T. according to BREDEM.

Using analysis from the empirical study in this thesis plus aspects of the theory and literature introduced in Chapters 1-3, a new conceptual model of *M.I.T.* can be constructed. A visualisation of this is shown in Figure 114. Whereas all the relationships in the BREDEM influence diagram were physics-based, the empirical-based diagram contains a number of types of relationships:

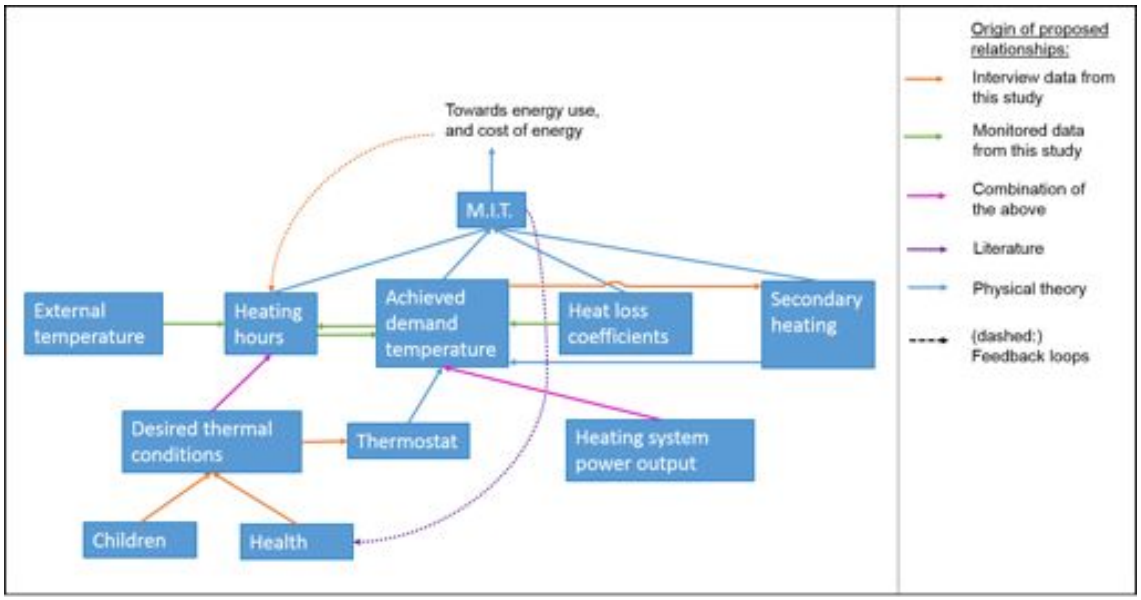



Figure 114: Influence diagram for *M.I.T.* according to the analysis in this thesis.

Figure 114 will now be used to explore some of the new relationships proposed.

### 11.2.2 *A comparison of the old and new models of mean internal temperature*

#### 11.2.2.1 *Form of the model*

Two features of the form of Figure 113 and Figure 114 can be contrasted. Firstly, it can be seen that within the BREDEM modelling paradigm, modelled M.I.T. is created through a one-directional function; that is, there is no feedback between modelled M.I.T. (nor its energy/cost consequences) and the set of input variables. The empirical-based model, however, does not treat *M.I.T.* as simply a dependent variable but contains feedback loops - firstly from *M.I.T.* to health, and secondly from energy cost back to heating hours.

Secondly, in the BREDEM configuration all of the variables contributing to the creation of the modelled M.I.T. are independent of each other - there is no covariance. In contrast, within the empirical-based model these variables in fact depend on each other. Some of these interrelationships will now be discussed, in doing so highlighting some impacts on BREDEM and SAP.

#### 11.2.2.2 *Influence of external temperature on daily heated hours*

From Figure 114 the following relationship can be observed:

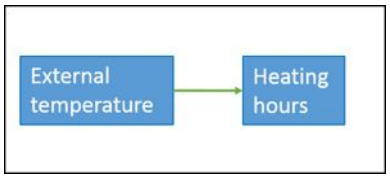



Figure 115: Relationship between external temperature and *daily heated hours.*

In the SAP model, modelled daily heated hours is assumed to be a constant value whose only variation is that between weekdays and weekend days. Recent studies have shown that this particular distinction is not representative of heating behaviour in the U.K. (Section 3.3.3). In the empirical data from this thesis, it was found that there exist other reasons for variation in *daily heated hours*: Chapter 8 showed that in the case study dwellings the heating was on for longer on colder days. Chapters 9 and 10 explored the means by which this flexibility arose: the use of manual heating control, which the occupants preferred to timed or predictive systems.

#### 11.2.2.3 *Influence of the building and heating system on achieved demand temperature*

From Figure 114 the following relationship can be observed:

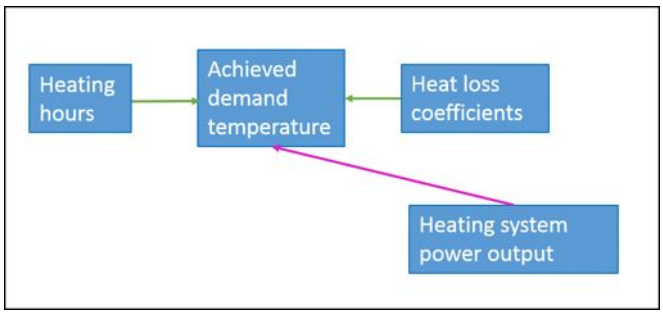



Figure 116: Heating timing-heating system-building fabric combination.

When modelling a real dwelling in BREDEM, if there is known to be a thermostat present then modelled demand temperature is based on the thermostat setting. However, in the case study dwellings, the *achieved demand temperature* was only influenced by the thermostat setting in a minority of cases (the thermostat is included in Figure 114, so that this minority is represented, but omitted from Figure 116). This was because

in general the thermostat was set too high for the internal temperature to reach the setpoint. This occurred for three reasons:

- The thermostat was not being used as a temperature control;
- The heating period was too short for the internal temperature to be raised to the setpoint;
- Even if the heating was left on until the internal temperature stabilised, the combination of the building fabric and heating system could not raise the internal temperature to the setpoint.

Therefore, the *achieved demand temperature* was determined not by the thermostat but by the heating system-building fabric combination, and the heating timing.

A consequence of this was that after retrofit, if the heating was left on for long enough then the reduced heat loss of the building fabric allowed the *achieved demand temperature* to rise.

Translation of this to the impacts on SAP modelling must be carried out with caution, due to the differences between the concepts of empirical *achieved demand temperature* and SAP modelled demand temperature. However, it is attempted below:

| |
|---|
| SAP Impact 1: in inefficient dwellings, modelled demand temperature does not represent the actual temperature profile during heated hours. Temperature during heated hours is a function of the heat loss coefficient and the heating period length. If the heating is left on for long enough for the internal temperature to stabilise, temperature during heated hours increases after retrofit due to the *achieved demand temperature* increasing. |

#### 11.2.2.4 *Influence of the building on use of secondary heating*

However, the mechanism shown above by which the heat loss coefficient influences the *achieved demand temperature* is not the complete picture. Expanding Figure 116 to include secondary heating, the following subsystem is found in Figure 114:

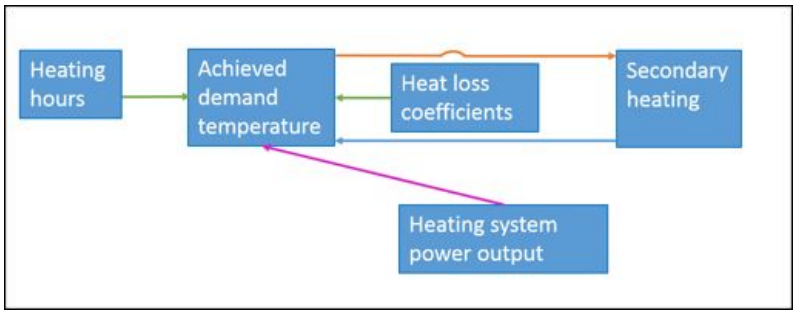



Figure 117: Heating timing-heating system-building fabric-secondary heating interaction.

In BREDEM-based models, energy use from secondary heating is assumed to constitute a fixed percentage of the overall space heating energy use; this is purely based on assumptions and not data (Section 3.3.5). DECC (2009) attempted to monitor energy use of secondary heating and BRE (2013e) surveyed how often it is used and made a partial attempt to uncover why. However, the relationship between heat loss coefficient and use of secondary heating has not previously been analysed.

This relationship cannot be quantitatively demonstrated in this thesis, but the following was found. Before retrofit, it was common for occupants to use secondary heating to top up the *achieved demand temperature*, as the (primary) heating system-building fabric combination did not allow a comfortable temperature to be maintained during heated hours. After retrofit occupants stopped using secondary heating, except for during the time they were waiting for the main system to warm the dwelling (Chapter 9). Expressed in the language of the variables in Figures 113 and 114, once the heat loss coefficient had decreased sufficiently for the primary heating system to reach a high enough *achieved demand temperature*, secondary heating was no longer needed to top it up. This is important, as secondary heating often has a higher $CO_2$ intensity than primary heating as well as being more costly per unit of delivered heat. Eliminating its use could be seen as a positive outcome in both of these terms.

SAP Impact 2: use of secondary heating is proposed to be a function of heat loss coefficient.

#### 11.2.2.5 *One zone*

An empirical equivalent to SAP Zone 2 modelled demand temperature has not been shown on Figure 114. This is because there was no reason to split the case study dwellings into two zones.

As explained in Chapter 2, BREDEM assumes one modelled demand temperature in zone 1 and another in zone 2, the latter normally being 3°C cooler than the former. It can be argued from a combination of the case study data and the literature that this two-zone representation is not necessary in this type of dwelling. In general all rooms are heated, by the central heating system, and in general the T.R.V.s are set to maximum. This does not necessarily lead to the living room being warmer (Figure 57); in fact, it is not possible to predict in this sample which room will be warmest. Nationally, bedrooms are found to be only 0.6°C cooler than living rooms in winter - see Section 3.3.3. Furthermore, DECC (2013b) suggests that households in smaller dwellings think of their home as one space, as opposed to a conglomeration of spaces (Section 3.2.3). This interpretation fits with the whole-dwelling heating behaviour generally observed in the case study sample presented in this thesis.

As dwellings become more efficient, physical theory predicts that natural temperature differences between rooms will decrease (Section 2.2.2.3). A small decrease was observed in most of the case study dwellings, although other effects dominated this purely physical phenomenon. Even though the effect was small it is in the direction of lessening the need for a two-zone model.

| |
|---|
| SAP Impact 3: a one-zone model is more appropriate than a two-zone model; this may become even more so as dwellings become more efficient. |

#### 11.2.2.6 *Influence of children on heated hours*

From Figure 114 the following relationship can be observed:

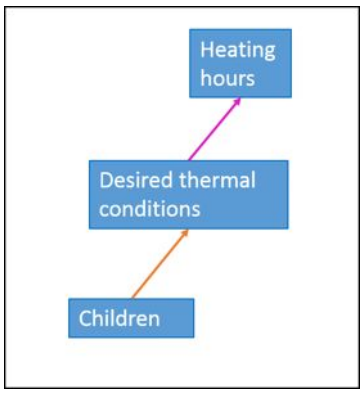



Figure 118: Influence of children on *daily heated hours*.

Occupants with children were unanimous in that the main purpose of the heating was for the children (Section 10.6). Whether the children lived there permanently or just

at weekends, several occupants reported heating timing revolving around the children: heating being on when the children were in (dwelling 1), the house needing to be pre-heated before they came home from school (dwelling 11), or the main day of heating use being when the child came to visit (dwelling 3). This did not lead to higher thermostat settings except in the case where a baby was present (dwelling 12) and the case where extra child benefit allowed the occupant to maintain a higher thermostat setting (dwelling 10). Households with children reported that it was not possible to keep the heat in a room of choice, as either the parents wanted the children to be able to move all around the dwelling (dwelling 9), or the children did so anyway (dwelling 11 - there is also quantitative evidence for this), and left the doors open as they moved around.

One implication of the above is that zoned heating solutions do not appear to be suitable for households with children. The analysis in this thesis suggests that people change rooms more frequently than is assumed in dynamic building models, especially in households with children. This means that not only will heat then be transferred between spaces more than currently assumed, but also it will not be trivial for a heating system to deliver heat to where an occupant is at the desired time. The most recent and relevant published study on what people may want from future heating systems, DECC (2013b), did not highlight children as an important theme in their analysis, but equally they did not have occupancy data to show how often children move around in a dwelling.

Figure 114 will now be used to demonstrate some of the outcomes of retrofit in the case study dwellings.

## 11.3 NEW INSIGHTS ON WHAT HAPPENS FOLLOWING RETROFIT

Given the new conceptual model of *mean internal temperature* proposed above, some of the outcomes of retrofit will now be restated in the context of this model. Figure 114 suggests that heat loss coefficient is not just related to *mean internal temperature* in a direct, physics-based relationship, but that the former also influences the latter through several additional variables. At this point it is relevant to restate the conceptualisation of retrofit by Lowe et al. (2012) given in the Introduction chapter:

*"The interactions between the different components (heating and ventilation systems, solar thermal etc) and the physical envelope of the dwelling, and with the people who retrofit and inhabit it, form a complex system whose behaviours cannot always be predicted, particularly during times of rapid change."*

Therefore, when one variable is changed (heat loss coefficient), it does not only affect mean internal temperature as in the BREDEM influence diagram in Figure 113, but a set of variables around it. Some of the relationships highlighted above will now be returned to in the context of building fabric retrofit. Firstly, the main results concerning *M.I.T.* will be restated and compared to the literature.

### 11.3.1 *Main outcome*

Across the 13 case study dwellings, the *M.I.T. increase* after external wall insulation (and in some cases double glazing) ranged from -7.6°C to 4.0°C. This is a very large range; if only those dwellings with the same occupants pre and post retrofit are taken into account, the *M.I.T. increase* ranged from -0.9°C to 4.0°C and was positive in most dwellings (mean of this subsample = 1.4°C; standard deviation. = 1.5°C)[1].

These results can be compared to other studies of *M.I.T* before and after building fabric improvement. Hong (2011) found a mean increase of 0.73°C and Martin and Watson (2006) found a mean increase of 0.6°C, both after shallow building fabric retrofit. The case study dwellings rose in temperature slightly more than those in other literature. However, not a great deal can be interpreted from this as not only was the case study sample small and its standard deviation high, but both the interventions and dwelling constructions were different from those in Hong (2011) and Martin and Watson (2006).

### 11.3.2 *Change during heating periods*

The measured change in two variables related to heating use explored in Chapter 8, *daily heated hours* and *achieved demand temperature*, is shown in Figure 119 below, with the change assumed in SAP (i.e. zero) shown for comparison:

1 this necessitated using the standardised metric of *M.I.T. increase*, in which the internal temperatures are adjusted to represent a situation in which the external temperature is 5°C as in Hong (2011). Also, dwelling 6 is omitted here as the central heating system was broken during the pre retrofit monitoring period.

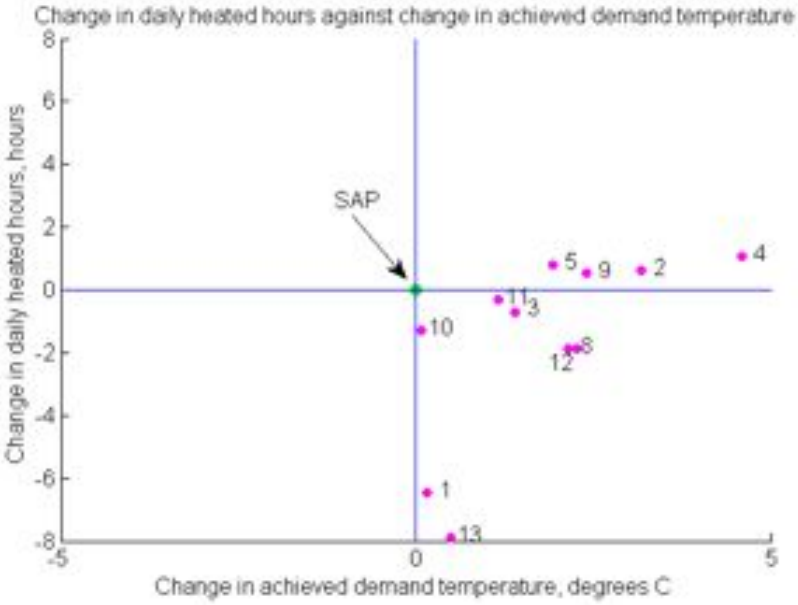



Figure 119: *Daily heated hours* and *achieved demand temperature* change.

It can be seen from Figure 119 that contrary to the SAP assumptions of modelled daily heated hours and modelled demand temperature remaining constant following building fabric retrofit, instead in most cases *achieved demand temperature* increased and *daily heated hours* decreased (although in some cases *daily heated hours* increased). Sections 9.6.2 and 9.6.1 explored each of these results respectively. A summary is as follows:

#### 11.3.2.1 *Change in achieved demand temperature*

It was shown in Section 7.9 that a suitable definition of 'demand temperature' in this thesis is the air temperature achieved during a heating period, without a constraint of this temperature being stabilised over time. This was because one consequence of the nature of the occupants' heating control often being manual and their heated hours being relatively low was that they frequently turned off the heating before the air temperature stabilised. The definition was termed *achieved demand temperature.*

The proposed link between heat loss coefficient, heating system power and *achieved demand temperature* was discussed above in Section 11.2.2.4. It was shown that although after retrofit, the *achieved demand temperature* increased across most of the sample, this did not occur due to occupants increasing their thermostat setting as is commonly assumed, but was proposed to occur due to the building fabric allowing a higher temperature to be maintained.

This is arguably a positive outcome: Figure 120 shows that the *achieved demand temperature* even post retrofit was still lower than the national average. One effect of the retrofit was to bring the *achieved demand temperature* nearer, but not quite up to, the national average.

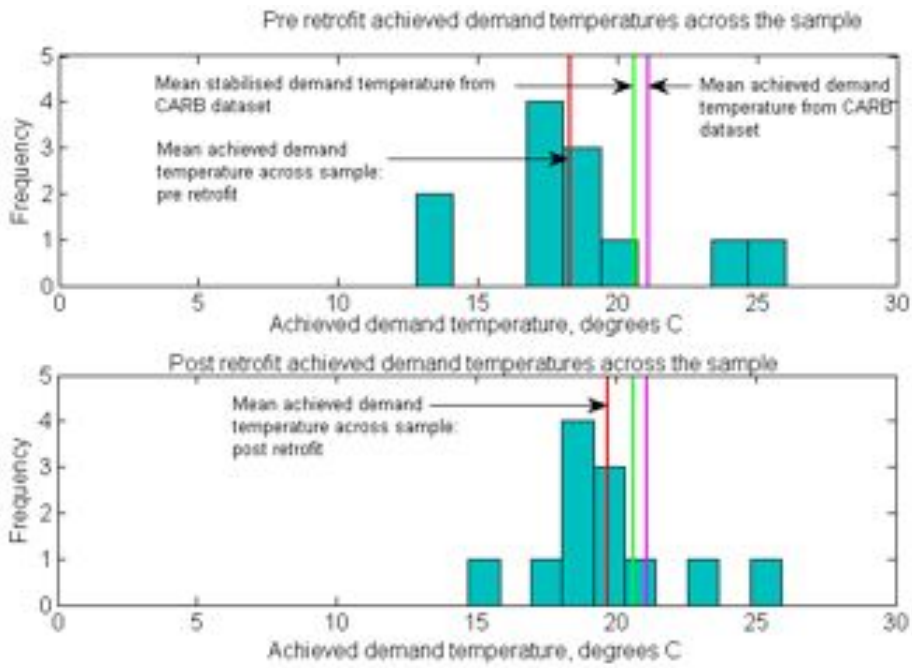



Figure 120: *Achieved demand temperatures* in the sample compared to larger studies.

Please note that the histograms in Figure 120 include all the dwellings in which is possible to calculate *achieved demand temperature*, in order to show the variation across the sample, whereas the red lines showing the mean across the sample are for the purpose of pre and post retrofit comparison, and therefore exclude those dwellings which can be compared longitudinally: 4,6,7 and 12 (see Section 7.15.3).

None of the occupants reported needing extra (secondary) heating during the heating period after retrofit, implying that their demand for heat during heated hours was now satisfied. Two of them did however use secondary heating to attain an appropriate temperature quickly whilst the central heating system was warming up the dwelling.

In two dwellings, after retrofit the heating period was shortened to such an extent that the *achieved demand temperature* could not increase. Thus, the *achieved demand temperature* and heating period are related (as shown in Figure 114); the latter is the subject of the next section.

#### 11.3.2.2 *Change in daily heated hours*

Given that a relationship was found between *daily heated hours* and external temperature for most of the sample, this suggests that switching the heating on and off is at least partially triggered by thermal sensation as opposed to time of day. After retrofit, the building should cool more slowly when heating is turned off, thus it may be expected that *daily heated hours* decrease. In general, this occurred. Where this did not happen, it was in some cases (dwellings 2 and 8) associated with the occupants' thermal comfort during unheated hours not being satisfied after the retrofit.

To summarise the change observed following retrofit concerning heated periods, there was one downwards change instigated by occupants - concerning heating timing (*daily heated hours*) - and one upwards change brought about by building physics - concerning heating temperature (*achieved demand temperature*).

### 11.3.3 *Change during unheated periods*

In contrast to the previous section, the relationship to be explored here - that between heat loss coefficient and internal temperature when the heating is off - is a purely physics-based one, where an outcome is produced without the occupants changing their behaviour in any way.

Most of the temperature effect of retrofit occurred during unheated hours as opposed to heating periods. Perhaps the main reason for this is that most hours were unheated: only 0.4-9.1 hours per day[2] pre retrofit, and 0.9 to 6.7 hours per day post retrofit, were heated (Section 8.2.2). Quantifying the relative effect of unheated hours on total *M.I.T. increase* in Section 8.3 gave a range of 77-87%.

This finding is in line with the modelling exercise carried out by Deurinck et al. (2012), reviewed in Chapter 3, arguing that empirically observed increases in mean internal temperature are of a size comparable with that which would occur if the occupants did nothing differently regarding their heating behaviour. In Deurinck's study, all of the increase in modelled mean internal temperature was constrained to occur during unheated hours. In the empirical study in this thesis, the temperature did generally increase during heated hours but this formed a small fraction of the total *M.I.T. increase*.

2 discounting dwelling 7 whose heating use was continuous

### 11.3.4 *Overall comments*

Taken together, the results concerning heated hours and unheated hours give an important finding.

The most common behaviour across the sample consisted of the occupants doing nothing to increase their use of heating after retrofit; they actually reduced their *daily heated hours*. However, in general the building physics acting during heated hours to increase the *achieved demand temperature*, and even more so during unheated hours to slow the rate of cooling, outweighed the occupants' heating reducing actions. Thus, the *M.I.T.* increased following retrofit.

The above interpretation of what happened after retrofit is a very different mechanism from the microeconomic paradigm explained in Chapter 1. The occupants in the empirical study did not react to the retrofit by rationally increasing their demand for comfort. They did not 'undo' the energy saving effect of the retrofit by demanding more heat. Section 11.4.3.1 later on will discuss how occupants are often blamed for doing just this; meanwhile the discussion will move on to the implications of the results in this thesis for future retrofit projects.

## 11.4 IMPLICATIONS FOR RETROFIT OF SOCIAL HOUSING

The rest of this chapter will use the findings from the empirical study to evaluate the effectiveness of the retrofit and make suggestions concerning future retrofit schemes. The key aims of domestic retrofit in general were outlined in Section 1.4. Of these, two are generally recognised as the main aims of social housing retrofit in practice: increased warmth and CO2 emissions reduction through energy saving. These are treated in turn below and subsequently brought together.

### 11.4.1 *Prioritising occupants: were their heating needs met?*

To expand upon the aforementioned motivation of affordable warmth for occupants, a set of heating needs is listed which emerged from the analysis of the interview data (in some cases supplemented by the monitored data). This is not an exhaustive list of

heating needs in general; it consists only of those identified within this dataset. They are stated below, and then commented on in the context of retrofit.

- Perceived control over operation of their heating system;
- Within budget, feeling comfortable when the heating is on without the use of secondary heating;
- Within budget, feeling comfortable whilst being able to adequately ventilate the property;
- Keeping the children warm whilst allowing them to use the whole dwelling.

#### 11.4.1.1 *Perceived control*

The lifestyle of most of the case study occupants involved them being in the dwelling much of the time; often they did not have money to spend whilst out and as such did not go out much. Some had more routine than others: a minority worked shifts, some went out and came home at approximately the same time each day but not for fixed/regular appointments so not exactly the same time. Section 10.2 described how prediction of either time or temperature by the heating system was thus not seen as a positive attribute; manual control was a solution which worked and from which the occupants seemed reluctant to deviate.

In these terms, building fabric retrofit is preferable to other possible retrofit solutions, in that there are no new systems installed to which the occupants have to adjust. There is evidence that installation of new technologies - which have not been selected by the occupants - in social housing, whether in retrofit or new build situations, can lead to usability problems (Behar and Chiu (2013)). This can result in the occupants' heating needs not being met and in some cases energy bills being driven higher.

Related to the topic of new heating solutions, another finding emerged from the monitored use of space data. This analysis suggests that people change rooms more frequently than is assumed in dynamic building models. This has implications for zoned heating strategies, since not only will heat then be transferred between spaces more than currently assumed, but also it will not be trivial for a heating system to deliver heat to where an occupant is at the desired time. However, these statements should be interpreted cautiously as there is still insufficient knowledge in the literature around where and when occupants do want heat.

#### 11.4.1.2 *Within budget, feeling comfortable when the heating is on without the use of secondary heating*

The positive effect of building fabric retrofit on this particular need has already been covered in Section 11.2.2.4 earlier in this chapter. Almost all occupants in the sample noticed the comfort difference due to the efficiency measures when the heating was on.

#### 11.4.1.3 *Within budget, feeling comfortable whilst being able to adequately ventilate the property*

In Section 10.7, it was argued that the occupants did not seem to think that achieving fresh air whilst maintaining warmth was possible, even after retrofit. When it came to a choice between fresh air and retention of warmth, warmth was regarded as more important. This conflict was in the context of confusion about how to ventilate: confusion between the purpose of windows and of trickle vents, and confusion about how much each should be opened to provide adequate fresh air.

The retrofit had the effect of increasing the temperature and slightly reducing the R.H. in most dwellings. The Excess Vapour Pressure decreased or stayed constant in most dwellings, implying that in fact perhaps occupants were ventilating their properties more following retrofit (more data would be required to show this conclusively). However despite the reduction in R.H., the absolute levels were still high enough to allow the growth of house dustmites and to leave a risk of mould.

A possible solution to the confusion and the high R.H. would be not to prescribe a standard behaviour, since every home is different, but to provide a R.H. meter which gave some kind of signal if the R.H. exceeded, say, 50% or 60%.

#### 11.4.1.4 *Keeping the children warm whilst allowing them to use the whole dwelling*

Prior to the retrofit, occupants perceived that the needs of their children were so great that the heating strategy was set up specifically to meet them. The occupants wanted to be able to allow their children to use the whole house, and either did so at high cost, or confined them to one room. Retrofit helped with this need in a number of different ways in different case study dwellings - such as not having to confine the children to certain rooms whilst other rooms either warmed up or would not warm up at all (dwelling 1,

dwelling 9), and being able to maintain a high demand temperature without secondary heating (dwelling 11).

However, there is an implication of the existence of the need to keep the children warm and allow them to use the whole dwelling for the theoretical potential of retrofit in such dwellings. Even though parents may wish to reduce their energy use and/or comfort standards, the presence of children seems to set a minimum on what is acceptable to them. A graph from case study 1 can be used to illustrate this. Figure 121, reproduced from Section 9.3, shows how the time the heating is on post retrofit spans the period of the children's occupancy:

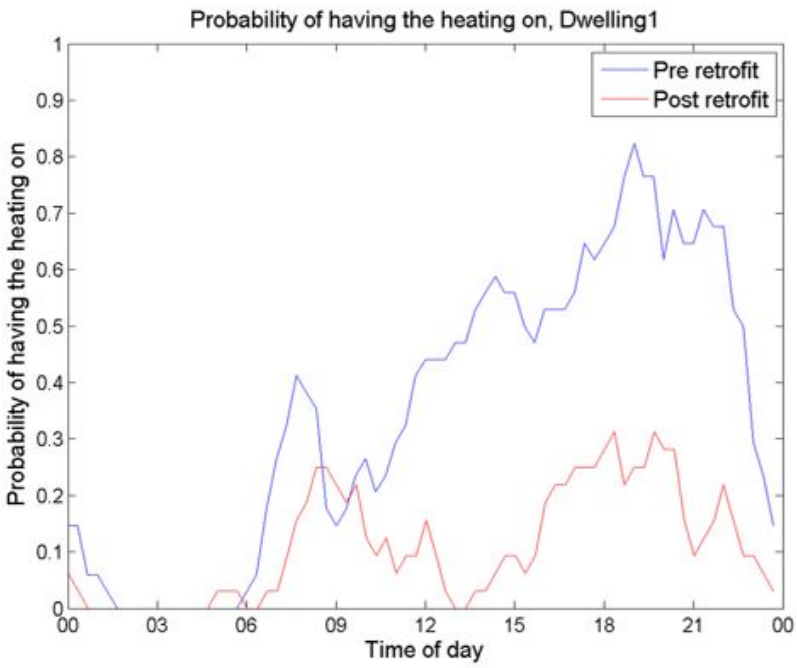



Figure 121: Dwelling 1, time the heating is switched on against time of day.

It is not being claimed here that having the heating on whilst the children are present is the behaviour of all households with children. However, it is hypothesised here that it is not so much the absolute needs of children but the parents' interpretation of these needs which will stop them reducing heating use below a certain minimum level, perhaps individual to that household or perhaps similar to the timing in case study 1 (whenever the children are in).

The discussion will now move on to the energy saving priority of retrofit, and its relationship to the occupant priority.

### 11.4.2 *Prioritising energy saving: treat the fabric or the occupants?*

#### 11.4.2.1 *The effect of building fabric retrofit on energy use*

As energy use was not measured in this study, the effect of the retrofit cannot be known from empirical data. However, the exercise in this section will be used to anticipate its effect. The disclaimer will be stated first: this exercise involves comparing empirical data with model results and as such is subject to the same forms of uncertainty as outlined in Section 1.8 early on in this thesis. The output, Figure 122, should not be taken literally but instead used as an illustrated concept.

In Chapter 4, a possibility space of space heating energy use against dwelling heat loss was mapped out. The vertical position of a dwelling at a given heat loss depends on occupant heating behaviour, which can either be directly modelled (Figure 18) or translated into a mean internal temperature and plotted that way (Figure 14). It was argued from these plots that variation in energy use arising from variation in behaviour can be decreased by reducing dwelling heat loss.

Then in Chapter 8, the extent of variation in behaviour in the case study sample was visualised using Figure 63, using *M.I.T.* as a proxy for behaviour. This graph was used to argue that in the pre retrofit sample the observed variation was almost as great as physically possible.

Given a range of monitored *mean internal temperatures*, and modelled energy use at different modelled mean internal temperatures, it is speculatively possible to link the two. By doing this, the potential benefit of the case study retrofit in terms of reduction in variation in energy use can be illustrated.

Plotting the empirical results onto the possibility space of energy use yields Figure 122 below:

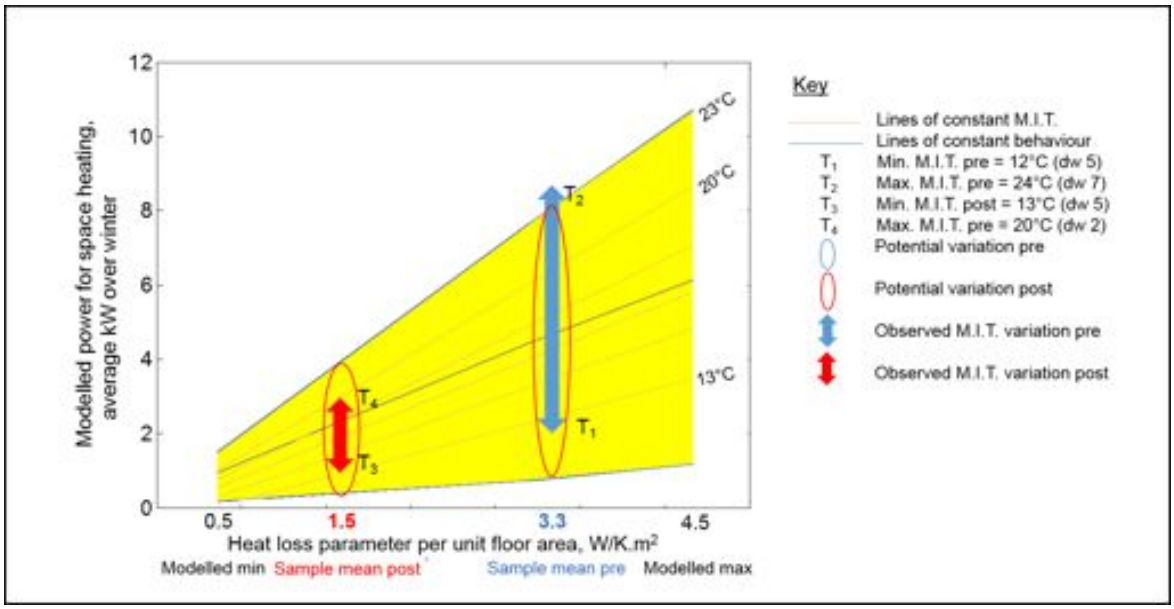



Figure 122: SHEU possibility space with visualisation of the case study M.I.T. data.

Figure 122 was created as follows:

1. The space heating energy use (SHEU) possibility space from Chapter 4 was replotted, this time not only with lines of constant behaviour but also constant M.I.T. The constant behaviour lines are flatter than the M.I.T. ones, reflecting the physical fact that upon reduction of the heat loss coefficient, if there is no change in the modelled behavioural variables then mean internal temperature rises naturally.

2. Arrows representing variation in M.I.T. across the case study sample were then superposed, to create Figure 122. These vertical arrows represent the variation in M.I.T. observed pre and post retrofit. As energy use is not known, the constant M.I.T. lines were used to determine the y-positions of the ends of these arrows.

3. The x-position of these arrows is determined from calculating and plotting their theoretical heat loss per unit floor area, compared to those used in the EnergyPlus model. This is likely to be an underestimate in the post retrofit case, due to the physical part of the performance gap described in Chapter 1, and with considerable uncertainty in the pre retrofit case as described in Stevens and Bradford (2013) and Craig et al. (2013). In order that Figure 122 is simpler, the x-position is the *mean* modelled heat loss across the sample, whereas the y-values represent the *range* across the sample.[3]

3 There are several such simplifications made such that Figure 122 can be plotted. Some of them involve major differences between the empirical and modelled data - for example, the external temperature used

4. The observed variation, represented by the aforementioned arrows can then be compared with the possible variation, represented by circles.

In theory, the retrofit undertaken in the case study dwellings was substantial - somewhere between the 'shallow' and 'deep' retrofit compared in Chapter 4. According to Figure 122, this should have limited the potential for high energy use after retrofit. The level of retrofit undertaken in the case study dwellings still allows for the existence of *rebound*; the only way to avoid this would be to retrofit to an even deeper level. The more efficient the building fabric, the lower the upper limit of space heating energy use and thus the more likely the guarantee of energy savings following retrofit.

This is not yet a universally agreed conclusion. Studies such as Sunikka-Blank and Galvin (2012) argue that instead of trying to save energy through deeper retrofit, occupant behaviour should be targeted instead. The next section will use evidence from the case study dwellings to propose that asking occupants to reduce their energy consumption through behavioural methods would in general be unfair and ineffective.

#### 11.4.2.2 *Increasing energy savings through targetting occupant behaviour?*

In comparison to both the SAP normative assumptions and the national average, the case study households heated their homes less. This can be shown in terms of both temperature and timing: Figure 120 in Section 11.3.2 above, showing *achieved demand temperature*, and Figure 123 below, showing *daily heated hours*. Please see the footnote for how these comparisons were made.[4]

in the EnergyPlus model is a three month weather file, whereas the empirical data superposed is standardised to 5°C externally. These types of difference highlight the importance of the disclaimer stated at the beginning of this section, that Figure 122 is illustrative only.

4 The national average daily heated hours was taken from Shipworth et al. (2010) using the CARB data. This figure for the mean represents the average over November 2007 to January 2008 inclusive. The sample daily heated hours were standardised to 5.5°C: the UK average external temperature over that period (from Met Office data). The national average M.I.T. was taken from BRE (2013d), and the sample *M.I.T.s* were thus standardised to 5.6°C corresponding to the external temperature for that period given by BRE (2013d). However, please note that in the BRE study M.I.T. was calculated by averaging over two rooms, whereas the method used in the case study data was volume-weighted averaging over all rooms available. As with Figure 120, the histograms include all the data in order to illustrate variation whereas the sample means are meant for pre-post comparison and therefore exclude dwellings 4,6,7 and 12 as explained in Section 7.15.3.

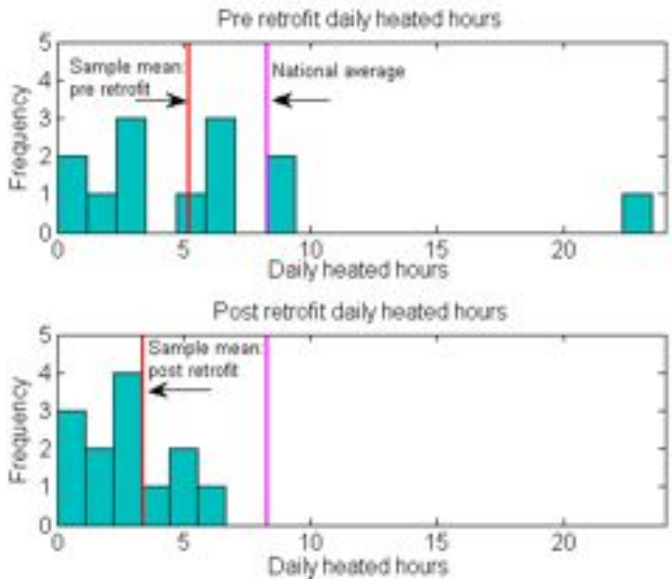



Figure 123: Histogram showing *daily heated hours* compared to the national average.

Figures 123 and 120 are thought to be partly responsible for the lower *mean internal temperatures* observed in the case study sample compared to the national average, shown in Figure 124 below.

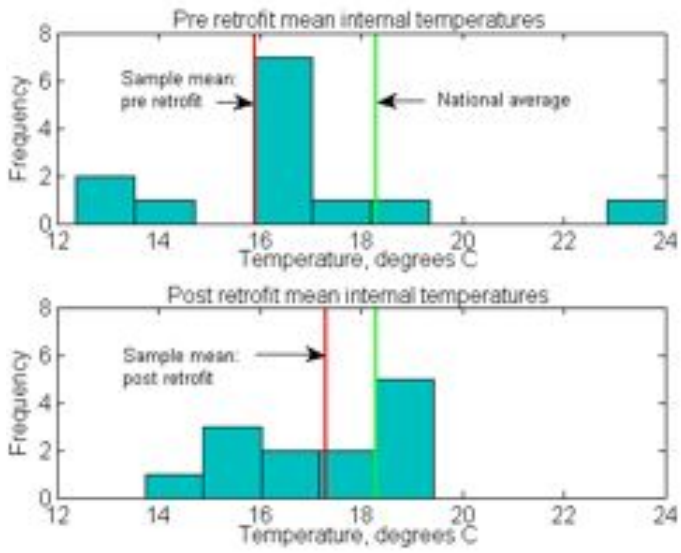



Figure 124: Histogram showing *M.I.T.* compared to the national average.

The arguable implication of occupants underheating their homes is that it is not appropriate to ask them to heat even less. Having seen that heating timing and temperatures are both less than the national average in most cases, and also that after retrofit use of secondary heating was almost eliminated, the only heating behavioural variables (defined in Section 3.3) left to reduce are:

- Number of rooms heated; yet it was already shown in Section 10.8 that this does not allow occupants to meet their needs, especially if children are present.
- Degree of window opening: yet Section 10.7 indicated that in many of the dwellings windows need to be opened *more*, not less, to maintain an adequate supply of fresh air.

It could potentially be stated, given knowledge of the behaviour of the occupants and observation that in general their heating behaviour is not wasteful, that the theoretical potential for minimum energy use - given the occupants' needs - is already the case, and that further reduction in energy use is not appropriate.

### 11.4.3 *Occupants and energy saving: recommendations for retrofitting social housing in future*

Points from the above discussion of the needs of occupants, and the energy saving potential of the building fabric and occupants, will now be drawn together to make recommendations for future social housing retrofit projects.

#### 11.4.3.1 *Energy saving versus increased warmth?*

Throughout this chapter two key aims of social housing retrofit have been considered: energy saving and increased warmth. It is acknowledged in policies such as ECO (Section 1.5) that the latter compromises the former – for example, there is a 40% reduction in predicted energy savings in the 'priority' group of ECO recipients on the assumption that this group takes more of the benefit of retrofit as increased internal temperature than other groups.

This thesis has indeed given evidence of underheating (see the previous section), and of increase in temperature following retrofit. However, the occupants in this particular sample did not rationally increase their demand for temperature following retrofit.

This provides a small amount of evidence that occupants are not to 'blame' when predicted energy savings are not realised. Even if occupants had *decided* to maintain their homes at a higher temperature following retrofit, the finding that they were underheating their homes beforehand and in some cases afterwards would justify such behaviour as not wasteful. However, both the incidental and any potential rational increase in temperature demand after retrofit still offsets potential energy savings from retrofit: the two aims are at odds with one another. There may be one way to avoid this trade off, discussed below.

#### 11.4.3.2 *Energy saving and increased warmth?*

According to the modelling in this thesis, there is one way to obtain both energy savings and increase in comfort level following building fabric retrofit. This is to increase the level of fabric efficiency beyond what was carried out in this scheme. In this thesis no quantitative recommendations for the heat loss coefficient were given, as the modelling exercise was meant as an illustration of a concept as opposed to specific guidance on U-values., for example to the Passivhaus standard. However, since there is likely to only be one opportunity between now and 2050 to carry out mass retrofit of housing, including social housing, this author advocates deep building fabric retrofit as the optimal solution for achievement of both energy savings and occupant thermal comfort.

#### 11.4.3.3 *Occupant engagement*

It was argued in this chapter that delivering energy saving advice to occupants in retrofitted homes is unlikely to result in energy savings unless the organisation imparting the advice has good evidence that the occupants are exhibiting wasteful behaviour. However, the author receommends that occupant engagement should still be carried out. This topic has not been treated in detail in this thesis but recommendations are given and the evidence behind them described in Appendix C. Engagement needs to cover not only how the heating system (especially the thermostat) works, but take a broader approach of how heating and ventilation work together to maintain a healthy building and why this is important for the occupants.

#### 11.4.3.4 *Simultaneous interventions*

Evidence has been given to argue that upon installing the building fabric efficiency measures, two further actions should be carried out. One is the rebalancing of the heating

system, to avoid temperature imbalances between rooms as observed in dwelling 2 (see Section 9.4.4.2), which led the occupants to use more heating than they otherwise would have, to try to obtain an even temperature across the dwelling. The second is to clear any mould present. The post retrofit dwellings can be maintained at a low enough R.H. to render the risk of mould low, but if mould present from before retrofit is not cleared off, new mould can grow on top.

## 11.5 CONCLUSION

This chapter has reversed the order of research questions, arguing that if *mean internal temperature* and its drivers can be understood, the outcomes of retrofit can be better anticipated. A new conceptual model of *M.I.T.* which differs in structure from the BREDEM version was presented, and used to highlight some relationships not taken into account in normative models of retrofit. This understanding was then used to make recommendations about the difficult balance of priorities of meeting occupant needs and delivering energy savings.

A summary of the key findings can be found in the next chapter. After this, the topic turns from the findings to the research design itself.

# 12

# CONCLUSION

## 12.1 INTRODUCTION

The conclusion chapter is used in this thesis for the following purposes. Firstly, the key findings from the PhD are summarised, and necessary further work suggested if the findings are to be used to inform retrofit policy. This is followed by a critical reflection on the research design, including what could have been done differently. Finally, the immediate impact of the PhD research on the case study estate is documented.

*Restatement of the problem*

At the time this PhD project was started, the issue of models not correctly predicting energy use in UK buildings was being seriously raised. A key factor proposed was the set of (confounded) terms around comfort taking/rebound/takeback: that is, the idea that occupants increase their demand for heat following retrofit. However, it was unclear how people actually responded to retrofit in terms of changing their heating behaviour. Reasons for this knowledge gap included a lack of physical monitoring of temperatures in all rooms, of longitudinal data, of high time resolution heating use data and of the occupants' point of view of how their behaviour may have changed. As such, changes in behaviour were mostly inferred from monitored data, which involved many unsubstantiated assumptions rather than discussion with occupants themselves.

This thesis used a novel longitudinal methodology, combining monitored data and interview data to understand the interactions between the building and the occupants triggered by building fabric retrofit. The main findings are summarised as follows:

## 12.2 SUMMARY OF KEY FINDINGS

1. In this sample of social housing undergoing building fabric retrofit, *mean internal temperatures* generally increased. However, there was considerable variation between cases. Some of this is likely to be due to differences in the buildings; this thesis did not focus on measurement of the thermal properties of the building but instead on the heating behaviour of the occupants.

2. Most of the change in *M.I.T.* occurred during unheated hours, and thus was a result of the change in the thermal efficiency of the building fabric, not of occupant behaviour.

3. A small amount of the change in *M.I.T.* occurred during heated hours. The general trend was for *achieved demand temperature* to increase and *daily heated hours* to decrease after retrofit. Each variable is commented upon specifically in the next two points.

4. It was found that the most appropriate definition of 'demand temperature' was *achieved demand temperature*: highest achieved temperature during a heating period. Using this definition, the observed increase in *achieved demand temperature* across the sample was not caused by occupants turning up a thermostat, but due to the building fabric and the heating system. It seems that in some cases the heating system was undersized given the level of heat loss from the pre-retrofit building yet could achieve a higher temperature post retrofit; SAP does not take this into account.

5. *Daily heated hours* may have reduced because thermal comfort was achieved with fewer hours of heating per day. This is proposed to be for two main reasons: the perception that the dwelling retained heat better after the heating was turned off, and the reason for heating being kept on in the first place: to attempt to attain a certain comfort temperature. This desired temperature was in some cases not achievable before retrofit but was afterwards (see the previous point), hence the heating could be switched off. This change in *daily heated hours* was facilitated by the occupants using manual heating control triggered by their real-time thermal comfort, as opposed to a timer.

6. From points 4 and 5, temperature increase during heated hours was not caused by the occupants; combining this with point 2, the increase in *M.I.T.* was essentially not due to occupant behaviour.

7. Neither microeconomic theory nor the BREDEM modelling paradigm (and the SAP assumptions of unchanging values of heating behaviour variables) represent the mechanism through which internal temperatures changed following retrofit in the case study dwellings. However, SAP may predict approximately the same *M.I.T.* change for different reasons. SAP assumes constant *daily heated hours* and constant modelled demand temperature whereas the case study dwellings exhibited a decrease in *daily heated hours* and an increase in *achieved demand temperature*: the differences may cancel out.

8. An empirically-based conceptual model of *M.I.T.* in the case study dwellings is shown in Figure 125. It contains interdependence between variables previously assumed to be independent, and feedback loops.

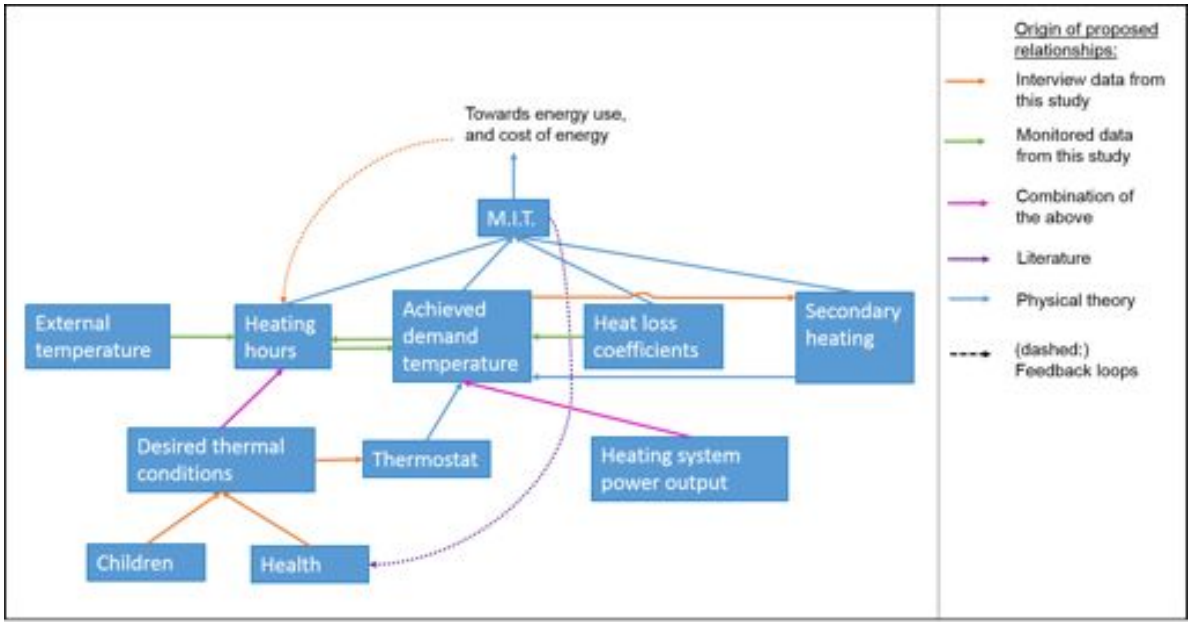



Figure 125: Influence diagram for *M.I.T.* according to the analysis in this thesis.

9. Figure 125 could help researchers understand how *M.I.T.* might change following building fabric retrofit in this type of housing. The latter is represented by a change in one variable: the heat loss coefficient. It can be seen that as well as being directly linked to *M.I.T.*, when the heat loss coefficient is changed several other variables within the system are also affected.

10. A couple of notable relationships in Figure 125 will be highlighted here. Use of secondary heating was found in the sample to decrease after retrofit; the energy and $CO_2$ savings from this are not currently taken into account when the value

proposition for retrofit is made. It can also be seen that heating timing is influenced by many other variables, of which the most notable is external temperature.

11. Children play a major part in the determination of heating schedule, the internal temperature and the interior zoning of the dwelling. However, these often originate from the parents' decisions about what is good for the children, rather than the level of comfort that the children desire themselves.

12. Considering the needs of the occupants inferred from the data, this type of retrofit satisfied most of their demands, although some needs, such as fresh air, were traded off against others such as warmth.

13. Considering energy use, this level of retrofit is likely to have helped to some extent with capping space heating energy use, so that whoever moves in next cannot drastically increase the energy consumption. However, deeper retrofit would have achieved this to a greater extent. An argument for deep retrofit is the guarantee of both thermal comfort and low energy use, whereas shallow retrofit can perhaps only provide one or the other.

14. To maximise the benefits of shallow building fabric retrofit, two further simultaneous interventions are advised: cleaning off of any existing mould, and rebalancing the heating system.

## 12.3 FURTHER WORK

The 'Further work' section in this thesis is specifically targetted towards potential extensions to the work already carried out which would enable contribution to UK retrofit policy. In this thesis there were two types of finding: those emerging from the empirical study (Chapters 8 to 10) and modelling results (Chapter 4). These are different types of knowledge, and as such extensions to each will be treated in turn.

### 12.3.1 *Empirical results*

#### 12.3.1.1 *Generalisability and extrapolation*

It will be argued here that the findings from the empirical study in this thesis cannot directly be used to inform policy in their current state, but that their use as a basis for a larger study could lead to this.

The sample of case study dwellings was neither set up to be representative of social housing nor of housing in general: this is not the purpose of case study research. Some authors including Flyvbjerg (2006) argue that extrapolation beyond the case study population is possible in some cases, for example using a critical case study research design, but the relevance of this to the energy and buildings field was argued against in Section 5.3.2.2.

Although the relationships found in the empirical study, many of which are displayed within Figure 125, cannot be assumed to occur outside the case study population and thus cannot be translated straight into policy, they can be used as a starting point to guide the collection of further evidence as to whether the observed relationships are widespread. Therefore, the purpose of the rest of this section is to make recommendations for how findings could be translated into hypotheses which could then be tested in a larger study.

#### 12.3.1.2 *Making and testing hypotheses*

Certain hypotheses concerning how occupant behaviour does or does not change following building fabric retrofit, in different types of dwelling and household, can be formed using the findings in this study by knowledge of why they occurred in the case study dwellings.

For example, the observation that the case study households generally shortened their *daily heated hours* following the retrofit can be turned into a general hypothesis that occupants reduce their *daily heated hours* following building fabric retrofit. Moreover, since it was proposed in this thesis that one reason *daily heated hours* reduced was due to the heating strategy of manual heating control, the hypothesis could be tested in dwellings in which heating is controlled in different ways: for example manual heating control versus use of a timer. The scope of a study would not necessarily need to be restricted to social housing.

Similarly, given the finding that *achieved demand temperature* increased following retrofit and the proposition that this was due to it falling short of the thermostat setting - which in some cases was proposed in turn to be due to the high heat loss of the fabric and undersizing of the boiler - it could be hypothesised that *achieved demand temperature* increases following retrofit in dwellings with high heat loss.

The above two hypotheses could be tested as part of a large-scale quantitative longitudinal research design, in which internal temperatures and radiators were monitored in the same way as was carried out in this thesis, and in which the thermostat setting was observed and the occupant asked several structured questions about the conditions under which its setting changes.

Turning specifically now to social housing, it would be useful to know to what extent the finding that the less automated control and the more manual control present in a heating system, the more the occupants feel that their heating needs are met (Section 10.2). This knowledge could be used to design heating systems which meet people's needs using as little energy as possible. It would also be useful to observe whether the factors in the case study dwellings leading to all rooms being heated - children, use of the dwelling as one zone, and false beliefs about how much energy is saved if room radiators are turned off - are widespread. Further exploration of these relationships would take place not by a large scale quantitative study as proposed above but further qualitative work.

Taking a wider perspective, given the creation of Figure 114, a possible long term project would be to operationalise this conceptual model of M.I.T. using quantitative data. This would require obtaining distributions for the non-dependent variables, and quantifying the relationships between them. The output would be a predicted mean internal temperature, whose sensitivity to initial conditions could then be tested, in terms of changing the heat loss coefficient at different configurations of the other variables. The most important variables which co-varied with the heat loss coefficient, and thus changed upon retrofit, could then be identified.

### 12.3.2 *Physics-based modelling*

The modelling work in Chapter 4 on the potential for variation in energy use was presented as a conceptual argument as opposed to absolute truth, as it was heavily caveated. However, if the model results could be validated, the argument made from them in

favour of deep retrofit could be strengthened. Currently, the modelled variables (space heating energy use, heat loss coefficient) lack empirically determined equivalents. However, recent work carried out by Andy Stone of UCL Energy Institute, using the 1996 English House Condition Survey (EHCS), has come closer to providing such data. Space heating energy use has now been disaggregated from gas consumption in the EHCS dataset. Heat loss coefficient is more difficult to obtain: dwelling age band has now been converted into SAP rating but as mentioned in Chapter 4 this is not equivalent to building fabric efficiency.

Further modelling is being undertaken by colleagues at UCL Energy Institute to increase the relevance of the argument to the UK stock. Whereas in this thesis only one dwelling was modelled since it was the shape of the space that was of interest as opposed to the absolute values of energy use, this further work populates the space with archtypes representing the make-up of the UK dwelling stock. These archetypes have been modelled in SAP and weighted by their relative frequencies. Preliminary results show that heavy insulation eliminates the risk of backfire (see Section 1.9) across the stock whilst shallow insulation still allows for it. These further modelling results are subject to the same caveats as were described in Chapter 4.

The discussion now turns from how the findings could be used to the research design itself.

## 12.4 A CRITICAL REFLECTION ON THE RESEARCH DESIGN

The empirical work carried out and documented in Chapters 6 to 10 used a novel approach of the combination of observational (physical) and self-reporting (social) methodologies. After reflecting on the appropriateness and success of some of the individual methods, there follow reflections on the methodology of using physical and social approaches together.

### 12.4.1 *Interviews: could people talk about their practices?*

The first method to be evaluated is the interviews. One premise of this method was that, *"people can talk about their practices"* (Hitchings (2011)), explained in Section 6.3.1.5. It was possible in this thesis to test this premise through triangulation of the interview

data with monitored data, the results suggesting that occupants could generally, but not always, describe their practices. A positive example will be given concerning heating use. In this study it did not matter whether occupants were able to describe the exact length of their heating period, as the latter is a quantitative variable as opposed to a practice, and also since the relationship between reported and measured heating period lengths was not a research question, unlike in Shipworth et al. (2010). The information that was instead hoped for was occupant perception of need for heating and level of routine. For example, whether occupants were aware of the times of day the heating was on and why; did they switch it on when they felt cold, did it come on automatically according to a prior timing decision, was heating timing due to habit, and so on. It was found that occupants were usually aware of the degree of routine and why they might turn heating on.

However, in some cases people did not report what they actually did. An example of this is from dwelling 3, in which the interview and monitored data contradicted. The occupant reported that since the retrofit, he never switched the heating on in the morning any more. He gave reasons for this, such as the building retaining warmth throughout the night. However, the radiator data showed an increase in frequency of morning heating period following retrofit (see case study 3 in Section A.1). For the author, then, proposing a mechanism leading to the observed *M.I.T. increase*, as specified by Research Question 2, was difficult in this case. It is not only the contradiction of the two types of data which renders this problematic, it is the statement by the occupant of reasons behind his decision not to turn the heating on in the morning any more. This suggests that the qualitative data cannot be discounted as a reporting error, given that the occupant clearly thought about it.

One cannot expect occupants to accurately report on phenomena of which they are unconscious. For example, it was found that on the first day of the pre retrofit monitoring period, when occupants reported being aware of the presence of the occupancy sensors and thus of their movement around the dwelling, one occupant reported being surprised by how frequently she passed under doorframes. She had previously not been aware of this high frequency. This suggests that perhaps occupants can describe generally which rooms they spend time in, but that this is a simplified version of actual movement around the dwelling. As such, interviewing people about their use of space, and possibly heating needs, might lead to oversimplified data. The researcher may be informed of the main rooms in which the occupants spend time, but not the extent of movement around the dwelling.

### 12.4.2 *Monitoring strategy: what would be done differently?*

Following reflection upon the monitoring strategy, four modifications to its design and implementation which could have rendered it more successful are suggested below:

#### 12.4.2.1 *Extend the monitoring period*

It will be explained later on in Section 12.5 that the original research questions were not in fact those stated in this document. They instead concerned occupant use of space and its dynamic relationship to heating pattern and air temperature. An original requirement of the empirical study had therefore been high-time-resolution data, for example to enable examination of the impact of an instantaneous temperature gradient on whether occupants move room. This meant that data was collected every 20 minutes from temperature/humidity loggers and to the nearest second from occupancy sensors. It had not been anticipated that in fact, although this high resolution data was very useful (e.g. for observing the internal temperature at the time when the heating was switched on and off), for the main metric in this thesis which was *M.I.T. increase*, daily average internal temperatures would form the basis of the calculation. Given this, a one-month-long monitoring period was not enough: there were only about 30-35 data points per monitoring period for each dwelling. The effect of this low number of data points in the calculation of derived quantities such as *M.I.T. increase* will now be discussed.

It is not necessarily true that obtaining more data points would reduce the scatter currently observed in plots such as those showing internal versus external temperature. This is because there was unlikely to be a defined line representing internal versus external temperature. The real relationship was probably more of a 'band' shape, due to inherent variance which was not measurement error but the effect of occupant behaviour (and other implicit heteroskedasticity). Other studies have found the same inherent variance in quantities related to internal temperatures within one dwelling (Gesche Huebner 2013, pers. comm.) If the latter is true, then more data points would not reduce the R.M.S. error on the line plotted to represent the relationship. The benefit of more data points would instead be to enable the researcher to be more confident of the gradient of the relationship between internal and external temperature. It could also enable other explanatory factors to be observed, since one variable (e.g. external temperature) could be held constant, whilst there would still be enough data to plot internal temperature against another independent variable.

#### 12.4.2.2 *Lessons learned whilst attempting to measure occupancy*

Sensing where occupants are without filming or tagging them is known to be a difficult endeavour (Sixsmith et al. (2007)), especially within home environments. The challenge remains to do non-intrusive occupancy sensing well, since it was not accomplished in this PhD. However, some lessons learned from the process of trying are noted below, to help other researchers within this difficult area.

- Firstly, regarding the gaining of access to properties with a view to installing occupancy sensors, it was found that social landlords were more suspicious on behalf of the tenants than the tenants themselves. Despite clear explanation that downwards-pointing PIRs are not able to watch occupants in rooms, some RSLs declined to work with the author on the basis of the occupancy sensors (even though the tenants reported not minding the sensors as demonstrated in Section 12.4.5). Therefore if other researchers wish to work with social landlords, they shold note that the level of intrusiveness of the sensor used in this study is probably the maximum acceptable. In other words, using sensors pointing into rooms, or tagging occupants, may well hinder the researcher from gaining access to properties.

- Secondly, forming and testing a quantitative hypothesis (occupants spreading out more after retrofit) from a small amount of qualitative information is not always the right thing to do. This is not to say that it should never be undertaken. However, the researcher should think carefully through the hypothesis as a thought experiment before going ahead and designing an experiment to test it. In this study, the author had not thought carefully enough about the fact that if occupants already used central heating, the following was likely true. Firstly their use of space would be unlikely to change a great deal due to lack of theoretical reason for change in temperature gradient; secondly their use of space could not change much in many cases since they would not have many spare rooms; thirdly if their use of space changed it would not have energy consequences.

- Thirdly, occupancy should not be taken lightly as a variable to measure. Unlike temperature measurement, there do not exist many off-the-shelf systems for purchase, so a large part of a research project on occupancy will inevitably be the designing, making and testing of a bespoke system. This will probably require a team of people, including electronic engineers.

#### 12.4.2.3 *Measure energy use for space heating*

Arguably the main limitation of this study is that energy use was not directly measured. The reasons for this were explained in Section 7.12.1. The most accurate way to measure space heating energy use would be to avoid techniques which require disaggregating it from general gas use, and instead to measure it directly. It is proposed that metering heat flow from the boiler to the space heating circuit, as carried out in the UK condensing boiler field trials (DECC (2009)) would be a suitable method. In the context of housing this would require non-invasive metering (i.e. no pipes being cut open), for example using ultrasound. One such meter costs a few thousand pounds (see e.g. Micronics (2010)).

Aside from the principle variable of interest this measurement would provide - daily energy use for space heating - other useful variables would be obtained. One is an exact knowledge of when the heating system was doing work, and thus better representation of cycling than was obtained using the simple radiator monitoring technique in this thesis.

#### 12.4.2.4 *Measure mean radiant temperature (M.R.T.)*

Although the interviews were not set up to record whether the occupants experienced higher radiant temperatures from the walls and in some cases windows after retrofit, one occupant spontaneously offered this information. As was described in case study 9, the occupant was able to feel an increase in the temperature of the walls whilst sat a distance from them. It would be interesting to measure mean radiant temperature pre and post retrofit and combine this with some interview questions tailored towards this aspect of thermal comfort. This measurement would require a globe thermometer, which does not exactly measure M.R.T. but a combination of M.R.T. and air temperature. It is possible to correct for the effect of the air, but only by measuring air velocity, which introduces yet another sensor. Unlike the air temperature sensors in this study, a globe thermometer may not be possible to blend into the background since it needs to be exposed on all sides and thus not rested on a surface.

### 12.4.3 *Evaluation of the mixed physical and social methodology*

#### 12.4.3.1 *Combination of physical and social data: how was this done in practice?*

Section 5.3.1 anticipated that the quantitative and qualitative data would be combined in a certain way from the list offered by Bryman (2006): quantitative explained by qualitative. It had been expected that, for example, an interesting feature of the monitoring data would be observed and deemed worthy of further investigation, and so the interview data would be scrutinised to give insight on what was happening. This type of analysis did occur, for example to answer Research Question 2 about mechanisms of change in M.I.T. A specific example was observation of a temperature decrease in dwelling 13, and subsequent interrogation of the interview data to try to work out why this happened. In this case, income decrease was identified and proposed as a causal factor.

However, this 'explanation' use of mixed methods (mixed methodology in this case) was not the only way in which findings emerged. The process which tended to produce the most interesting findings was in fact starting from the interview data, noting a feature which looked interesting and relevant to the monitored data, and looking for a quantitative manifestation of it in the latter. An example of this concerns use of space. Frequency of 'pottering', and thus the set of histograms of number of occupancy events per hour which was carried out for every dwelling in which the data existed, was a metric which occurred because of a comment made by the occupant of dwelling 8 about how she 'potters' around her flat at certain times of day. Thus, quantitative metrics emerged as a result of qualitative insights. Similarly, as mentioned in Section 9.3.4.1, an occupant's comment about heating timing revolving around the children could be seen in the monitored data and also tested for in other case studies. This use of qualitative data followed by quantitative is quite classical: using qualitative data to generate ideas or hypotheses, then using quantitative data to test them in wider contexts than those in which they were generated.

#### 12.4.3.2 *Occupants thinking in terms of different constructs to those being measured*

A fundamental construct underlying much of the analysis in this thesis is that of 'mean internal temperature'. This construct is necessary in the calculation of space heating energy use, at least in simpler models. However, in analysing the qualitative data it became clear that occupants did not have a well-defined concept of 'mean internal

temperature'. This may seem obvious but requires expounding nonetheless. Firstly, as described in Section 9.6.4, the occupants of dwelling 10 and dwelling 13 thought that the temperature had increased whereas the monitored *mean internal temperature* actually decreased. Furthermore, so had the temperature in the rooms where they spent most of their time, and the minimum temperatures had not increased either. Now, this may be a framing issue with the physical data (see Section 7.15.4.1). Alternatively, it may be that when they used the word 'warmer', the occupants were not just reporting perceived temperature, but the output of a set of interactions of various thermal comfort variables.

Similarly, it was described in Section 9.4.4.2 how, in dwelling 2, monitored *mean internal temperature* was not what the occupants experienced after retrofit as they went to bed with the feeling that their bedroom was cold. In this case, it was proposed from the analysis that instantaneous temperature gradient between rooms was influencing the occupants' perceptions of 'warm' and 'cold'.

What can be done about this inevitable discrepancy between variables constructed from monitored data and constructs reported by the occupants? This is one important area in which the socio-technical framework proposed in Section 5.3.3, but not developed to a great extent in this thesis, has a role to play. Meanwhile, more research is needed into what makes occupants feel warmer or cooler in a domestic environment.

### 12.4.4 *Doing mixed methodology work as one person*

In the field of energy and buildings, multidisciplinary work is normally carried out within a team. For example, in Lowe et al. (2012), different experts carried out the physical monitoring and the occupant interview aspects of the study. In this thesis, however, one researcher carried out both aspects. The advantages and disadvantages of this approach will now be explored.

One advantage is that this approach made it easier to spot links between pieces of data collected using different methods. Since Research Question 2 required combining monitored and interview data to propose causal mechanisms, this process was sped up since the author knew both datasets. The question could have been answered by a team; this would however have required more time and communication between members.

A second advantage was that it was easier from a practial sense (in terms of collecting the equipment at the same time as doing an interview) and likely to be clearer and less disruptive to the occupant to have only one person to communicate with.

In terms of disadvantages, this approach meant that the author had to be trained to PhD standard in all of the methods of modelling and data collection:

- Development of an occupancy sensor;
- Installation of monitoring equipment;
- Logistics of finding an estate, recruiting, monitoring and interviewing;
- Interview design;
- Analysis of qualitative and quantitative data;
- Physical modelling.

Furthermore, in terms of practially carrying out the data collection, instead of for example carrying out 2 interviews per day and spending time in the evening reflecting upon them as is common in qualitative work, after carrying out multiple interviews per day it was necessary to spend time working with the dataloggers, to ensure the data was downloaded and secure.

Finally, concerning analysis, not only was the analysis of qualitative data not the author's background, the complex longitudinal multi-case study approach with the added dimension of treating the data from a more positivist point of view for easier comparison to the quantitative data rendered this aspect likely to be weaker than the quantitative analysis. If the study had been carried out in a team, as in Lowe et al. (2012), both aspects would have been perfomred by experts in the relevant disciplines, so one aspect would not be weaker than the other.

A temporary disadvantage, described in Section 5.3.3, is that the theoretical framework for this mixed social and physical research design is not yet fully developed. However there is likely to be some work carried out on this by the author and colleagues in the near future.

In conclusion, there is great scope for this type of mixed methodology study to be used in the future by other individual researchers or a team. This is because there are many outstanding questions which would benefit from the intimate, as opposed to merely superficial, combination of physical data with social data.

### 12.4.5 *Ethical issues*

The topic of research ethics was introduced in Section 6.4.1 as a major consideration before starting the data collection process. In this section it is returned to in the light of what actually happened.

A concern in Section 6.4.1 was the issue of occupants potentially feeling watched. This turned out not to be a significant issue: a combination of the explanation and the appearance of the sensors seemed to convince the occupants that they were not being spied on, as shown by the following extracts, both from dwelling 9:

*Interviewer: "Did you mind [the occupancy sensors being there]?"*

*Occupant: "No, not at all. It was explained to me in the papers."* (Dwelling 9, pre retrofit)

*"But I noticed one of my friends, when he popped in, he asked me, what the hell is this? And I said, oh, these are the sensors, I explained that this lady from London, she is assessing this for her school, and he said are you sure they're not cameras? And I said what kind of camera is that, come on?! So, yeah, so it was fine."* (Dwelling 9, post retrofit)

Conversely, the other monitoring techniques of monitoring air and radiator temperatures did not have anticipated ethical implications in theory; however, two such issues arose in practice.

- In dwelling 6, the author returned to the property at the end of the first monitoring period, and could not interview the occupant as he had throat cancer and thus talking (and most other activities) caused him pain. However, he allowed the sensors to be retrieved. Upon observation of the data, it appeared that the heating system had been turned off on the first day of the pre retrofit monitoring period. By the second monitoring period the occupant was recovering and could talk. He explained that the previous year the author's sensors had broken the heating, but that he had not called a plumber to mend it as he did not want to get in the way of the study. He had therefore used a single electric heater to heat the property, at this most crucial time in his illness when he needed warmth to relieve pain. Although the author could not think how the sensors could possibly have broken the central heating system, it was terrible to realise that, in protecting her study, the occupant had sacrificed his health. In hindsight, there should have been some clear statements to the occupant before the start of the study that if anything went wrong, he/she comes first - not the research - and if possible the researcher should be contacted.

- The post retrofit occupant of dwelling 7 was a particularly vulnerable woman who had recently been the victim of domestic abuse, so when visiting her it was arranged for the author's accompanying colleague to be female.

## 12.5 HOW THIS PHD DID NOT EVOLVE IN A LINEAR MANNER

At the start of the PhD process, research questions were designed whose focus was change in use of space following retrofit. However, two things then occurred which necessitated a change of emphasis: the occupancy sensors did not work as well as anticipated, and it was realised that due to most dwellings heating all the rooms pre-retrofit there would not be much potential for change in use of space to lead to change in use of heating. At this point, use of space became a minor part of the investigation and the other measured variables, temperature and heating use, became more important. The research questions were changed to reflect this. The thesis could have been written up in this order - that is, changing the questions halfway through - but this would make for confusing reading. So as to be more logical, it was written up in its modified form. Not everything changed - there was still originally a mixed methodology research design - but the main variable of interest was changed from use of space to change in internal temperature.

Given the above, what follows is some lessons learned about real-world research from this process, and an indication as to how the empirical study would have been carried out differently if the current research questions - concerning mean internal temperature - had formed the research design from the beginning.

#### 12.5.0.1 *Real-world research*

Many points relating to this have already been covered in this chapter. However there were two main lessons learned specifically relating to real-world experimental design and analysis. The first is to build as much redundancy into the monitoring strategy as is possible. That is, if there are enough spare sensors, two instead of one should be installed in every location if there is a risk of failure, so as to decrease the risk of losing data. This is because monitoring in the context of a longitudinal study around retrofit can only be carried out once - if it goes wrong, the researcher cannot start again. This redundancy lesson was applied to the occupancy sensors for the post retrofit monitoring.

The second main lesson concerns exploratory data analysis. However considered the research questions are at the time of method development, the researcher should not feel bad for not anticipating every possible constructed variable or potential graph before collecting the data. As explained above in Section 12.4.3.1, the nature of the data analysis was more like that used in qualitative research: unanticipated features of interest emerged during the analysis process. Related to this, the development of metrics was much easier once the longitudinal data were present.

#### 12.5.0.2 *What would be done differently*

If it had been known from the start that the occupancy sensors were not going to work, the author would not have undertaken quantitative measurement of use of space at all: the three years would instead have been used to carry out three winters of monitoring instead of two. One winter could have been pre retrofit and the other two could have been post retrofit. In this way, the outcome variables and their associated mechanisms could be investigated over time, to discern whether retrofit caused a temporary change in behaviour/comfort standards or a permanent shift. It is hoped that other researchers might carry out this type of work.

Secondly, arguably more thought and discussion should have gone into possible ways to measure energy use instead of assuming that radiator state would be sufficient. This highlights the importance of discussion of all of the physical variables with an expert as the research design is evolving.

## 12.6 IMPACT: WHAT HAPPENED AFTERWARDS

This section is about the impact of the feedback provided to the RSL whose estate was monitored for this study. This feedback was provided partly because the RSL was interested in the physical conditions of the dwellings post retrofit and this was one of the factors which led to access to the estate being granted, and partly because the author had some points of concern to express and recommendations to make.

The main effect that the RSL had been interested in was relative humidity, and whether it increased as the buildings were better sealed following fabric retrofit. In fact, the relative humidity slightly decreased with the temperature increase in most dwellings. This was fed back to the RSL but in addition the opportunity was taken to comment

on a number of issues relating not to the physical works but the occupant engagement throughout the process. A report was therefore compiled and is included (after anonymisation) in Appendix C.

Given that occupant engagement is a large topic in itself and requires potentially different research methods from those used in this thesis, it was not included in the research questions. However, the author was able to gain an impression of how the particular engagement programme employed, and the variety of misunderstandings of the occupants about how to maintain a healthy building, together contributed to some unintended consequences. The report's main recommendations can be summarised as follows:

*"- Since it transpired that many occupants do not know how to operate a heating system effectively, it is very important that they receive informed advice, perhaps in the form of a home visit, where the occupants are shown an efficient manner of operation. This visit should also cover ventilation and health aspects of a refurbished property.*

*- The advice visits would be most well-received and beneficial to the occupants if they were carried out by a party whose incentives were not selling energy, and if they were overseen or checked by [the RSL] in terms of their content.*

*- Some occupants would appreciate communication of how it was decided which works would be carried out, before the start, to feel part of the process. Similarly, since some occupants did not appear to understand the purpose of the works even though they had received letters and leaflets, perhaps there is room for thought on how this could be more effectively expressed.*

*- It may also be beneficial to communicate to tenants how they can anticipate changing their heating behaviour after the retrofit. This may aid their understanding and choice of how to take the benefit of the refurbishment." Love (2013)*

Upon reception of the report, members of the RSL were very grateful. It was fed back to the author that, since they were to shortly begin retrofitting 6,000 more dwellings, they were intending to take into account the recommendations made in the report. Furthermore, they expressed interest in sending it beyond their organisation. Therefore an anonymised version was prepared in which the location, RSL, energy company and main contractor's identities were removed. The RSL sent this to several contractors and to the city council. With the RSL's permission, the author then disseminated it to other social landlords who were interested in the findings.

It is hoped that this report, and also this thesis, will help inform best practice in retrofit works in the near future.

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# A

# THE REST OF THE CASE STUDIES

## A.1 CASE STUDY 3

### A.1.1 *Context of the household*

This occupant was a single man aged about 70. He lived alone, although his teenage son came to visit one day per week. His income was just enough to get by; in the pre retrofit winter he was worried about his benefits being cut although it turned out this was due to a misinterpretation.

His daily pattern was to have breakfast then either be at home all day or use his bus pass to go and walk around town. The latter was generally the preferred option since it was boring being at home, but he did not have money to spend when he was out, so sometimes stayed in. However, he sometimes did not enjoy being constrained to sitting still by having guests round, since that made him cold.

In general he said he was warm blooded and coped with the cold, sometimes using blankets and extra clothes. He was on a lot of medication and described himself as a 'walking time bomb'.

Before the works, he had had problems with clothes going mouldy in his wardrobe. However he had not wanted to open the windows apart from for a few minutes in the morning.

His philosophy for energy efficiency was simple: to use as little as possible, and to turn off the radiator in the unused room. His slight feeling that he was paying too much for energy pre retrofit developed into a strong feeling of resentment towards energy companies when they announced their profits and simultaneously put up their prices slightly before the post retrofit monitoring period.

Before the retrofit, this occupant was expectant that the insulation would save him money. However, the change which seemed to really save him money was when Age Concern found him a new, cheaper tariff.

| | |
|---|---|
| Rooms present | Living, kitchen, main bedroom, spare bedroom |
| Rooms with complete longitudinal air temperature dataset | Only the kitchen and spare room |
| Primary heating system | Gas central heating with TRVs |
| Secondary heating system | Gas fire in the living room |
| Location of thermostat | Hall |
| Retrofit measures undertaken | E.W.I. |
| Zone 1 *achieved demand temperature* increase | 1.4°C |
| *Daily heated hours* increase | -0.7 hours |
| *M.I.T. increase* | 1.7°C |

Table 20: Summary physical information about dwelling 3.

### A.1.2 *Summary of occupant comments on standard topics*

Table 21: Dwelling 3, occupant responses to standard topics.

| **Theme** | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How is heating switched on/off | Turn thermostat from 0 to 20°C. | Turn thermostat from 0 to 20°C. |
| Heating timing | 7-10pm, and also on Sundays. | On for 3 hours when he comes in in the evening, then not in the morning since it was still warm enough from the night before. |
| Thermostat | 20°C (on) or zero (off) | 20°C (on) or zero (off) |
| Radiator valves | All rooms heated on maximum setting, except the spare bedroom where the radiator had been turned off as it was wasting money. | All rooms heated on maximum setting, except the spare bedroom where the radiator had been turned off as it was wasting money. |
| Secondary heating | Gas fire not used, since had been told by a maintenance man it was very expensive. | |
| Other related factors that changed apart from the works | One of the radiators had been bled. | |

| | | |
|---|---|---|
| Thermal comfort | Quantitative data not obtained, but he stated that the flat did get very cold pre retrofit as he tried not to have the heating on very much. After retrofit there was a noticeable improvement. | |
| Hopes/expectations of works (pre); opinion of what changed after the works (post) | Expecting to pay less since a friend had cut down his heating hours after insulation of his house. | Impressed. Heat stayed in overnight. More comfortable. |
| Perception of energy/energy saving | Use as little as possible.<br>However, switching it on and off uses more energy than leaving it on. | |
| Perception of change (or lack of) in own heating behaviour | No longer needed a heating period in the morning. The heat stayed in all night, through to the next morning. | |
| Perception of how long it takes to warm up and cool down, and difference after retrofit | <Not obtained> | Warm up – 10 minutes. Cool down – about an hour. |

### A.1.3 *Observations from monitored data*

There was an increase in mean internal temperature of 1.7°C following retrofit in this dwelling. This can be broken down into the proportion which occurred in unheated hours (83%) and heated hours (16%). Indeed, it can be seen from Figure 126 that both heated and unheated hours became warmer after retrofit.

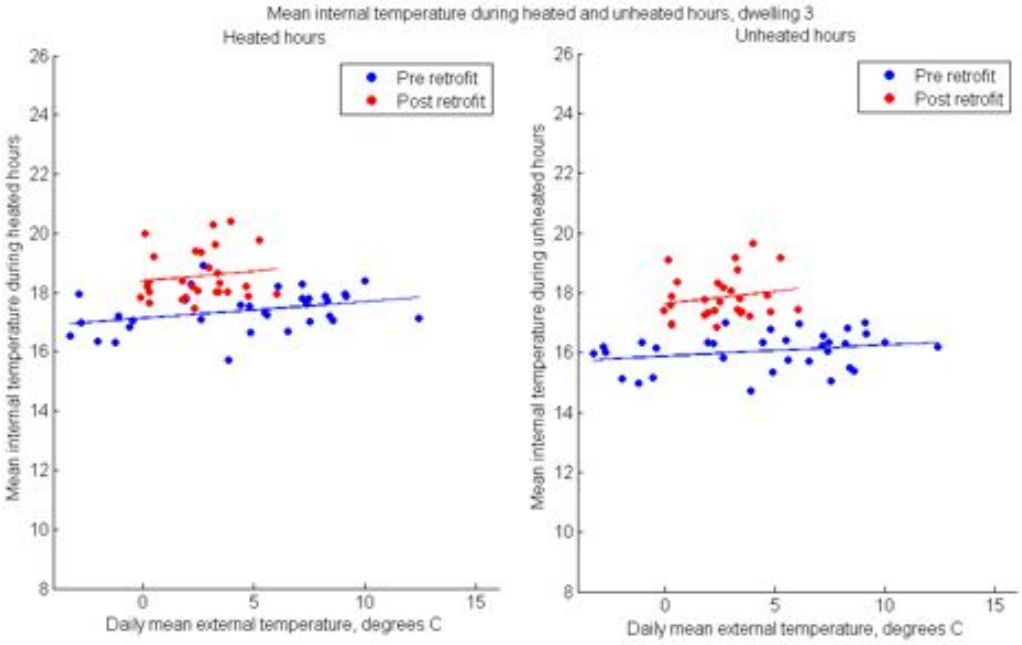



Figure 126: Dwelling 3, mean internal temperature during heated and unheated hours.

There is evidence that the thermostat limited the temperature increase during heated periods. Figure 127 shows that the temperature pre retrofit was not often attaining the thermostat setting, whereas afterwards it did so more frequently.

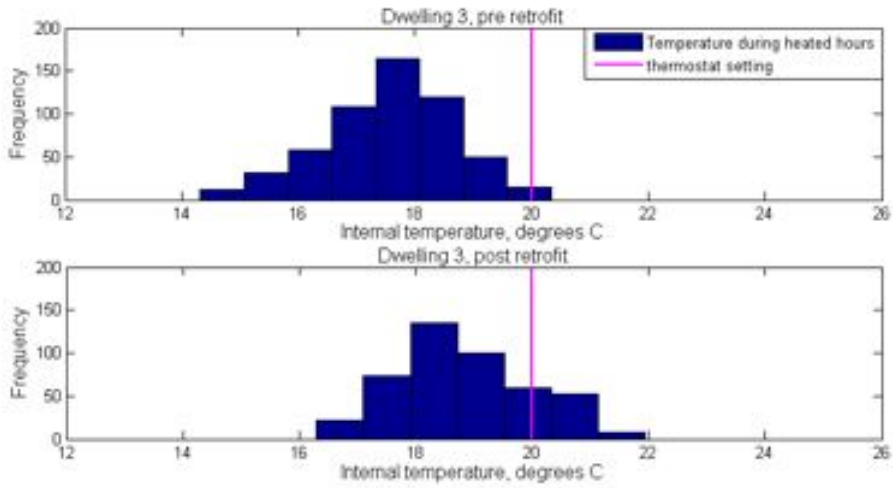



Figure 127: Dwelling 3, internal temperatures during heated periods.

One reason for the thermostat setting not being achieved in these dwellings is that some occupants' heating periods were very short, such that the internal temperature did not stabilise. In this particular dwelling there were some short heating periods, but in general the temperature did stabilise during the heating period. The temperatures at

which this occurred are shown in Figure 128. Thus, even when the heating period was long enough for the internal temperature to stabilise, it still usually did not reach the thermostat setting of 20°C.

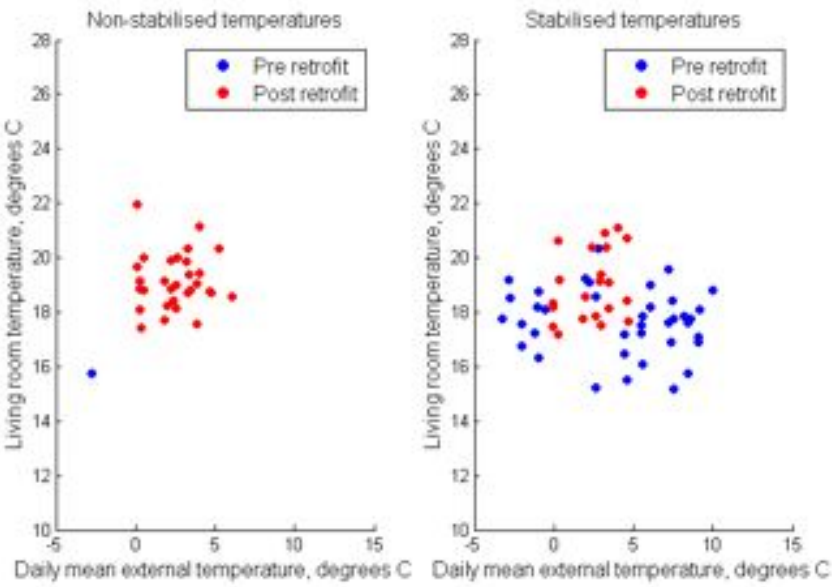



Figure 128: Dwelling 3, temperatures achieved during the heating period.

Turning now to change in heating behaviour of the occupant following retrofit, there was a slight shift in daily heating schedule. Figure 129 shows that the evening heating period became shorter and the likelihood of a morning heating period slightly increased. However both of these changes were fairly small; the occupant's heating behaviour remained approximately the same after retrofit.

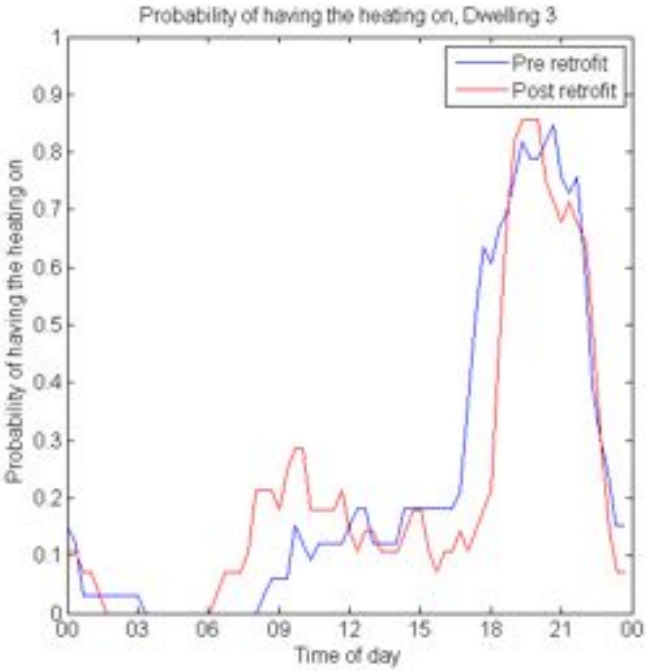



Figure 129: Dwelling 3, probability the heating is on at different times of day.

It could be hypothesised that the shortening of the evening heating period could result in morning temperatures being cooler after retrofit and thus a morning heating period becoming more likely - this is tested later after more monitored data is introduced.

It is possible from Figure 130 to qualitatively observe a reduction in rate of night cooling. However, as the lines on the left two subplots are not straight, a thermal time constant cannot be extracted from their gradients.

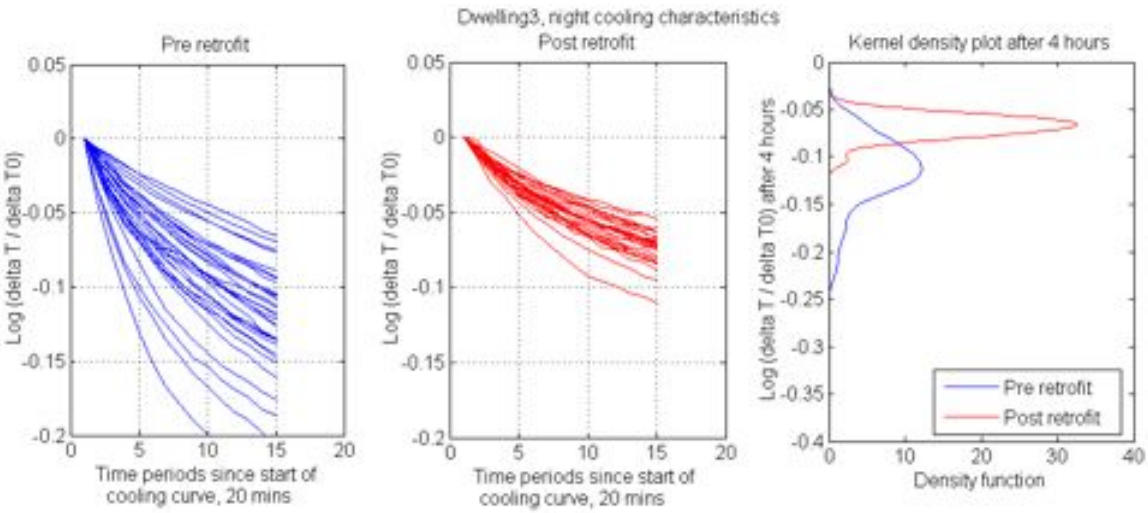



Figure 130: Dwelling 3, rates of night cooling.

### A.1.4 *Further analysis (mixed methodology)*

#### A.1.4.1 *Heating in the morning*

A noteworthy feature of the data from this dwelling is the discrepancy between the occupant response and the monitored data concerning the effect of retrofit on heating use. The occupant commented as follows:

*Occupant: "Well I've not got the heating on now [in the morning], I don't bother with it, because I can put it on when I come in, have it on for 3 hours, and then I switch it off, then when I get up in the morning, it holds the heat in."*

*Interviewer: "You don't have to have it on in the morning?"*

*Occupant: "Don't put it on, never. Cos the heat is still in the walls, in the room, it's not gone out of the windows or anything. Do you understand me? It stays in the house like. A big difference. When I used to get up in the morning, about 7, you were putting it on."* (dwelling 3, post retrofit)

Although in the previous section evidence was presented that the dwelling does *"hold the heat in"* better (Figure 130), it is not true that the likelihood of heating use in the morning decreased after retrofit - in fact, its frequency was low to start with and then slightly increased.

At this point the discussion of what to do with contradictory datastreams in Section 7.15.4.1 can be drawn upon. This apparent contradiction could either be a framing issue with the physical data, in that the monitoring periods did not capture the usual behaviour of the occupant, or it could be a self-report issue with the social data, in that the occupant was not able to report his practices (contrary to the argument made in Hitchings (2011)).

Since the data is available, it is useful to observe the internal temperature at the time at which the occupant was likely to put the heating on in the morning. This time was taken as 06:00 using a combination of the occupancy sensor data and interview data. Figure 131 shows that early mornings were warmer after retrofit than before. The occupant's sense that the dwelling retained heat was correct. Despite this, the occupant still slightly increased the frequency of morning heating.

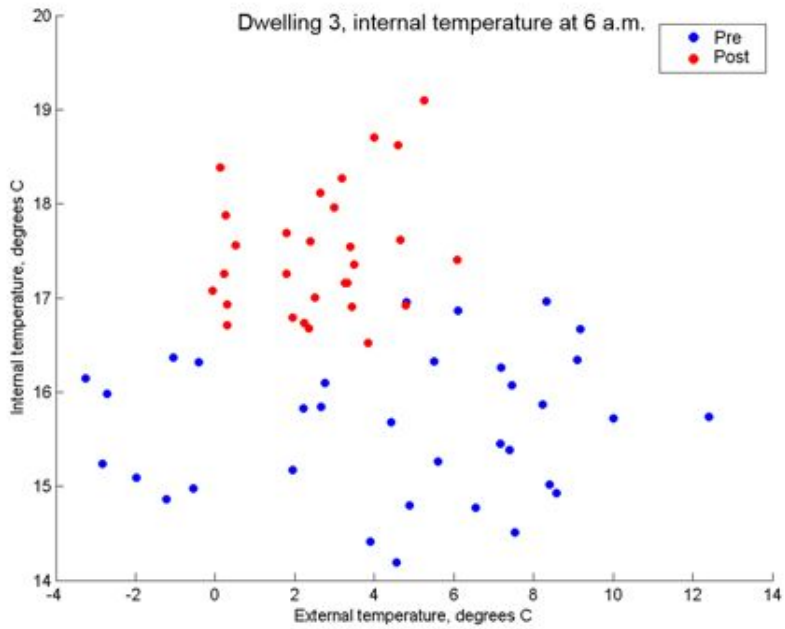



Figure 131: Dwelling 3, internal temperature at 6 a.m.

### A.1.4.2 *Two types of heating profile*

Before retrofit, the occupant stated that his use of heating on a Sunday, the day his thirteen year old son visited, was different to that on other days:

*Interviewer: "So do you put the heating on when your son's here because he asks for it, or do you have it on anyway?"*

*Occupant: "I have it on anyway. On a Sunday I put it on cos it's cold, and I put it on in the morning. Sunday's about the main day that I use the heating, do you get me?"* (pre retrofit)

After retrofit, he no longer claimed that Sunday was the main day he used the heating:

*Interviewer: "Do you use the heating in here differently when he comes?"*

*Occupant: "Nah, not really. Go collect him on a Sunday morning, he comes at 11 o'clock, if it's cold then he's not bothered and I'm not bothered so I don't bother switching it on!"* (post retrofit)

These statements can be visualised in the monitored data, in Figure 129. The week is broken down into 'Sundays' and 'Monday to Saturday':

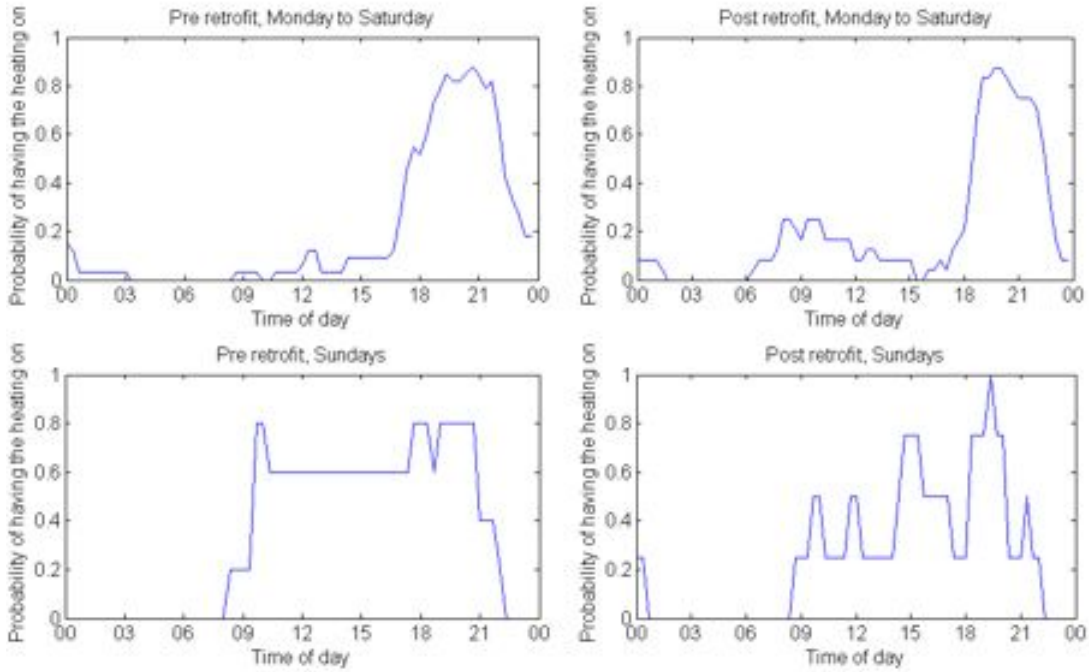



Figure 132: Dwelling 3, probability that the heating is on at different times of day, grouped by Sundays and other days.

Figure 132 shows that indeed the daily heating profile was different on a Sunday to that of the other days. The occupant's heating pattern changed, although the occupant did not directly relate this to the presence of his son. Perhaps the different occupancy routine associated with the days of the son's visit also influenced the change of heating pattern.

### A.1.5 *Proposed causal mechanism*

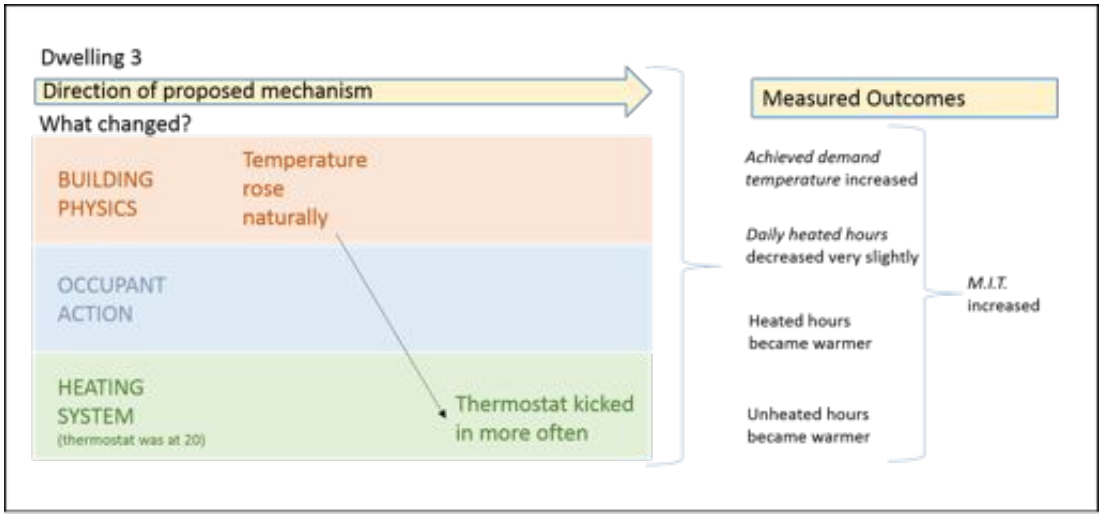



Figure 133: Dwelling 3, mechanism diagram.

### A.1.6 *Conclusion*

In this dwelling, the *mean internal temperature* rose by 1.7°C. The majority of the *M.I.T. increase* took place during unheated hours (83%), and a minor component occurred during heated hours (16%).

It seems that the occupant did not consciously turn up any of the heating settings (in temperature or time) due to the retrofit. *Achieved demand temperature* increased despite the thermostat being at a reasonable setting (20°C), but this is likely to be because this thermostat setting was not being achieved prior to retrofit and then sometimes was afterwards. *Daily heated hours* slightly reduced, but there was not a large change. The evening heating period was slightly shortened and the morning heating period became slightly more frequent, despite the occupant reporting to the contrary. However on the whole the occupant's heating behaviour remained approximately the same.

There is evidence that the night cooling rate was slower, although a single number could not be extracted from the relevant graphs. This does match with the occupant's perception that the heat was better retained overnight after retrofit.

There was no change in which rooms were heated following retrofit, and the occupant did not report change in use of rooms either. The spare room was used one day per week by his son, and this was its only purpose both before and after retrofit.

There was however a confounding factor in this case study, which was the change of energy supplier between the monitoring periods, causing the occupant's monthly energy expenditure to fall despite his heating behaviour remaining more or less the same after retrofit.

## A.2 CASE STUDY 4

### A.2.1 *Context of the household (different occupants pre and post retrofit)*

#### A.2.1.1 *Pre retrofit*

The occupant was a lorry driver who often worked nights. His origin was black African. He was trying to start a new life after a break-up, and did not know how long he would be in this current flat. For him therefore, during the week the flat was just a place to come back to after work, eat, and sleep. Weekends were slightly different – he was in the flat most of the time, where he spent a lot of time watching football. Occasionally he had a friend round to watch football but he did not know people in the area due to his odd working hours.

Although he thought the flat was too small, he tried to make the best of it, since it had positive points such as being in a quiet area.

The flat was very cold, and his strategy for staying warm depended on which room he was in and for how long. If he planned to spend a while in the living room, he switched the central heating and gas fire on. If he was going to bypass the living room and go to his bedroom, he used the electric heater only. However, money was an issue, and he was aware that it cost him a lot to use secondary heat sources. Sometimes he felt that he had no choice, since the central heating was not sufficient.

Perhaps due to the combination of not knowing anyone who had had the retrofit, and not being sure he would be in the property very long, he was not clear on the intended effect of the retrofit.

#### A.2.1.2 *Post retrofit*

The new occupant was a friend of the old one, and still a single man from Africa, this time a part-time pastor and part-time self-employed. His working hours were more standard than those of the previous occupant although he was out teaching classes many evenings.

He used the space in almost the same way as the previous tenant – that is, mostly the living room, although he mentioned a larger range of activities (eating, praying, exercise, TV) than the previous tenant (eating, TV).

He was quite surprised that the flat was so warm. His strategy for heating was simply, *"I come in, I warm the house, it stays warm!"* The secondary heating was used to warm

up the floor so that the occupant could be comfortable in bare feet, as is the custom in Africa.

His self-stated philosophy was that each person only has one life, so should make it comfortable. He was really only able to maintain this philosophy since he had enough money to heat the house adequately. Money did not seem to be a hindering issue; fuel bills were not particularly noticeable.

This occupant wanted a uniformly warm house, so that if he popped into another room, it was the same temperature there as in the living room.

Although no one had explicitly told him about the retrofit, he was aware that something had happened to improve the quality of life on the estate.

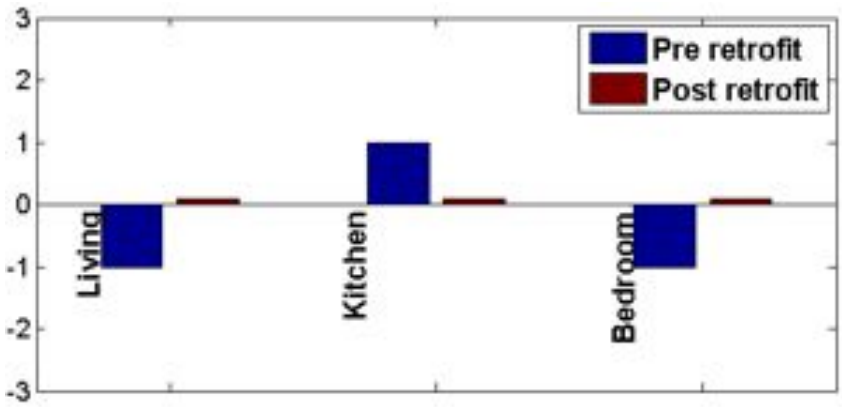
| | |
|---|---|
| Rooms present | Living, kitchen, bedroom |
| Rooms with complete longitudinal air temperature dataset | Living, kitchen, hall, bedroom |
| Primary heating system | Gas central heating with T.R.V.s |
| Secondary heating system | Gas fire in the living room, portable electric fan heater normally in bedroom 1. Not monitored as nowhere to put the logger given that the heater was portable. |
| Location of thermostat | Hall |
| Retrofit measures undertaken | E.W.I. and double glazing |
| Zone 1 *achieved demand temperature* increase | 4.6°C |
| *Daily heated hours* increase | 1.1 hours |
| *M.I.T. increase* | 3.5°C |

Table 22: Summary physical information about dwelling 4.

### A.2.2 *Summary of occupant comments on standard topics*

Table 23: Dwelling 4, occupant responses to standard topics

| **Theme** | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How is heating switched on/off | Turn thermostat from 0 to max (30) | Turn thermostat from 0 to 20. |
| Heating timing | If he knew he would be at home for the next few waking hours, he used the central heating, if he came in from work and went straight to bed, he used the electric fan heater in his room. Timers were for people with children. | He put it on for an hour when he came home in the evening. The flat was still warm enough the next morning to not require heating. |
| Thermostat | 30 (on) or zero (off) | 20 (on) or zero (off) |
| Radiator valves | Not adjusted. | Not adjusted. |

| | | |
|---|---|---|
| Secondary heating | An electric fan heater in his bedroom was used instead of central heating, before going to bed, or when he was on his laptop at the weekend. It was not on for long, as either it cost a lot or the room became warm/hot.<br>A gas fire in the living room was used whilst waiting for the central heating to warm up, if he was installed in the living room. | A gas fire is used for 20 minutes at the start of the central heating period, to warm the floor. |
| Other related factors which changed apart from the works | The occupant. | |
| Temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Hopes/expectations of works (pre); opinion of what changed after the works (post) | It should make the house warmer - but he did not know how to reconcile that with saving energy. | Did not know the exact nature of the work but knew that something had been done to improve quality of life on the estate. |
| Perception of how long it took to warm up and cool down | Warm up - one hour. Cool down - 15 minutes. | Warm up – 10 minutes Cool down – about an hour. |

### A.2.3 *Observations from monitored data*

In this dwelling it is not possible to separate the effect of the change of occupant from that of the efficiency measures. Several graphs illustrating the combination of these changes will be shown nonetheless.

The internal-external temperature relationship is shown in Figure 134. This masks the fact that the range of internal temperatures in the post retrofit monitoring period was almost completely different to those in the pre retrofit case, as shown in Figure 135.

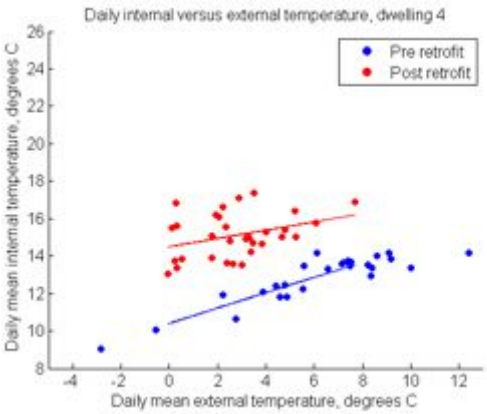



Figure 134: Dwelling 4, internal versus external temperature relationship.

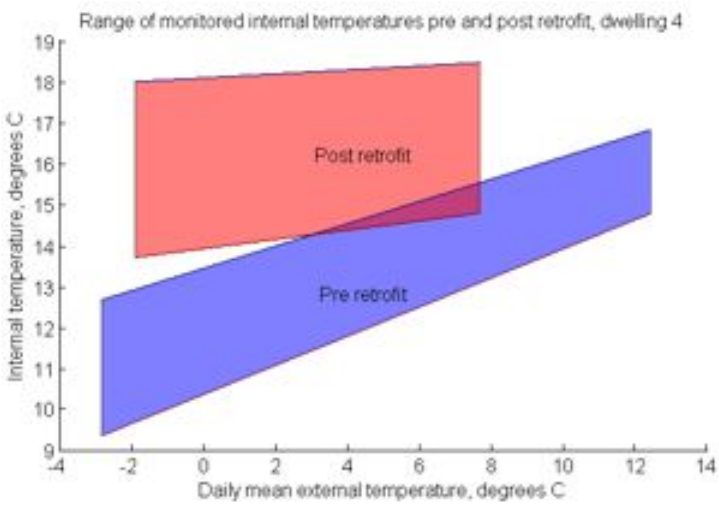



Figure 135: Dwelling 4, range of internal temperatures.

The above increase in range of temperatures is likely to be partly due to the change of heating pattern that was associated with the change of occupant. Before retrofit, the occupant hardly used the central heating (Figure 136) and occasionally used the gas fire

(Figure 137). After retrofit, although secondary heating data is not available, it can be seen from Figure 136 that the central heating was used more.

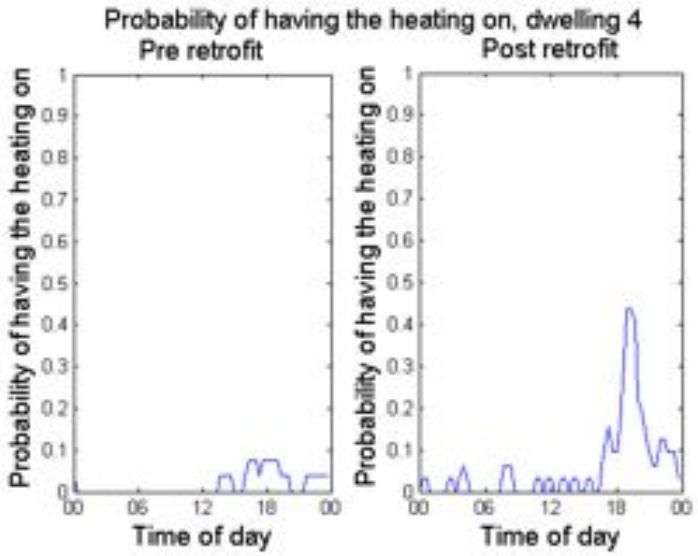



Figure 136: Dwelling 4, probability the central heating is on.

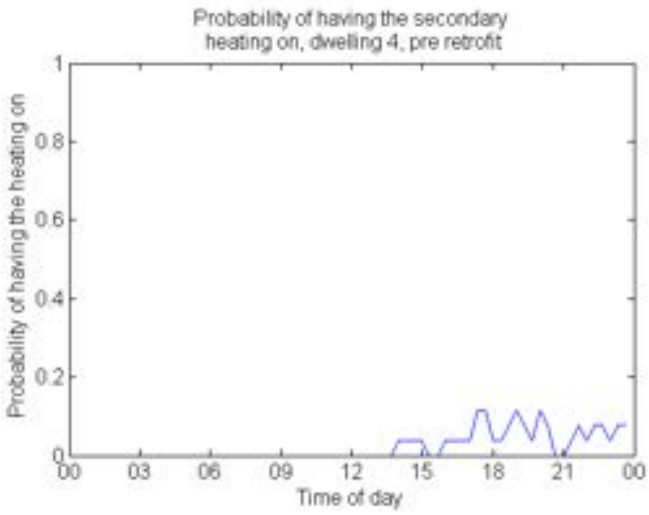



Figure 137: Dwelling 4, probability the secondary heating is on, pre retrofit.

### A.2.4 *Further analysis*

#### A.2.4.1 *Same dwelling, different occupants*

Even though the change of occupant renders most aspects of longitudinal comparison inappropriate, to a limited extent the story of the dwelling can be told by combining the pre and post occupants' statements. For example, the first occupant reported a long warm-up period and quick cool-down period, then the second occupant reported potentially the same warm-up period but that instead of being lost immediately, the heat was retained in the flat all night. Thermal comfort in the spaces in which the occupants were sedentary (living room and bedroom) became more comfortable. Living room secondary heating was used post retrofit for an arguably less important reason - that of allowing the tenant to walk around barefoot - than pre retrofit when it was needed to warm up the whole occupant, and bedroom secondary heating was used pre retrofit and not post retrofit.

There was a difference between the occupants' attitudes concerning how acceptable it was to only heat one room. Upon returning home from work, the pre retrofit occupant would sometimes bypass the central heating and just heat his bedroom for the time he went to sleep. This type of heating strategy was not regarded as desirable for the post retrofit occupant, whom upon being asked if he ever just heated one room stated,

*Occupant: "...for me it makes sense to have a house that is uniformly warm."*

*Interviewer: "What do you mean, uniformly warm?"*

*Occupant: "If I only put on this [fire], it only warms this room."*

*Interviewer: "You mean uniform across the rooms."*

*Occupant: "Yeah. But if I go to the toilet, and I walk into the cold...I would like it such that when I go into the bathroom I find it's already warm, when I go to the kitchen it's warm as well. But if I only put on the fire, it's only going to warm here. I don't want to go into the bedroom and walk into a cold room. So I put on both."*

The thought of not having the freedom to walk around the flat and experience the same temperature was not acceptable to the post retrofit occupant.

#### A.2.4.2 *Same occupant, different dwelling*

It is interesting to consider this case study from the point of view of the post retrofit occupant, who gave some qualitative information about his previous house. He felt that the latter was colder than the case study dwelling. Upon moving into the newly insulated dwelling, he was very pleased with how warm it was:

*"In comparison to a lot of houses I think it is warm. I was surprised really when I came into this house, it was warm"* (dwelling 4, post retrofit)

The new dwelling also cost less to heat:

*"In the previous house, gas was more expensive [...] The previous house, it was more expensive, but I didn't stop doing what I wanted to do because of the cost."* (dwelling 4, post retrofit)

The occupant set the thermostat at 20°C in both his previous dwelling and his current one. An alternative conceivable behaviour would be to have decided that the new property was cheaper to heat than the old one and thus set the thermostat higher. However, this did not occur.

It would be useful to know on a national level whether people's heating behaviour changes upon moving into a more efficient dwelling. Section 3.4 described findings from BRE (2013b), linking level of underheating to shorter heating hours and lower 'demand temperature'. However it is not clear what the latter term refers to in this particular relationship. There is also cross-sectional evidence from Shipworth et al. (2010) that higher thermostat settings are associated with presence of double glazing and draught proofing (although not for presence of roof insulation, and there is no figure for presence of wall insulation). In terms of how an individual occupant's behaviour changes as he/she moves between dwellings, the only study so far is Sonderegger (1977). The topic may be investigated in the forthcoming panel study mentioned in Section 4.4.

### A.2.5 *Conclusion*

In this dwelling, a change of occupant between the monitoring period renders longitudinal comparison difficult. However, certain insights can be gained from studying a dwelling with different occupants before and after retrofit. The first is the almost completely different range of internal temperatures occurring in the two monitoring periods.

The second, partly explaining the first, is the difference in attitude to heating and zoning strategy and what is acceptable in terms of *inter-room temperature gradient*. The third is the interesting fact that the particular post retrofit occupant in this case noticed the increased warmth of the newly retrofitted dwelling but did not use higher temperature heating settings than he had in his previous dwelling.

## A.3 CASE STUDY 5

### A.3.1 *Context of the household*

This 60-year-old single man was a long-term resident of his flat. He had been doing odd jobs for years, mostly over the summer. He had a positive spirit and did not seem to mind the cold and the bad state of his flat. At first there was a younger friend present much of the time; he had moved away by the second monitoring period. The occupant's activities on weekends were similar to those during weekdays in general; it all depended what work he had. He followed a fairly regular pattern of having breakfast then going to town for about 6 hours (otherwise he would get bored), then coming back and going on the computer or watching TV. His bed was at one end of the living room as it was a very small flat.

During the first monitoring period his heat source was an electric bar heater that he moved around the room, heating only the area in which he sat. It was important to him to keep the heat in one room, so he kept all the internal doors closed. He had found a way to heat himself; just because central heating was there it did not mean he had to use it.

There was a large change in his income between the two monitoring periods, as he turned 60 and started receiving a pension. As well as increasing the amount of food he could buy, he was also able to pay back the large amount of debt he owed for gas – and thus could switch the gas heating on without an amount being deducted to repay the arrears. He still did not use the gas central heating much, but he had started using the gas fire instead of the electric heater. In the post retrofit interview he did not mention being cold, nor going to bed early, so it seemed that he had experienced an increase in comfort level.

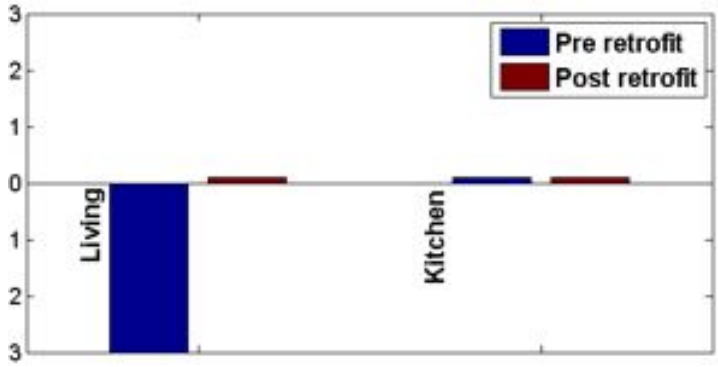
| | |
|---|---|
| Rooms present | Living room that was a bedroom at one end, kitchen |
| Rooms with complete longitudinal air temperature dataset | Living, bedroom |
| Primary heating system | Gas central heating with T.R.V.s |
| Secondary heating system | Gas fire in the living room, portable electric bar heater pre retrofit, different electric heater post retrofit |
| Location of thermostat | Living room |
| Retrofit measures undertaken | E.W.I. and double glazing |
| Zone 1 *achieved demand temperature* increase | 1.9°C |
| *Daily heated hours* increase | 0.8 hours, although the heat source was different so the comparison pre and post cannot be made directly |
| *M.I.T. increase* | 1.9°C |

Table 24: Summary physical information about dwelling 5.

### A.3.2 *Summary of occupant comments on standard topics*

Table 25: Dwelling 5, occupant responses to standard topics.

| **Theme** | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How is heating switched on/off | Switch on and off the electric bar heater | Switch on and off the gas fire |
| Heating timing | <Data not obtained> | Half an hour in the morning; a couple of hours in the evening. |
| Thermostat | 20°C, and he knew its purpose as a regulatory device, but rarely used the central heating. | 20°C, and he knew its purpose as a regulatory device, but rarely used the central heating. |
| Radiator valves | On max; never adjusted. | On max; never adjusted. |
| Secondary heating | Central heating was the secondary heating in this case; used only in situations of extreme cold. | |
| Other related factors that changed apart from the works | Income doubled as he started receiving a pension. | |

| | | |
|---|---|---|
| Temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Hopes/expectations of works (pre); opinion of what changed after the works (post) | The purpose was for warmth and to improve the look of the area. | It was warmer and looked nicer but was maybe done to cover up the cracks. |
| Perception of change (or lack of) in own heating behaviour | Aware that now his income was higher he could pay off his gas arrears, and maintain a warmer flat. | |
| Perception of how long it took to warm up and cool down, and difference after retrofit | Warmed up instantly, since he moved the electric heater to where he is located. | Warm up: 15 minutes. Cool down: an hour. |

### A.3.3 *Observations from monitored data*

This was the coldest dwelling in the sample, both before and after retrofit. For example, the pre retrofit *M.I.T.* was only 11.8ºC.

The *M.I.T. increase* following retrofit was 1.9ºC, with colder days outside becoming proportionally warmer inside as in Figure 138:

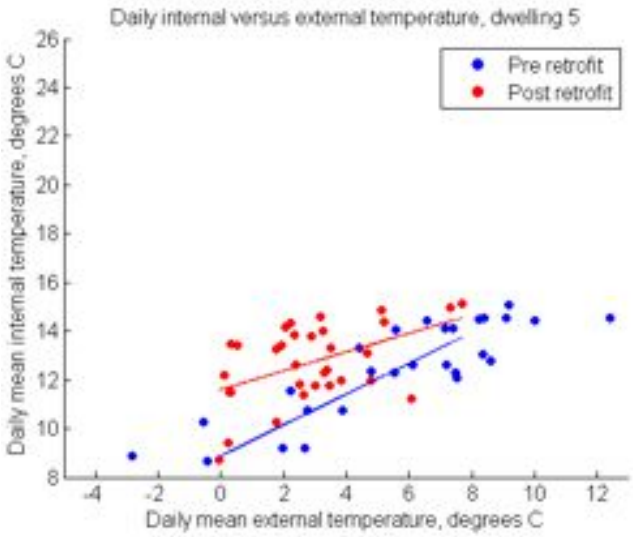



Figure 138: Dwelling 5, daily *mean internal temperature*.

This *M.I.T. increase* mostly occurred in unheated hours, showing the increased capability of the building to retain heat (Figure 139)

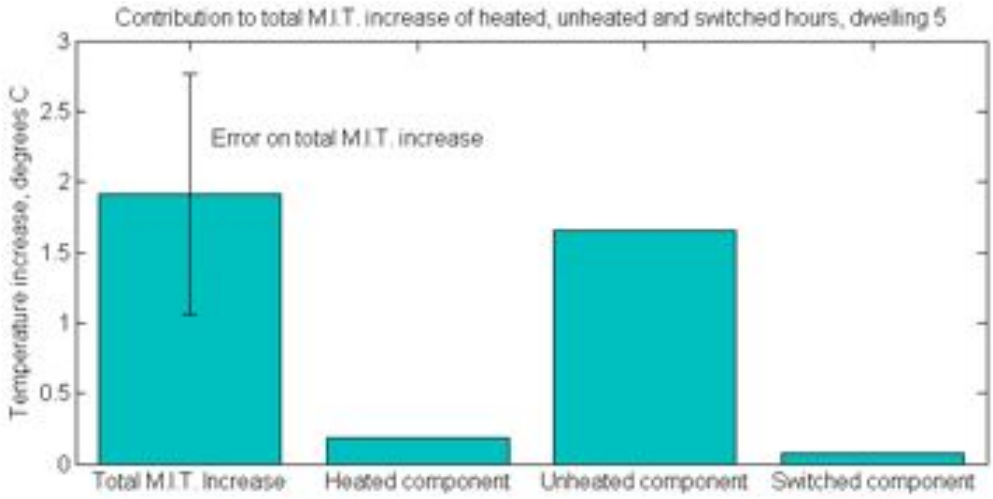



Figure 139: Dwelling 5, attribution of *M.I.T. increase* to heated, unheated and switched hours.

Figures 140 and 141 demonstrate that the *daily heating hours* slightly increased, although the actual schedule remained very similar after retrofit:

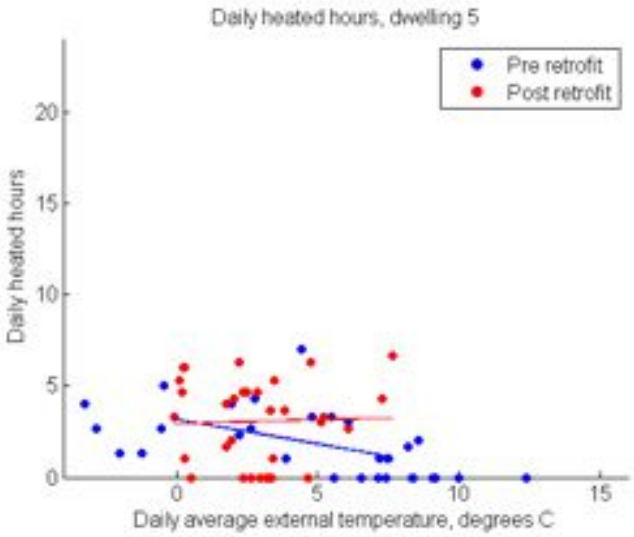



Figure 140: Dwelling 5, *daily heated hours*.

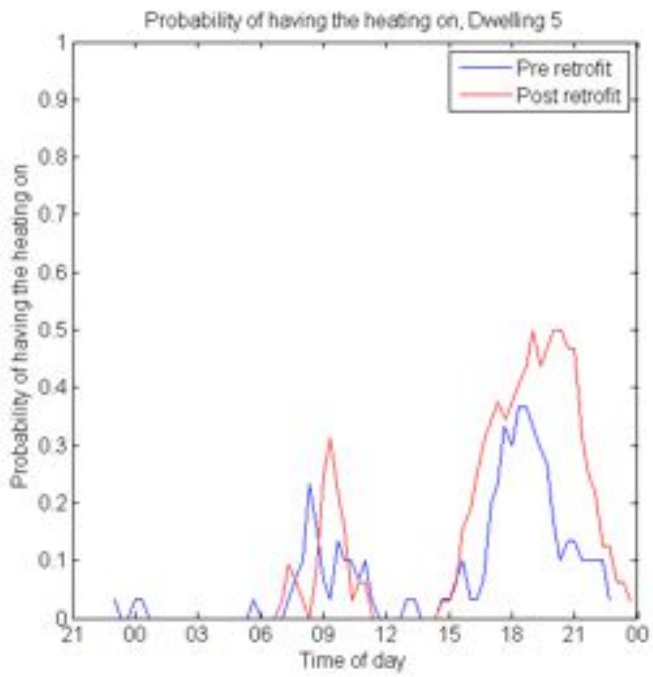



Figure 141: Dwelling 5, probability that the heating is on at different times of day.

### A.3.4 *Further analysis*

Since the heating use in this dwelling could be considered an extreme example of underheating, the first part of this discussion will explore why this happened, how the occupant adapted to it and the difference made by the retrofit.

#### A.3.4.1 *Coping with the cold*

As is typically the case in fuel poor households, a combination of the physical characteristics of the building and difficult financial circumstances of the occupant contributed to notable underheating. This occupant had strategies to keep warm without relying on using fuel:

*Interviewer: "So what do you do to try and warm up?"*

*Occupant: "Keep all the doors shut. Doors, windows shut, that's it. And sometimes, if it's too bloody cold, go to bed early."*

The phenomenon of occupants going to bed early to avoid the cold has been reported elsewhere, by CSE (2010) and Gilbertson et al. (2006). It can affect occupants' social life and is a restrictive way to spend free time.

There was a further restrictive aspect of life in this cold flat to which the occpant had become accustomed: the electric bar heater used as the primary (in fact the only) heating system heated only the space directly in front of it. The occupant therefore moved it around to wherever he was sitting:

*"I stand by that one there, then when I work on the computer, I unplug it and move it over there. You can move it around, it's a movable one. You can put it where you like."* (pre retrofit)

One year later, however, cold was less of a problem. Not only had the retrofit taken place, but as mentioned above the occupant's income had doubled. He still kept the living room zoned off from the hall and kitchen to preserve heat, but found his flat comfortable now (Section A.3.2) and was very pleased with the retrofit.

#### A.3.4.2 *Income*

Part of the extra income that the occupant had started receiving between the two monitoring periods had been put towards heating. This allowed him to operate a higher

output power device, a gas fire, for slightly longer hours. In this case the occupant had made a conscious connection between the extra money and increased use of heating:

*"That [amount of money]'s what I used to get before, a fortnight, which I couldn't afford to pay the gas. You can't afford to put gas on. But now, I'm on double benefit, I can put gas on."* (dwelling 5, post retrofit)

This income effect is different from reinvesting financial savings from retrofit back into energy. In this dwelling, income elasticity of demand was qualitatively observed to have a greater influence on energy use than efficiency elasticity.

### A.3.5 *Conclusion*

This dwelling represents a case of extreme underheating. In such dwellings, it could be argued that the most important aim of retrofit would be to allow the achievement of a higher internal temperature rather than to focus on energy savings. Under this metric, the retrofit was successful in that the internal temperature increased; however, its post retrofit value was still only 13.3°C. The level of underheating meant that the extent of retrofit undertaken was still insufficient to bring the temperature of the property up to what would normally be considered an acceptable standard.

It is difficult to know what to make of the fact that retrofit still left the property at a temperature which would normally be considered unacceptably cold, due to the occupant's particular heating strategy. Since the models used to predict the outcomes of retrofit generally assume a normative heating pattern, this type of issue is not anticipated in choosing the level of retrofit.

## A.4 CASE STUDY 6

### A.4.1 *Context of the household*

This was an exceptional occupant in several ways. During the pre retrofit monitoring period he was suffering from throat cancer, alone in his flat. He experienced pain while talking, so was not interviewed after the monitoring period. Furthermore, due to circumstances detailed in Section A.4.4, no heating use data was obtained from this flat, and the pre retrofit internal temperature data is not representative of the occupant's normal heating behaviour. Thus, the dataset for this dwelling is lacking some major components.

By the time of the post retrofit monitoring period, the occupant was recovering from his illness and was able to be interviewed. It transpired that he had previously been a drug-lord in Ghana, then was sent to prison, repented and became a Christian in quite a dramatic way. This completely changed his life and his attitude to material possessions: in his words, he had previously tried everything life had to offer, and saw that it had not satisfied him. He now only held lightly onto material things and tried to live as simply as possible.

The occupant's heating use was influenced by his illness, and also the simplicity principle introduced above. It was very important to him to maintain a temperature of 20°C in the rooms he used; any less and his throat became more painful. A drop of even one or two degrees was noticeable in the level of pain in his throat. On the other hand, he would never be excessive and use more heating than he needed.

He was very grateful for the insulation, which appeared to have allowed the transition from a state of struggling with the cold and with energy bills and to one of coping:

*"We are OK because of insulation."*

He was also resigned to high energy prices, and felt a strong sense of injustice on behalf of people who could not afford their fuel bills whilst those high up in energy companies reaped large profits. However, he was not concerned for his own welfare; he had seen how God had brought him through many trials and this was just another one.

### A.4.2 *Physical information post retrofit*

Since no data was obtained regarding heating use, it is not possible to use the same methods as elsewhere in this thesis to infer when the heating was on. This means

that metrics depending on this knowledge, such as daily heated hours and demand temperature, cannot be obtained. Furthermore, due to the heating system being broken during the pre retrofit monitoring period but operational the year after, comparison of temperature before and after insulation is not meaningful. Instead, the rest of this case study will focus on conditions after retrofit and especially whether they met the particular needs of the occupant given his health condition.

| | |
|---|---|
| Rooms present | Open plan living room and kitchen, bedroom |
| Rooms with complete longitudinal air temperature dataset | Living room, bedroom |
| Primary heating system | Gas central heating with TRVs, although this was only operational post retrofit |
| Secondary heating system | Electric oil-filled radiator, mostly in living room but portable |
| Location of thermostat | Hall |
| Retrofit measures undertaken | E.W.I. |
| *M.I.T.* post retrofit | 19.4°C |

Table 26: Summary physical information about dwelling 6.

### A.4.3 *Observations from monitored data*

The post retrofit internal-external temperature relationship is shown in Figure 142:

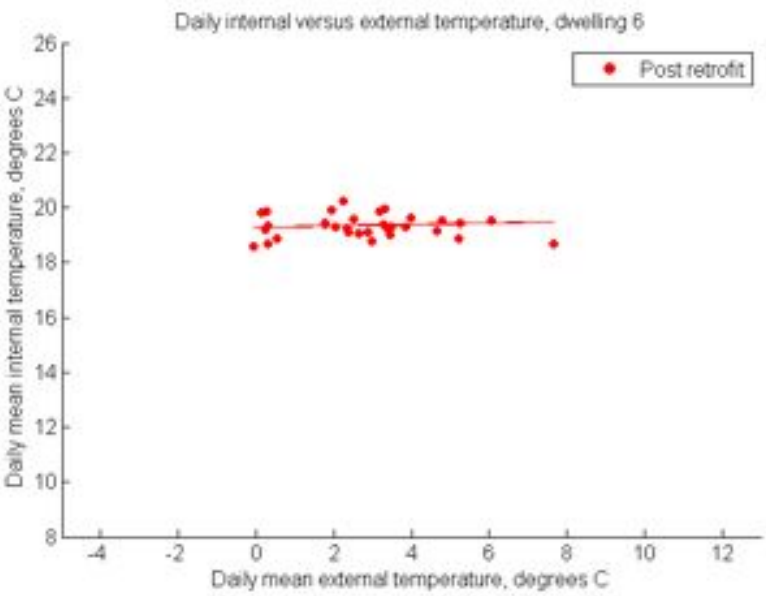



Figure 142: Dwelling 6, *M.I.T.* versus external temperature.

The relationship between *M.I.T.* and external temperature is relatively flat compared to those in other dwellings. This suggests either constant heating under thermostatic control, or increase in daily heated hours at lower external temperatures. Whichever of those behaviours is the case, the relationship in Figure 142 indicates that the combination of the post retrofit efficiency of the building fabric and the occupant's finances results in being able to maintain 20°C - the level stated by the occupant to be required to ease the pain in his throat.

### A.4.4 *Ethical issues*

The reason that no heating use data was available from this dwelling is as follows. On the first day of the pre retrofit monitoring period, the central heating system broke down. The occupant did not call a plumber to mend it as he did not want to get in the way of the study. He also did not inform the author, presumably as talking caused him significant pain. He had therefore used a single electric heater to heat the property, at this most crucial time in his illness when he needed warmth to relieve pain. Although he stated he needed the dwelling to attain 20°C when he was present, the pre retrofit range of temperatures was below 18°C, as shown in Figure 143:

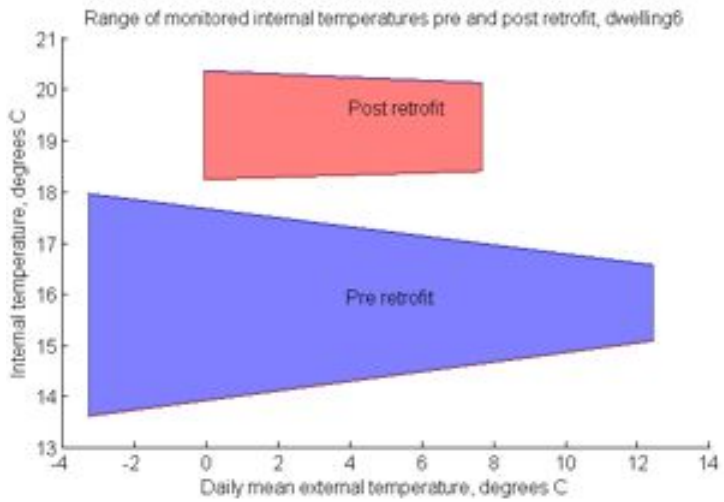



Figure 143: Dwelling 6, range of internal temperatures.

In protecting the author's study, the occupant had sacrificed his health. This was certainly not what the author would have wanted, but ethical issues of this type had not been anticipated before the start of the study. In hindsight, there should have been

some clear statements to the occupant before the start of the study that if anything went wrong, he or she should take priority over the research.

### A.4.5 *Conclusion*

Although the monitored data from this study cannot be used to isolate the effect of the retrofit on internal conditions, this case study can be used to highlight a number of important points. Firstly, the efficiency measures had made a critical difference in terms of bills: between struggling and coping. The post retrofit temperature data showed that the occupant's need of 20°C to ease his pain was met, without the occupant incurring an impossible fuel bill. Finally, concerning the study itself, additional measures could have been put in place to ensure that occupants did not feel they had to make personal sacrifices for the sake of the author.

## A.5 CASE STUDY 7

### A.5.1 *Context of the household (different occupants pre- and post-retrofit)*

#### A.5.1.1 *Pre retrofit*

During the pre retrofit monitoring period this dwelling was occupied by a middle aged couple with learning difficulties. They occupied this 3-bedroomed house by themselves. At one point their children had been living there, but a difficult situation meant the children were taken away. They were both unemployed, and followed a similar daily pattern to several of the other case study occupants – that is, after breakfast they went out to town and returned at about 4pm. Sunday was the only day in which this did not happen.

The man had issues with his spine and therefore liked to maintain a high temperature; however this dwelling felt exceptionally warm even for someone with this type of health need. The occupant's explanation was that he liked to keep it *"consistently warm"* and so never turned the heating off. Given that the couple had fallen out with their old energy company and had not yet received a bill from the new one, how their first bill would change their behaviour remains unknown.

This house was already partially retrofitted by the time the monitoring equipment was installed. Prior to this, it seemed that the occupants had used even more energy, since as well as the central heating they had also used the gas fire.

#### A.5.1.2 *Post retrofit*

The post retrofit occupants were a single mother and her two teenage daughters. They had recently had some family traumas and had been housed in a hotel; upon moving into this house they appreciated having their own space again. Since the mother had learning difficulties and some other problems, her 16-year-old (eldest) daughter looked after her to some extent. At weekends she went to stay with her dad. The mother had learning difficulties together with other health issues; to some extent the elder daughter acted as carer for her mother, but at weekends she went to stay with her dad. The younger daughter was not present very often.

According to these occupants, there was no routine heating strategy; instead they reacted to feeling cold by turning on the central heating and/or the gas fire.

The elder daughter was wearing light clothing during the interview, and said she always wore a similar level of clothing at home. There were a couple of rooms which tended to be cooler but every room was more or less comfortable.

The mother spent most of her time at home. She considered her main activities to be cleaning and decorating, and was very proud of what she had done so far. It seemed that after being in temporary accommodation for a while, she wanted to make her house a home.

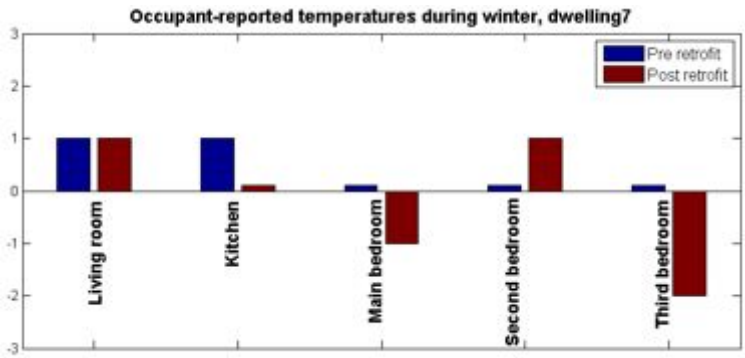
| | |
|---|---|
| Rooms present | Living, kitchen, main bedroom, two further bedrooms |
| Rooms with complete longitudinal air temperature dataset | Living, kitchen |
| Primary heating system | Gas central heating with T.R.V.s |
| Secondary heating system | Gas fire in the living room |
| Location of thermostat | Halfway up the stairs |
| Retrofit measures undertaken | E.W.I. and double glazing |
| Zone 1 *achieved demand temperature* increase | -5.9°C |
| *Daily heated hours* increase | -17.5 hours |
| *M.I.T. increase* | -7.6°C |

Table 27: Summary physical information about dwelling 7.

### A.5.2 *Summary of occupant comments on standard topics*

Table 28: Dwelling 7, occupant responses to standard topics

| **Theme** | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How is heating switched on/off | At the programmer | At the programmer |
| Heating timing | Only turned off in hot weather | When the occupants feel cold |
| Thermostat | 10°C, although it must have been broken as the heating was on continuously | 18°C |
| Radiator valves | Not adjusted. | Not adjusted. |

| | | |
|---|---|---|
| Secondary heating | A gas fire in the living room, which used to be used a lot before the windows were double glazed but afterwards was not used much. | A gas fire in the living room. Sometimes used on top of the central heating, sometimes used instead of it. |
| Other related factors which changed apart from the works | The occupants. | |
| Temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Perception of how long it took to warm up and cool down | Data not obtained | Warm up: 10 minutes. Cool down: 10 minutes |

### A.5.3 *Discussion*

Although it is not entirely possible to separate the effect of the change of occupant from that of the retrofit, two points can be usefully made concerning this case study.

#### A.5.3.1 *Extreme case of heating*

This was the dwelling in which the highest *mean internal temperature* of the entire sample was recorded. The pre retrofit occupants maintained a mean internal temperature of 24.1°C, by the use of continuous central heating. This may have only been possible to achieve due to the fact that the dwelling already had double glazing intalled and one external wall insulated by the time of the installation of monitoring equipment.

Figure 144 shows the relatively constant temperature maintained over the range of external temperatures in the pre retrofit monitoring period:

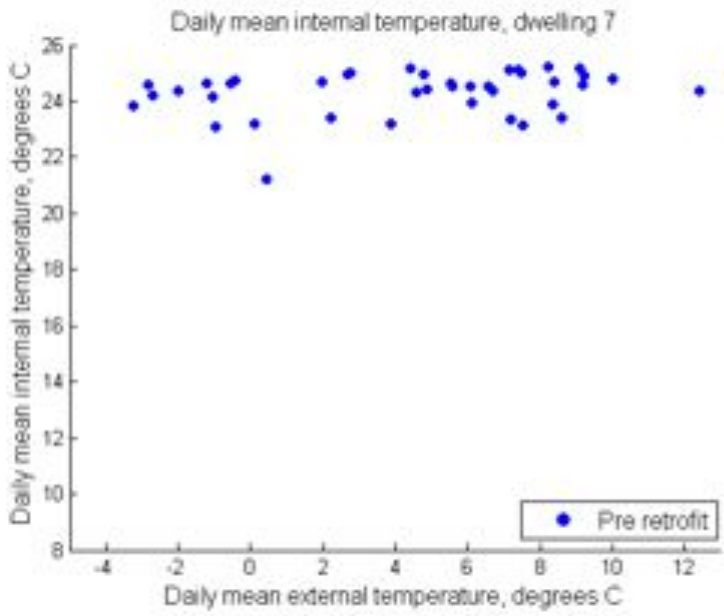



Figure 144: Dwelling 7, daily mean internal temperature pre retrofit.

The relationship in Figure 144 was achieved by the use of continuous heating, shown in Figure 145. To maintain a flat relationship between internal and external temperature as observed in Figure 144, either a thermostat or T.R.V.s must have been controlling the temperature.

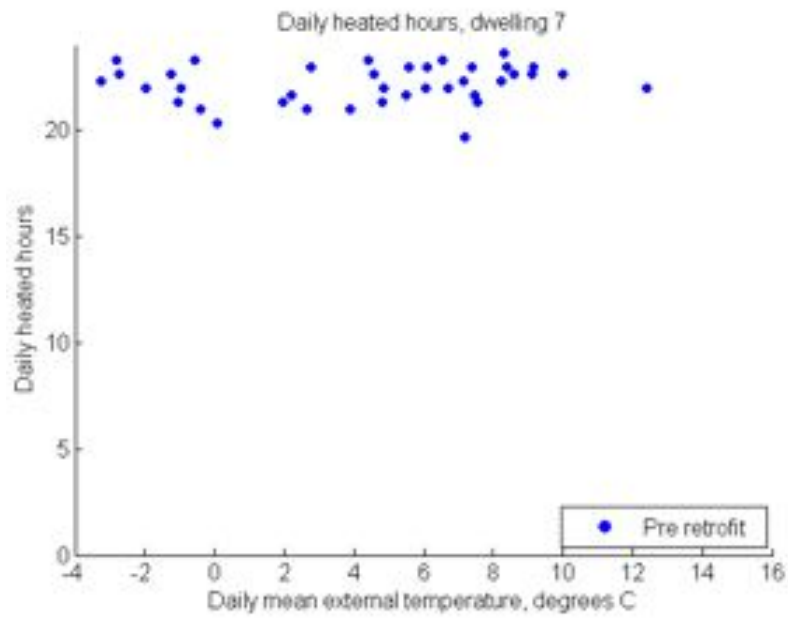



Figure 145: Dwelling 7, *daily heated hours* pre retrofit.

In Section 8.6, this example of a very high *M.I.T.* is discussed in comparison to dwelling 5 - the case of the lowest *M.I.T.* across the sample. This is to demostrate the variation in heating behaviour across even this small sample of dwellings.

#### A.5.3.2 *Magnitude of change following retrofit*

Partly as a result of the very high level of heating by the pre retrofit occupants, this was also the dwelling in which the largest change in *M.I.T.* was observed after retrofit (albeit in a negative direction): -7.6°C. That is, the effect of a change of occupant outweighed the effect of the insulation applied after the first monitoring period.

This can be related back to the theoretical context developed in Chapter 2. Figure 7 in Section 2.4 visualised the possibility space of mean internal temperature for one dwelling given all possible behaviours; superimposed onto this were two cases of 'normative' behaviour before and after a shallow retrofit. It was observed that the size of the entire space was much larger than the distance between the two normative lines. This would suggest that in a non-deep retrofit scenario, the change in *M.I.T.* brought about by the efficiency measures alone is small compared to the *possible* change in occupant behaviour. This appears to be the case in this dwelling: the change of occupant had a larger effect than that of the physical efficiency measures.

### A.5.4 *Conclusion*

This case study was not suited towards answering the research questions, which in their strict sense are aiming to isolate the effect of the retrofit. However, it is an interesting representation of extreme heating behaviour. It is useful to know why the dwelling is heated to such an extent: in this case a combination of the occupant's perception of his health needs and his personal preferences.

It is also useful to observe the effect of a change of occupant dominating the effect of the retrofit. This concept was introduced in theory in the modelling work in Chapter 4, although in the opposite sense. There, it was hypothesised that a decrease in energy use could be more than offset by a set of new occupants with higher comfort preferences; in this case study the temperature increasing effect of insulation was more than offset by the decrease in heating use.

## A.6 CASE STUDY 8

### A.6.1 *Context of the household*

This first floor flat was occupied by a single woman in her fifties. She had separated from her husband some years ago, which triggered a period of depression and led to her being unable to work. However, she was normally a happy person, and sounded positive.

Home was very important to her – she had made a lot of effort to decorate the flat very beautifully. Additionally, she spent time every day cleaning, dusting and tidying. She liked having a smart flat, and also enjoyed spending time making it that way.

Her daily pattern consisted of breakfast, then 'pottering' about cleaning and dusting, followed by going to see her mother nearby. She usually returned by mid-afternoon and pottered about some more before settling down to watch television.

This routine was different at weekends when her grown-up sons came to visit or stay, one of whom brought his own son. Despite the forthcoming spare room tax, she wanted to be able to carry on hosting these family members, so was prepared to pay the rent increase. She also used the heating more when her family was present. She heated all the rooms but the spare one had its radiator set on low just to keep the chill off.

Money was tight, and she got by without using much heating. She achieved this by having a bath mid-evening, then wrapping up in a dressing gown for the rest of the evening. Also, by moving around a lot between rooms, she did not get cold. She had similar strategies for saving water.

She was delighted to find out the walls would be insulated, since she had made enquiries herself about insulation a few years previously, what with the flat being so cold. However, the insulation only made a slight difference, and the heat was still lost quickly when the heating was switched off. Until the post retrofit interview, she had not thought about the difference that the insulation might have made to her gas bill. When she retrieved the latest bill during this interview, she remarked that in fact the bill was lower than usual, and wondered if she had in fact used the heating less since the flat was insulated.

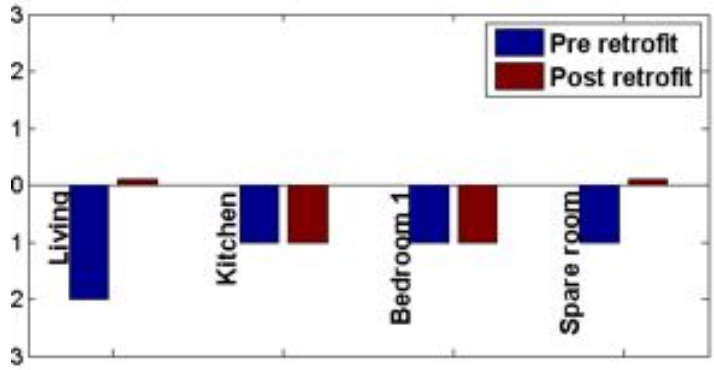
| | |
|---|---|
| Rooms present | Living, kitchen, main bedroom, spare room |
| Rooms with complete longitudinal air temperature dataset | Living, spare room |
| Primary heating system | Gas central heating with TRVs |
| Secondary heating system | Gas fire in the living room |
| Location of thermostat | Hall |
| Retrofit measures undertaken | E.W.I. |
| Zone 1 *achieved demand temperature* increase | 2.2°C |
| *Daily heated hours* increase | -1.8 hours |
| *M.I.T. increase* | 0.7°C |

Table 29: Summary physical information about dwelling 8.

### A.6.2 *Summary of occupant responses to standard topics*

Table 30: Dwelling 8, occupant responses to standard topics

| **Theme** | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How is heating switched on/off | Press 'on' at the programmer. Only on a timer during visits from guests so as to not have to think about heating. | Press 'on' at the programmer. Only on a timer during visits from guests so as to not have to think about heating. |
| Heating timing | <not mentioned> | <not mentioned> |
| Thermostat | Left on 20°C and never touched. | Left on 20°C and never touched. |
| Radiator valves | One kept on low in spare room to keep the chill off | One kept on low in spare room to keep the chill off |
| Radiator valves | Not adjusted. | Not adjusted. |
| Secondary heating | Fire used, less than once per week. | Fire not used. |
| Other related factors which changed apart from the works | <none came up> | |

| | | |
|---|---|---|
| Temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Hopes/expectations of works (pre); opinion of what changed after the works (post) | Warmer and pay less. | She felt warmer when the heating was on, but the flat still lost heat fairly quickly. The unheated room (the kitchen) had not become warmer since the insualation. |
| What constitutes energy saving | Until the interview she had not realised that she had saved money but then attempted to post-rationalise the saving as subconscious awareness that she should be using less heating due to the insulation, leading to her doing so.<br><br>She also held to the belief that it does not save energy to turn individual room radiators off, since then that cold room makes the rest of the house colder and so the heating system has to work just as hard. | |
| Perception of change (or lack of) in own heating behaviour | Warm up: 30 minutes. Cool down: within an hour. | Warm up: 15 minutes. Cool down: an hour. |

### A.6.3 *Observations from the monitored data*

It is fairly difficult to compare the pre and post retrofit *M.I.T.* and daily heated hours data, as the ranges of external temperature over the two monitoring periods do not overlap to a great extent. However, Figures 146, 147 and 148 can be used to show that the post retrofit heating behaviour was similar to that pre retrofit, despite the post retrofit monitoring period being colder outside. In other words, the effect of the retrofit

was to allow the same *M.I.T.* as before with the same heating behaviour, all at a lower external temperature.

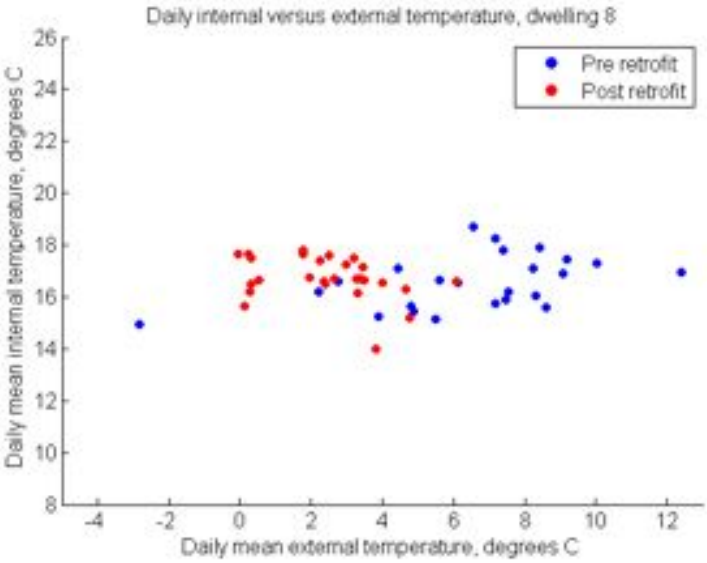



Figure 146: Dwelling 8, *mean internal temperatures*.

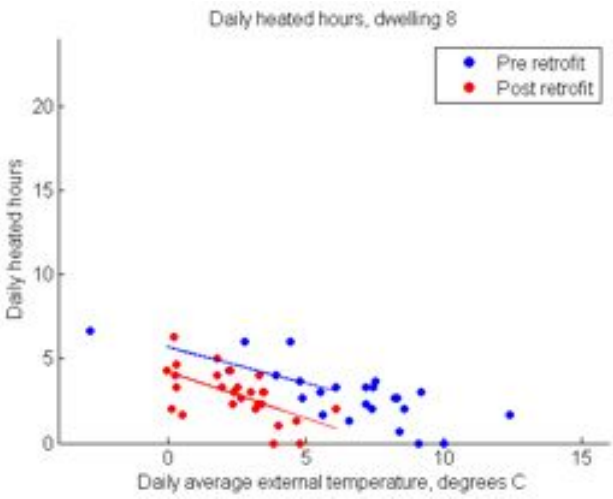



Figure 147: Dwelling 8, *daily heated hours* against external temperature

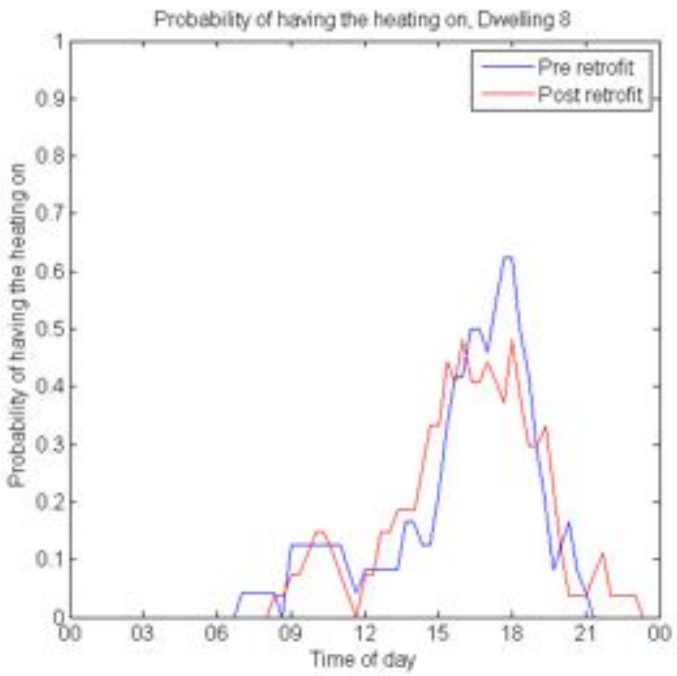



Figure 148: Dwelling 8, probability the heating is on at different times of day.

### A.6.4 *Further analysis (mixed methodology)*

From the occupant's point of view, the insulation seemed to make a difference to the temperature when the heating was on:

*Interviewer: "So can you describe how you feel about this room, this year in particular?"*

*Occupant: "It's been fine, and I have found a difference when the heating's on, you know, so there is a slight difference."* (dwelling 8, post retrofit)

However, heat was still lost from the dwelling very quickly when the heating was turned off:

*"I find that the heating, when it's on, it does its job, but as soon as you turn it off, it doesn't retain the heat. [...]. And you think, you know, perhaps on a Saturday or Sunday I've had it on for 3-4 hours maybe, and it's boiling, but as soon as you switch it off, half an hour later, you think well I've wasted 4 hours of heating, you know what I mean?"* (dwelling 8, post retrofit)

These impressions will now be compared to the monitored data.

Firstly, Figure 149 shows the temperatures achieved during the heating periods, categorised by stabilised and non-stabilised according to the method laid out in Section 7.9. Aside from the observation that the temperature did not stabilise very often (perhaps due to the heating not being on for very long), it can be seen from the left hand subplot that a similar range of demand temperatures was achieved after retrofit compared to before, at a lower external temperature. So, indeed, the insulation appears to have made a difference during heated hours.

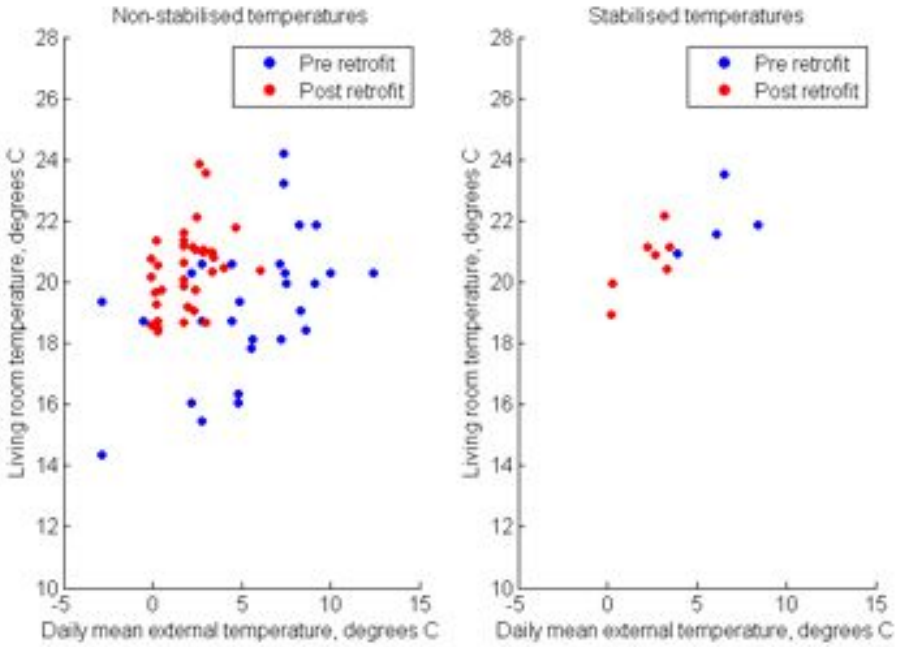



Figure 149: Dwelling 8, temperatures achieved during heating periods.

Secondly, regarding the occupant's comment that the building loses heat quickly, the night cooling method set out in Section 7.10 can be used to give a perspective from the monitored data. Log plots of the internal-external temperature difference are presented in Figure 150. Since in the pre retrofit data there were only four nights where the temperature timeseries passed the inclusion test (i.e. the rate of change of temperature being negative every timestep for 5 hours), the criterion was relaxed for this dwelling:

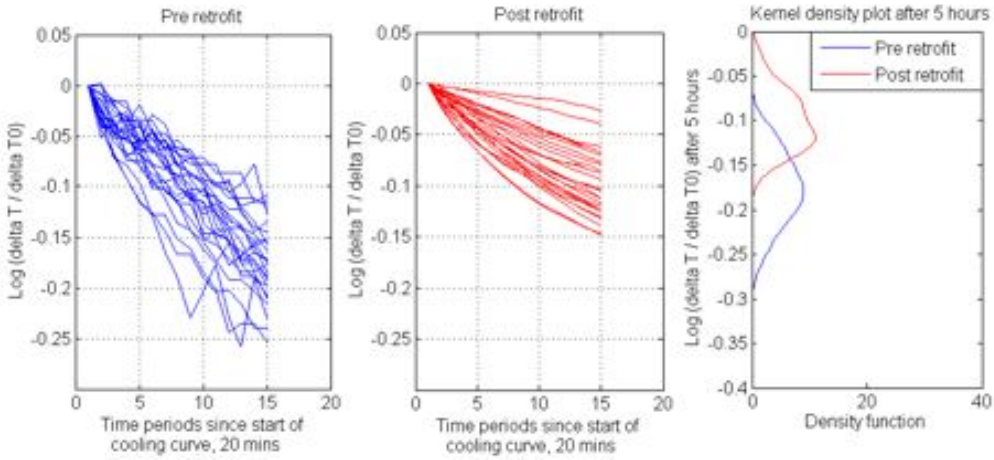



Figure 150: Dwelling 8, night cooling plots.

Figure 150 shows a decrease in cooling rate, which is clearer than that in most other dwellings. *Thermal time constants* were extracted from the average gradients of the pre and post retrofit plots; this process is fully documented in Section 8.4. It was calculated that the thermal time constant increased after retrofit from 28 to 50 hours.

Thus, the occupant's comments about heat being lost from the dwelling very quickly after the heating was turned off were made in spite of an 80% increase in the *thermal time constant*.

### A.6.4.1 *Thermal preferences*

Despite the occupant not being entirely satisfied with the apparent fast cooling of the dwelling upon turning off the heating, at one time of day - bedtime - she used this to her advantage:

"*[My bedroom] is quite cool, on the cool side, but that's how I prefer it, in here. You know, when the heating's on, it's on full blast for a couple of hours in the evening, and then by the time I come to bed, it's sort of cooled off...[...] as I say by the time I go to bed, 11, 12 o'clock, it has cooled down sufficiently for me to sleep.*" (dwelling 8, post retrofit)

The occupant liked to let the flat cool down before going to bed, as she preferred the bedroom cooler than other rooms at bedtime. Comparing this to other dwellings in the sample, there is no clear pattern: for example, the same preference for cooler bedrooms was stated by the occupants of dwellings 3 and 10, but a more uniform temperature was desired by the occupants of dwellings 2 and 9.

In terms of whether cooler bedrooms are generally preferred in the UK, little evidence is available concerning actual desired temperatures. The reality may also be more complicated than people simply desiring a fixed temperature difference between the living room and bedroom. For example, Section 3.2.3 described findings from DECC (2013b) that people like their bedrooms to be warm when they are getting ready for bed but cool when they are trying to sleep.

However, for the purposes of modelling it is often necessary to use one average temperature difference between zones. SAP uses a default difference of 3°C, although recent evidence from BRE (2013d) showed that this may be an overestimation of the difference observed in real dwellings.

### A.6.5 *Proposed causal mechanism*

The change observed after retrofit in this dwelling was not an increase in the standard metrics (*daily heated hours*, *achieved demand temperature*, *mean internal temperature*). Instead, these variables were observed to remain approximately constant at a lower external temperature. As such, the proposed mechanism in Figure 151 is constructed to show what would be expected to occur if the external temperature had been constant over the two monitoring periods. It is not based on observed findings but extrapolations, and is therefore written in the conditional tense:

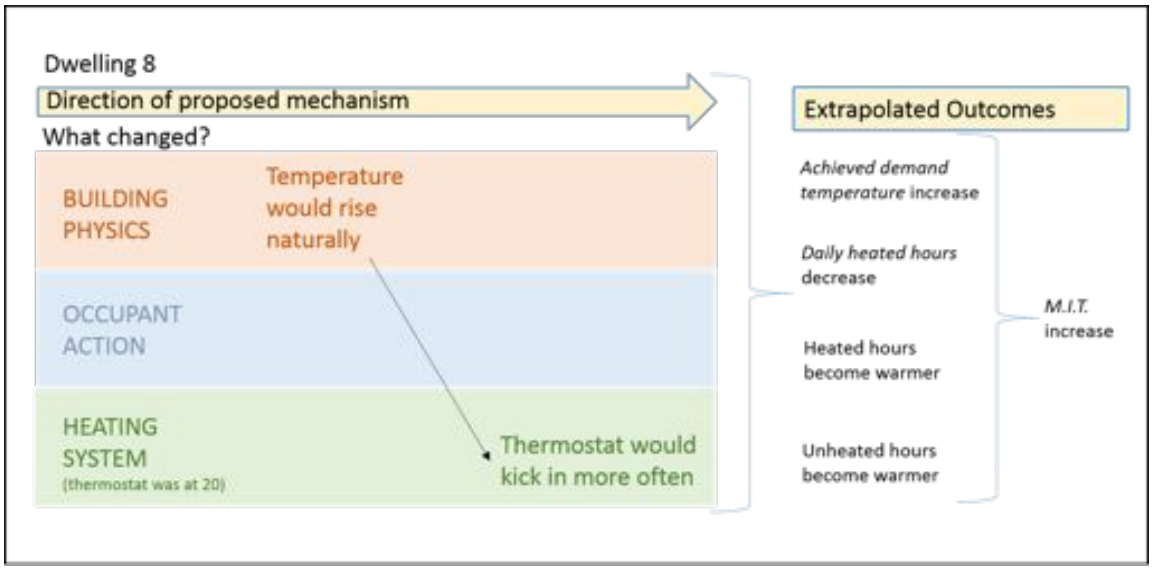



Figure 151: Dwelling 8 proposed mechanism.

### A.6.6 *Other interactions*

#### A.6.6.1 *'Pottering', use of space, and warmth*

Literature on the subject of life in fuel poverty, such as that introduced in Section 3.5.1, often documents how a cold home can constrain the occupants' movement within it, and therefore their activities. A commonly reported example is a person or household cooped up in one room, using a secondary heat source to heat only that room.

The occupant in this case study dwelling was not a typical example of the above. Despite describing her flat as too cold before the retrofit (Table 30), she did not feel that this was a constraint to her activity at home:

*"I tend to go in out of rooms most of the morning for something and another, like washing, so I do use the rooms quite a bit. And as you can see I do have a lot of cleaning, but I enjoy that, so I'm quite happy to spend two or three hours in a morning in here, and clean everything. And I do that on a regular basis, since I do like it just nice. The only room I tend not to use is the second bedroom – once I've cleaned it after the weekend, I don't use it. [...] So most rooms I use quite a bit – I can't say what I use them for, I'm just pottering normally."* (dwelling 8, pre retrofit)

This had an interesting consequence: instead of thermal comfort determining the occupant's movement, her movement determined her thermal comfort. That is, by keeping moving and circulating around all the spaces, she kept herself warm. For example, upon talking about the kitchen, an unheated room in which she would spend a few hours at a time cleaning, she agreed that she felt warm enough:

*Interviewer: "So do you find that when you're cleaning in here you forget the cold because you're moving around?"*

*Occupant: "Well yes. So I soon get warmed up."*

An occupant carrying out housework would be expected to undergo an increase in metabolic rate from $55\frac{W}{m^2}$ to $115\frac{W}{m^2}$ when compared to sedentary activity (British Standard BS EN ISO 8996:2004 in BSi (2005)), and therefore could feel comfortable at lower air temperatures. Metabolic rate emerges as an important thermal comfort variable in this case.

Turning now to the monitored data, a number of features can be observed relating to the above discussion of occupant movement. In Figure 152, the occupancy data from

the living room sensor is plotted as a histogram along with the heating use and internal temperature data. To be able to observe the behaviour of the occupant only, and not her family who visited at weekends, weekends are excluded from the Figure.

Figure 152 indicates that the occupant entered or left the living room up to 10 times per hour; this could be considered a high frequency of room change, consistent with her description of 'pottering' around the flat. It can also be seen that there were two main daily periods of movement, in the morning and then in the afternoon/evening. She reported leaving the flat in the middle of each day; this triangulates with the dip visible in the occupancy data in the middle of the day. However, perhaps the most interesting feature of Figure 152 is the coincidence of the evening heating period with the most high frequency occupant movement, despite the fact that moving around helped keep her warm as previously discussed.

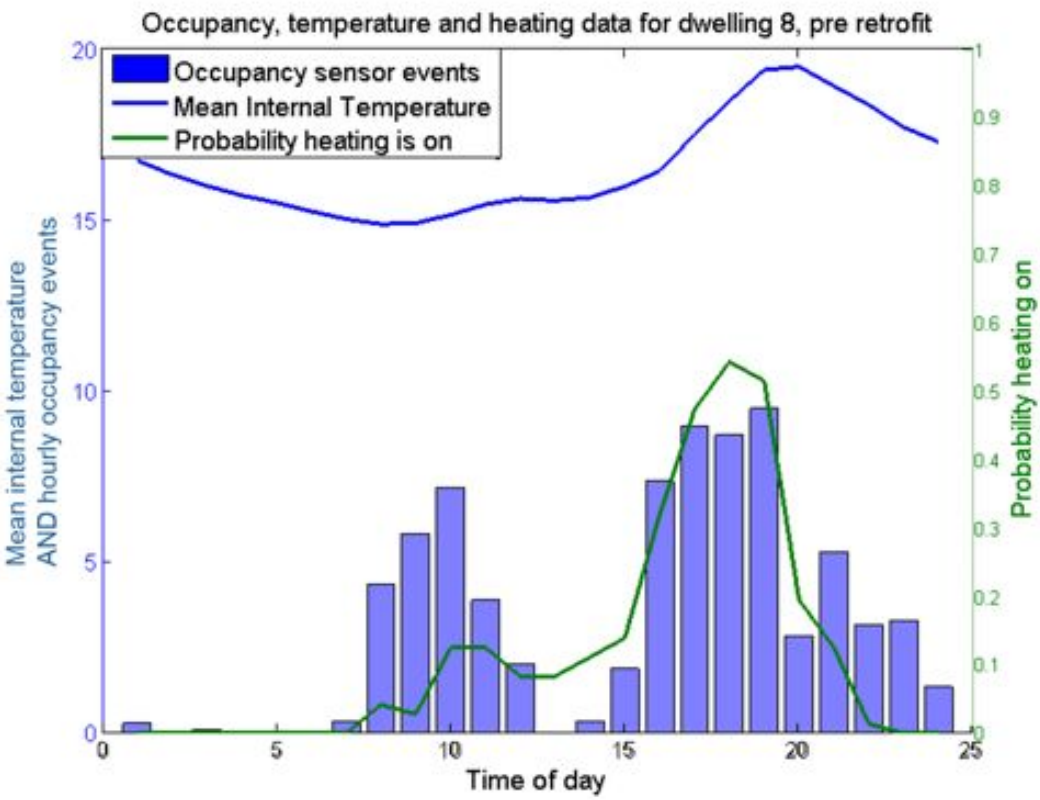



Figure 152: Dwelling 8: occupancy, internal temperature and heating use.

### A.6.7 *Conclusion*

It is difficult to document change in internal conditions and/or occupant behaviour following retrofit in this dwelling: instead, behaviour remained approximately constant at a lower external temperature. This is a result in itself, but it would have been helpful to have observed the occupant's behaviour at a similar external temperatures before and after retrofit.

However, two significant points can summarised from this case study. Firstly, it is an example of an underoccupied dwelling being used in its entirety. The building was essentially treated as one zone and circulated around frequently by the occupant. This use of the whole dwelling was a result of the occupant's activity, as she enjoyed 'pottering' around the different rooms tidying up. Her use of space then influenced her thermal comfort, as she was able to stay warm at home by keeping her activity level high at certain times of day.

Secondly, this case study is an example of an occupant not noticing the effect of the retrofit both on the internal temperature (during unheated hours), nor on her energy bill, despite the monitored data showing the rate of cooling to be slower and her energy bill showing that in fact her gas use had decreased. This latter point is brought up again in Section 10.3 in the context of comparison to occupants who interacted with their energy meters more frequently.

## A.7 CASE STUDY 9

### A.7.1 *Context of the household*

This is an example of a dwelling where the works were very positively received by a previously disengaged occupant. He was a single man, probably in his late 30s, from Zimbabwe. He had a steady 9-to-5 job as a caseworker, although by the post retrofit monitoring period he was looking to move to the NHS. He had been in the flat less than a year upon first contact by the author, and had a two-year-old daughter whom he looked after some weekends.

The only negative aspect of the flat was the cold – the property was on the second storey of a tall block which was totally exposed to the westerly wind. The cold was quite extreme: sometimes the heating had to be put on in summer. In winter, when the occupant was in the living room - his default room of occupation - he had to run both the central heating and the gas fire to get the room warm enough. If he wanted to pop out to the shops, he used to leave the heating on due to not wanting the displeasure of returning to a freezing flat. When his young daughter came, she naturally wanted to roam around the whole flat, so he had to keep her in the living room with the fire on while he waited for the other rooms to warm up, then open all the doors – different behaviour to usual. He also used much more heating when she came.

The property was then insulated and double glazed, the latter including a large glass door taking up a significant area of the living room external facade.

Although the occupant was looking forward to positive effects of the retrofit such as the building retaining heat and a reduction in noise, he had not really engaged with the leaflets and letters sent about the retrofit, and did not know how the measures being carried out to his property had been selected:

*"Let's just hope that it's going to work. Because we don't know how they did their tests to find out whether this is the right project to do, for the benefit of the people."*

After the retrofit, his attitude changed from vague hope to definite gratitude:

*"To be honest, I don't think I've got much to complain about, except to be thankful to the person who came up with this idea!"*

The winter following the retrofit felt very different to the one before. He never felt cold any more in his flat, never had to use his secondary heating, and was able to walk more freely around the flat and spend more time in his bedroom.

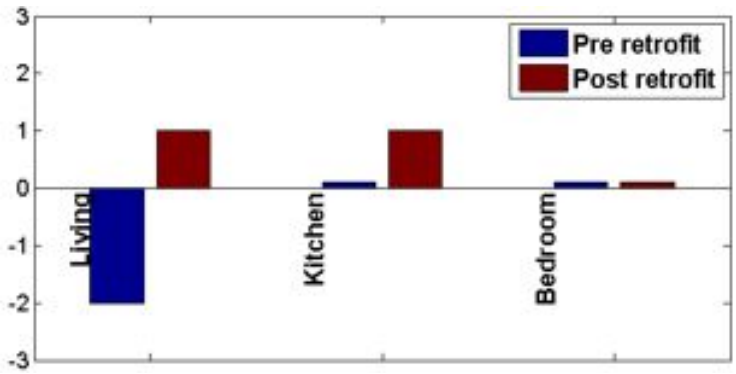
| | |
|---|---|
| Rooms present | Living, kitchen, bedroom |
| Rooms with complete longitudinal air temperature dataset | Living, kitchen, bedroom, hall |
| Primary heating system | Gas central heating with T.R.V.s |
| Secondary heating system | Gas fire in the living room |
| Location of thermostat | Hall |
| Retrofit measures undertaken | E.W.I. and double glazing, including of a large patio door into the living room |
| Zone 1 *achieved demand temperature* increase | 2.4°C |
| *Daily heated hours* increase | 0.5 hours |
| *M.I.T. increase* | 4.0°C |

Table 31: Summary physical information about dwelling 9.

### A.7.2 *Summary of occupant responses to standard topics*

Table 32: Dwelling 9, occupant responses to standard topics

| **Theme** | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How was heating switched on/off | Press on/off at the programmer. | Press on/off at the programmer. |
| Heating timing | On cold days, both the central heating and secondray heating were used in the evening. On less cold days, the central heating was used first, then switched off and the gas fire switched on. | Normally just an evening heating period using the central heating, from 6pm to before 9pm. |
| Thermostat | Stayed on 30 (max) | Stayed on 30 (max) |
| Radiator valves | All on max. | All on max. |
| Secondary heating | Gas fire used every evening (see 'Heating timing') | Gas fire not used. |
| Other related factors which changed apart from the works | <none transpired in the post retrofit interview> | |

| | | |
|---|---|---|
| Temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Hopes/expectations of works (pre); opinion of what changed after the works (post) | Not sure how they calculated that this was the correct project to do. Thought it was pretty futile to read the leaflets, but hoped that the works would mean the building retained the heat and lessened the noise. | Was very thankful to the person who came up with the idea. Had heard that the buildings were being upgraded to the latest standards to retain heat. |
| Perception of change (or lack of) in own heating behaviour following the retrofit | Did not need heating on in the morning any more, and did not put the fire on any more. | |
| Perception of how long it takes to warm up and cool down, and difference after retrofit | Warm up: more than half an hour. Cool down: 10 minutes. | Warm up: 15 minutes. Cool down: an hour. |

### A.7.3 *Observations from monitored data*

This was the dwelling in which the greatest increase in *mean internal temperature* following retrofit was observed. The difference is shown in Figure 153.

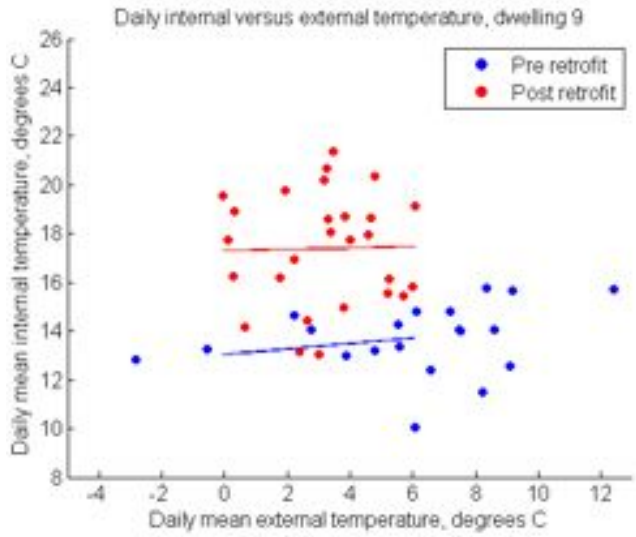



Figure 153: Dwelling 9, *M.I.T.* versus external temperature.

If, in attempting to explain how the occupant reacted to the retrofit in this dwelling, only the use of the central heating is investigated, this misses out a major aspect of what occurred. This is because the major change in dwelling 9 was the elimination of use of secondary heating from its previous regular part in the occupant's heating schedule. The metric in this thesis for change in use of heating - *daily heated hours* - concerns only the central heating. There was no clear change in use of central heating here (Figure 154). However, there was a clear change in use of the gas fire (Figure 155).

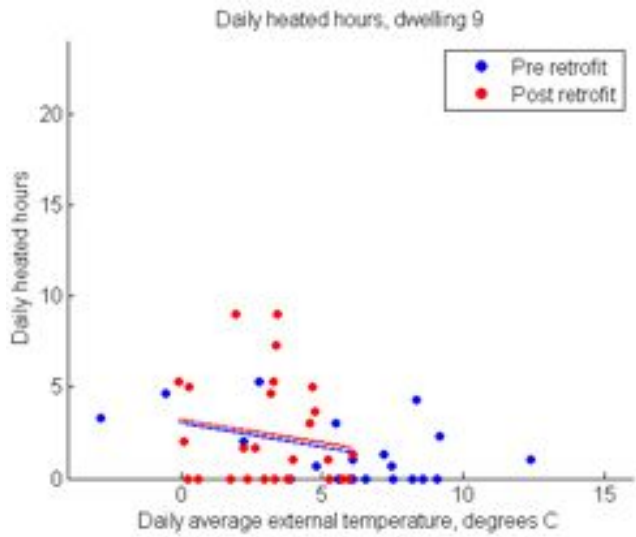



Figure 154: Dwelling 9, daily heated hours (central heating).

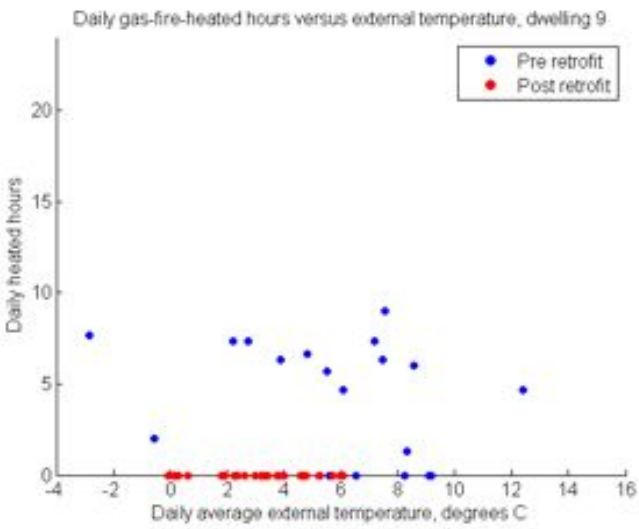



Figure 155: Dwelling 9, daily hours the gas fire was used.

At this point it is useful to observe the interaction between the central and secondary heating use, before and after retrofit. Figures 156 and 157 show an example week of heating use from this dwelling, before and after retrofit respectively. It can be seen that prior to retrofit, secondary heating was used either on top of central heating or, more commonly, instead of it. After retrofit, only central heating was used. This change in heating strategy following be further explored in Section A.7.4.1 below using the qualitative data to attempt to explain it.

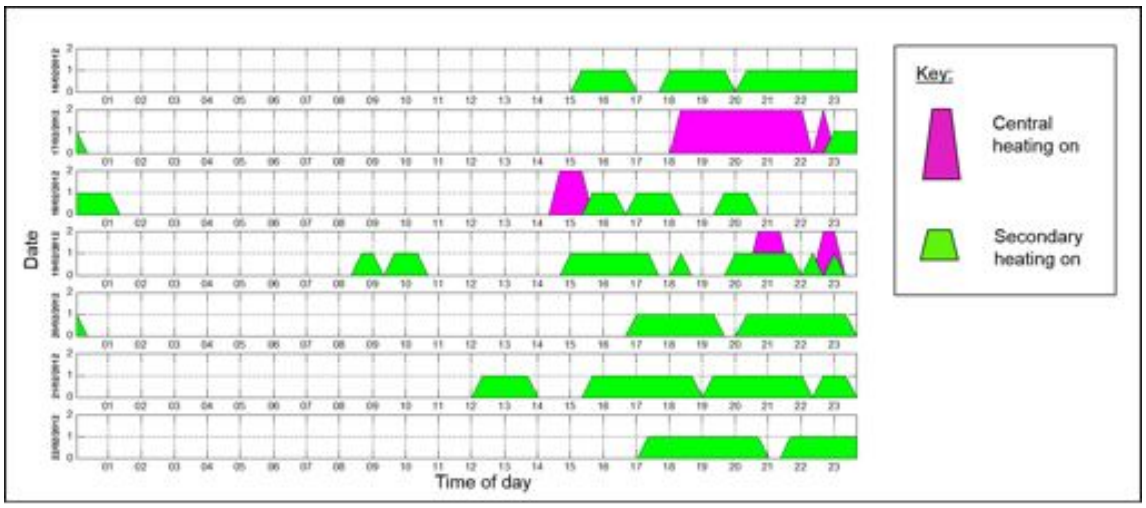



Figure 156: Dwelling 9 pre retrofit typical week: using secondary heating instead of central heating.

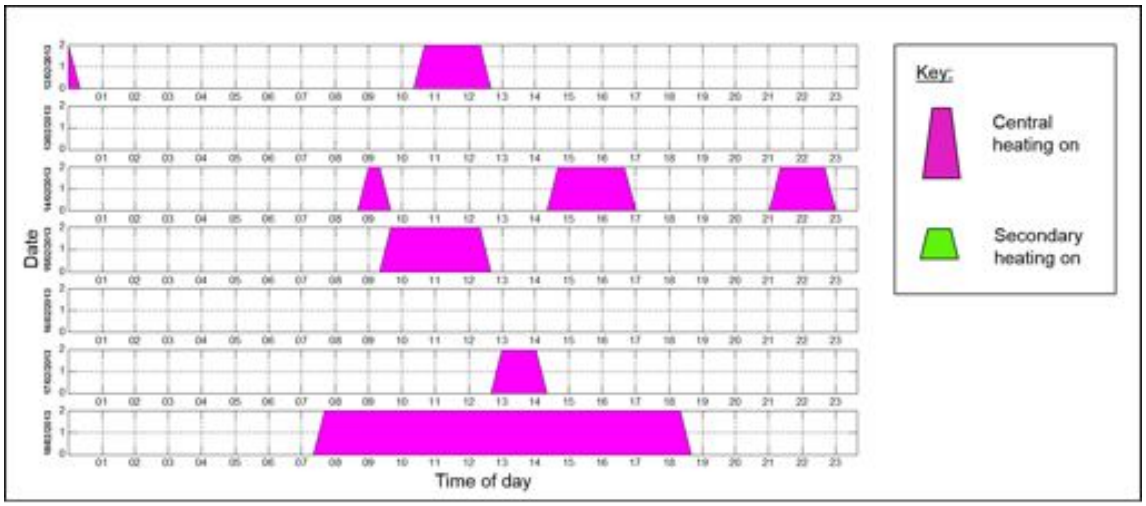



Figure 157: Dwelling 9 post retrofit typical week: using central heating.

The increase in internal temperature during both heated and unheated hours was larger than that observed in the other dwellings in the sample. This is shown in Figure 158. Heated hours only refer to when the central heating is on, for consistency with the other case studies. It is interesting, then, that unheated hours became so much warmer after retrofit, despite including some hours of secondary heating pre retrofit and none post retrofit. Please note that lines are not fitted through scatter plots of quantities related to heated hours in this case study, due to the small number of data points.

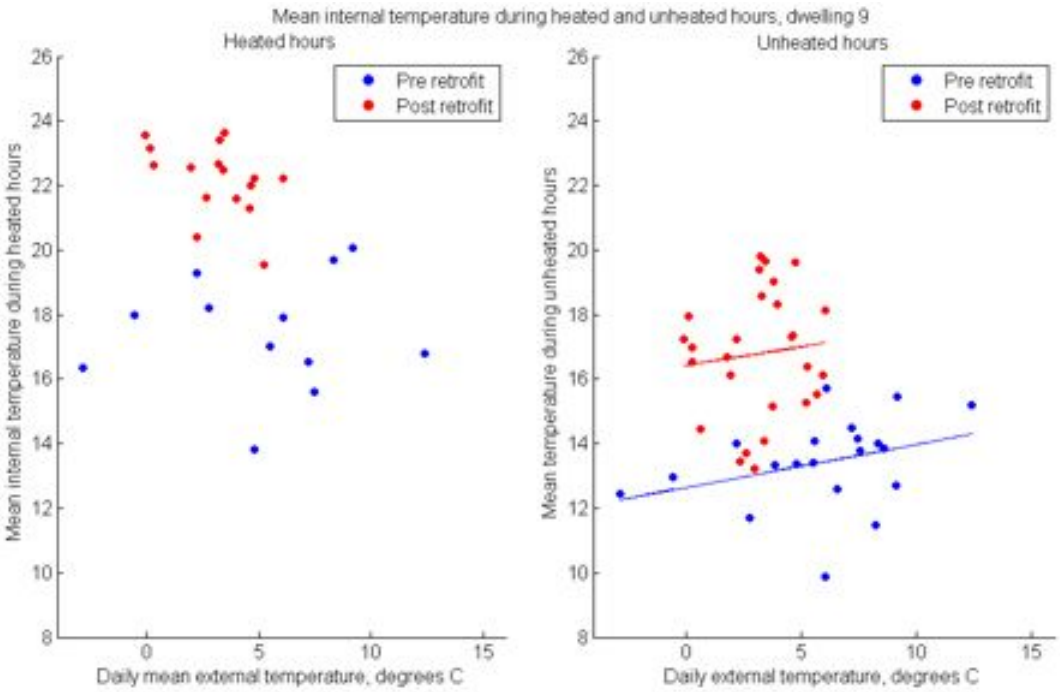



Figure 158: Dwelling 9, temeperature during heated and unheated hours.

Despite the temperature during heated hours increasing, and also the *achieved demand temperature* increasing (Table 31), most of the *M.I.T. increase* is still attributed to unheated hours becoming warmer, as shown in Figure 159:

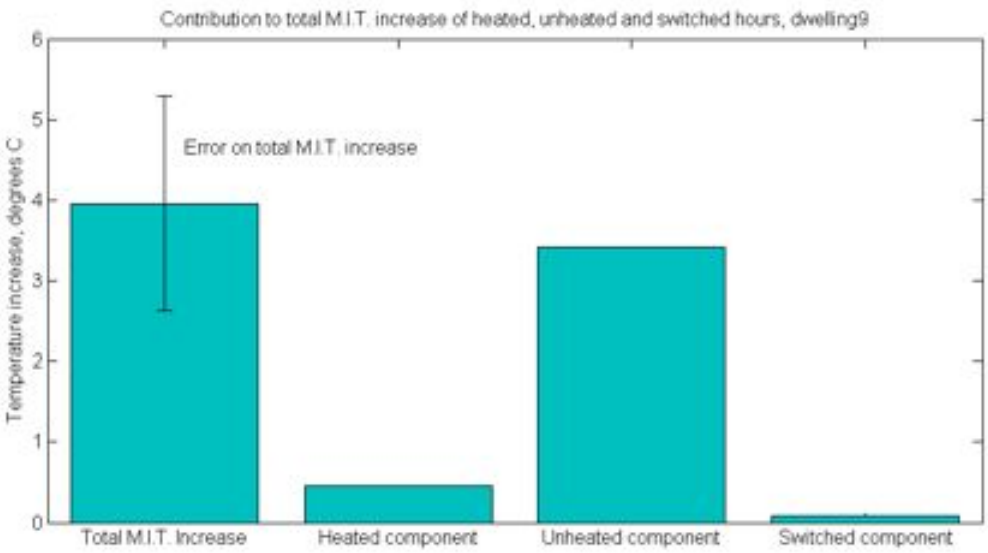



Figure 159: Dwelling 9, attribution of *M.I.T. increase* to heated and unheated hours.

Figures 160 and 161 show the temperature differences between rooms and the overall *inter-room temperature gradients* in this dwelling. The latter Figure shows a decrease in the width of its distribution. This could perhaps be attributed to the fact that before retrofit it was often the case that only the living room was heated, whereas afterwards either all rooms or no rooms were heated, Section A.7.4.1 below discusses this in relation to the occupant's use of space.

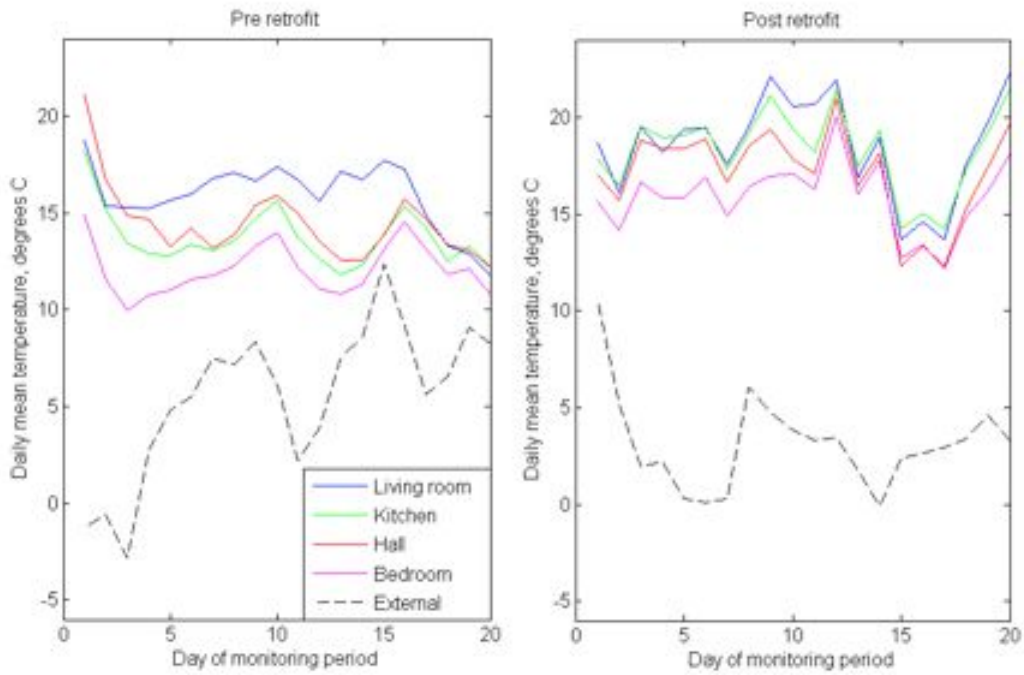



Figure 160: Dwelling 9, individual room temperatures across the monitoring periods.

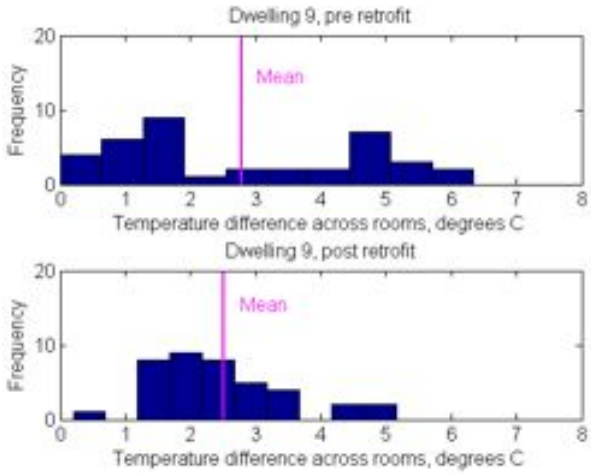



Figure 161: Dwelling 9, histograms of *inter-room temperature gradients*.

### A.7.4 *Further analysis*

#### A.7.4.1 *Change in heating strategy*

The shift from using predominantly secondary heating to central heating is possibly explained by the section of interview data below:

*Occupant:"I realised that... I might put the heating in my house, but as long as a neighbour doesn't use the central heating, it means that it's not gonna help much, my heating which I produce here, goes to other flats which are also freezing."*

*Interviewer: "...where would you put [the living room] now [on the comfort scale]?"*

*Occupant: "I pick two of them here. Comfortable, and comfortable but a bit on the warm, because what I normally do, like right now, is just put the central heating on, just about 10 minutes ago I put it on, and it's already warm enough that I can take off my jacket. So if it goes for the next one hour, two hours, then that's when I say comfortable but a bit on the warm side."* (dwelling 9, post retrofit, referring to pre retrofit)

It seems that before retrofit the occupant did not think the central heating was a worthwhile use of fuel: his flat was so leaky that his neighbours would gain the benefit more than himself. However, after retrofit the occupant could feel that the central heating had an effect, even after a short period of time. It even heated up the living room to the state of 'comfortable but a bit on the warm side'. Now that the flat kept the heat in, the central heating became worth using.

#### A.7.4.2 *'Rebound'?*

The thermostat in this dwelling was set to 30°C, and never touched by the occupant. This setting was too high for the thermostat to ever control the internal temperature. Therefore, when the efficiency measures were installed, from the steady state heat balance equation in Section 2.2.2.3 the internal temperature during heating periods would be predicted to increase.

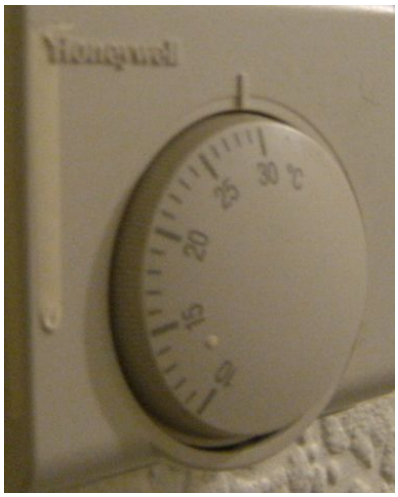



Figure 162: Dwelling 9, thermostat.

The occupant did not do anything differently after retrofit in terms of central heating temperature settings, and yet the demand temperature increased. From observing the monitored temperatures alone, some would term what occurred in this dwelling 're-bound' (Section 1.9). However, it is unclear to what extent the occupant deliberately demanded a higher temperature after retrofit. He was aware that this happened, and was pleased about it, but did not act to bring it about himself.

### A.7.5 *Proposed causal mechanism*

Given the above analysis, the following mechanism is proposed to have occurred in dwelling 9:

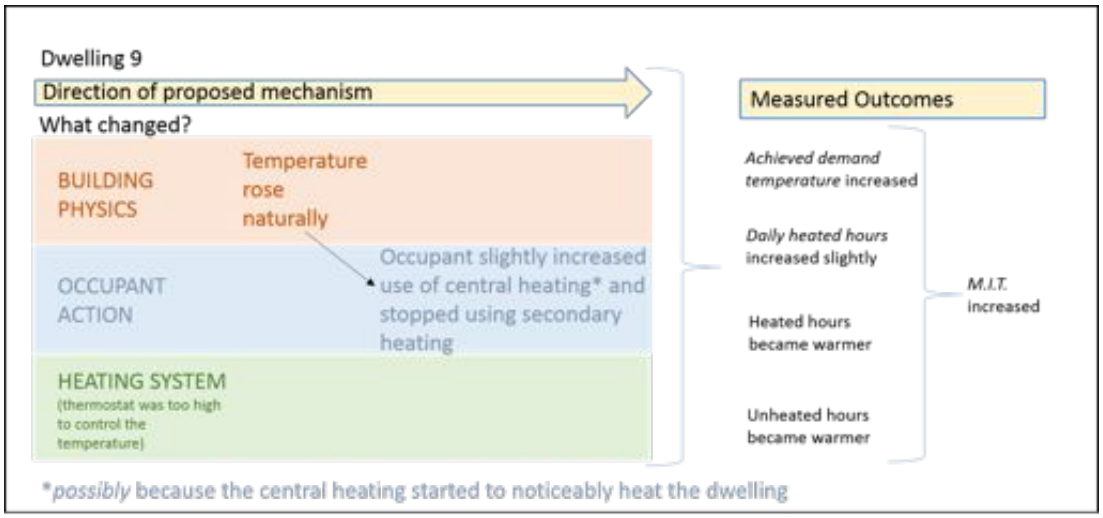



Figure 163: Dwelling 9, proposed causal mechanism leading to observed outcomes.

### A.7.6 *Other interactions*

#### A.7.6.1 *Change in use of space*

The occupant reported that since the rooms in his flat had become warmer since the retrofit, his use of space had changed. Prior to the efficiency measures, the living room had been his base and he left it only when absolutely necessary. If he wanted to perform a task in another room, he would either come back to the living room as much as possible during it, or try to preheat the other room:

*"I used to put something on the stove, then I'd run away and sit in here as it would be freezing, or if I wanted to have a bath, I'd connect a blower [electric] to try to warm it up first, then go and have a bath."* (Dwelling 9, post retrofit, referring to pre retrofit)

This changed following retrofit; the occupant felt free to walk around the flat:

*Occupant: "Right now I'm comfortable to go into any of my rooms any time, without thinking that it's freezing over there, cos I used to stay in here quite long than other rooms, this was a better room because of the fireplace...I've got a television in my bedroom, there are certain movies that I think, let me go and see them in the bedroom, watch from bed.*

*Interviewer: "Did you have that television before?"*

*Occupant: "Yeah it was there."*

*Interviewer: "Maybe I just didn't notice it. Did you used to watch it last time, or was it too cold in there?"*

*Occupant: To be honest, I started to use it this season, after they'd finished, because that's when I realised I can sit in my room.* (Dwelling 9, post retrofit)

As for whether this change can be seen in the monitored data, Figure 164 shows occupancy data from a room whose sensor being triggered was deemed to signify movement around the dwelling - here, the living room.

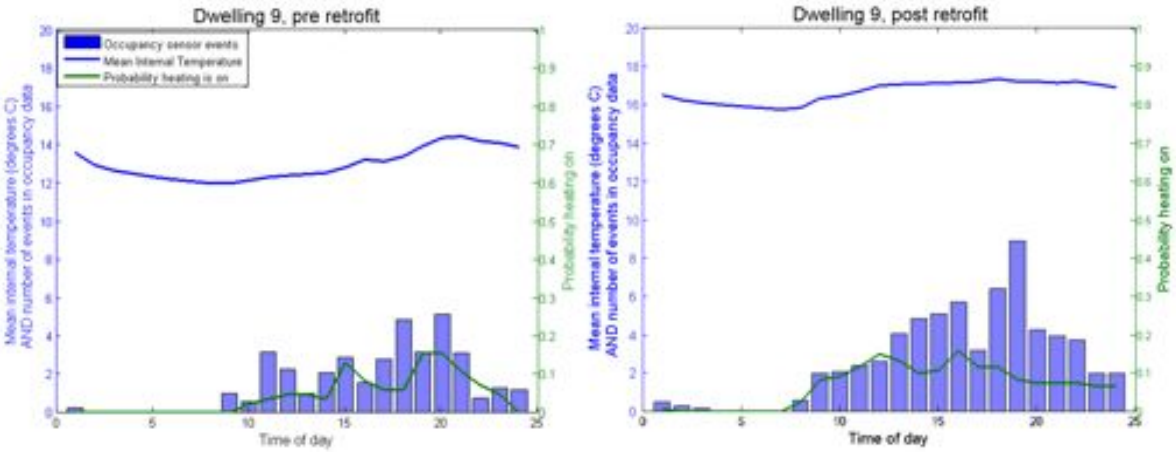



Figure 164: Dwelling 9, occupancy, temperature and heating.

There is indeed an increase in frequency of entering/leaving the living room in the post retrofit monitoring period. It is not possible to say whether this is an exact confirmation of the interview data, and thus due to the retrofit, or whether it was caused by other factors. However, it seems that the interview and sensor data are in agreement in this case.

### A.7.6.2 *Disengagement turning to delight*

This occupant was one of the least engaged before the retrofit. When asked how he had been informed of it (in the pre retrofit interview), he replied,

*Occupant: "I always get some flyers, explaining how you can work around with this glass to try to minimise... but to me it doesn't make any sense, because at the end of the day I have to go to the shops and top up my gas, I can't see the difference! I'm living in a cold house, I have to keep myself warm!"*

*Interviewer: "Really! What do these leaflets say?"*

*Occupant: "I never even read them!"*

In this particular exchange, the occupant seemed doubtful that anything could make the building warmer. Perhaps because of this, he was not enthused to read any new information put through his letterbox. It is not that reading was difficult for the occupant - he was fairly well-educated - it reflects a predecided attitude that his flat was cold.

This attitude, upon further investigation, turned out not to be one of complete lack of hope but more a lack of understanding and involvement:

*"Let's just hope that it's going to work. Because we don't know how they did their tests to find out whether this is the right project to do, for the benefit of the people. To be honest, I don't know."*

What the occupant meant by "work" above was fairly vague, but the next part of the conversation revealed that he was more open-minded to a positive outcome than the initial part of the conversation would have suggested, and was willing to think through the heating cost benefits of insulation:

*Interviewer: "...one thing people say about having insulation is that it takes a long time to cool down."*

*Occupant: "That will be quite good. Because, let's say if I have my heating, and the house is warm, and then to cut my expenses I switch it off with the knowledge that it's going to last one or two hours, you see, rather than the mentality that when you switch it off, it's gone off."*

One year later, the occupant was delighted:

*"To be honest, I don't think I've got much to complain about, except to be thankful to the person who came up with this idea!".*

He reported improvement in warmth, reduction in gas bill, increase in usable space, and also improvement in mood:

*"I think I'm OK because, you know, that's not nice when you think what the hell can I do to keep myself warm in my house. Now I don't even think about that, more relaxed."*

It appears that without knowing or caring a great deal about building energy efficiency measures, he was very satisfied with the works.

#### A.7.6.3 *Radiant temperature*

Although the interviews did not contain questions attempting to elicit occupant perception of radiant temperature, this occupant offered the following information in response to a comment by the interviewer not concerning radiant temperature specifically:

*Interviewer: "I remember that you were saying last time that when you want to go out to the shops, and you turn the heating off, then the flat will be freezing by the time you get home."*

*Occupant:"I remember sitting in this position and you can feel the cold of the wall without touching."* (dwelling 9, post retrofit, referring to pre retrofit)

The next part of the conversation was then surprising::

*Interviewer: "Does that wall link to the outside?"*

*Occupant: "It goes to another house."*

*Interviewer: "It goes to another house!"*

*Occupant: "I came to the conclusion that my neighbour doesn't switch on the radiators!"*

This is the only occupant who talked about the feeling of cold walls from a distance, but it is a very interesting comment in two ways. Firstly, it shows that radiant coolth is a tangible phenomenon in these dwellings; it was conscious for this occupant and he knew it came from the wall. Secondly, it appears that the increase in radiant temperature he sensed was in fact not from an external wall. Possible explanations for this are as follows: he could either have a new neighbour whom he did not mention, or there is an indirect effect from the neighbour's dwelling warming after retrofit which influences the wall temperature of his living room in a tangible way.

It would be useful to look further into the effect of the predicted increase in radiant temperature following retrofit; this discussion is taken up again in Section 12.4.2.4.

### A.7.7 *Conclusion*

In this dwelling, *M.I.T. increase* was high in comparison to that observed in the rest of the sample. Both heated and unheated hours became warmer; the thermostat setting of 30ºC allowed heated hours to increase in temperature by 4-6ºC after retrofit. Despite

this, 86% of the total *M.I.T. increase* was attributed to unheated hours, as the heating was off most of the time during both monitoring periods.

The occupant switched his heating strategy from predominantly secondary heating to central heating; this switch was accompanied by increased use of rooms other than the living room.

All this had occured in the context of the occupant knowing relatively little about energy efficiency measures and being doubtful that they would work. None of the changes in his behaviour which took place had been explained to him beforehand; he noticed the effects of the retrofit and adjusted his behaviour accordingly.

## A.8 CASE STUDY 10

### A.8.1 *Context of the household*

This dwelling was occupied by single man in his 50's and, initially, his teenage daughter. The man had been living in the area for 25 years and had physical disabilities which prevented him from working and often caused him pain. He had been housed in a 3-bedroomed mid-terrace since originally his two daughters and one of their babies lived with him; the eldest one and her baby had moved out by the time of the pre retrofit monitoring period, and the other had moved out to have a baby by the next year.

Money was extremely tight, especially as his daughters struggled financially and often borrowed from him. His financial situation directly influenced his heating behaviour: when the baby was living there and he received child benefit, the thermostat was set at 19°C, but when the baby moved out the child benefit stopped and so the thermostat was lowered to 16°C. He sometimes had to cut back on money spent on food although could always still eat.

The occupant rarely left the house, although he did slightly more by the time of the post retrofit monitoring period when both daughters had young children he would visit. His main room of occupation was the living room, where his computer and the large TV were situated. The daughter who was still living there in the first monitoring period did not spend much time with him and was out most of the time.

Damp was the occupant's main concern before the retrofit, arising because of water vapour from the kitchen making its way upstairs and condensing on the bedroom walls. He also had some specific needs, including a constant supply of fresh air at night, due to his sleep apnea.

External wall insulation was the only measure undertaken since the occupant had already double glazed the property.

By the post retrofit monitoring period, the 'spare room tax' was about to be introduced, and the Disability Living Allowance was being cut, so the occupant was very worried about his future. On the one hand, he acknowledged that he was under-occupying his house; on the other hand with his physical condition he would have found moving very difficult.

He was incredibly pleased with the insulation – the walls had noticeably begun to retain heat. However he felt that he needed less heat and less ventilation that year anyway, due to his second daughter moving out. His gas expenditure had dropped from £15 to £10

per week in winter. Added to the electricity expenditure, his weekly fuel consumption cost £25, which came to 25% of his weekly income; a proportion he found shockingly high. However, he did not think that anyone could give him energy efficiency advice, since all potential efficiency interventions to the property had already been made.

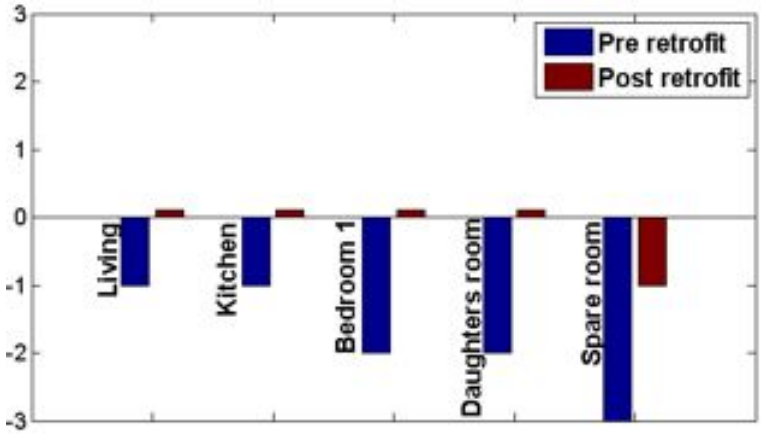
| | |
|---|---|
| Rooms present | Living, kitchen, main bedroom, bedroom 2 (daughter's bedroom), bedroom 3 (spare) |
| Rooms with complete longitudinal air temperature dataset | Living, kitchen, main bedroom, bedroom 2, bedroom 3 |
| Primary heating system | Gas central heating with T.R.V.s |
| Secondary heating system | Gas fire in the living room |
| Location of thermostat | Kitchen |
| Retrofit measures undertaken | E.W.I. |
| Zone 1 *achieved demand temperature* increase | 0.1°C |
| *Daily heated hours* increase | -1.3 hours |
| *M.I.T. increase* | -0.8°C |

Table 33: Summary physical information about dwelling 10.

### A.8.2 *Summary of occupant responses to standard topics*

Table 34: Dwelling 10, occupant responses to standard topics

| **Theme** | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How is heating switched on/off | Timer in the morning, timer in the afternoon. | Timer in the morning, manual if needed in the afternoon |
| Heating timing | 8-9 a.m., then 3.30 – 5 p.m. | 8-9 a.m., then occasionally in the afternoon |
| Thermostat | 16°C | 16°C |
| Radiator valves | One lowered in his bedroom to keep the room slightly cooler | None turned down, since he had decided the heating system has to work just as hard if a valve is switched off. |

| | | |
|---|---|---|
| Secondary heating | Gas fire in living room occasionally used, normally instead of the central heating, to take the chill off the living room if the temperature has dropped. | Never. |
| Other related factors that changed apart from the works | The daughter living there during the first monitoring period moved out to have a baby. The government announced reforms in the welfare system. | |
| Temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Hopes/expectations of works (pre); opinion of what changed after the works (post) | Thought that less heating would be needed to get the dwelling to the temperature that would render it comfortable | Less heating was needed; temperature more comfortable in every room; heat stayed in longer |
| What constitutes energy saving | There was no point turning a radiator valve off in an unused room since the heating system would have to work just as hard as with the valve open. | |
| Perception of change (or lack of) in own heating behaviour | Had lessened the frequency of his afternoon heating period, and eliminated his use of the fire. | |
| Perception of how long it takes to warm up and cool down, and difference after retrofit | Took an hour in the morning to rise from 13.5ºC to 16ºC, then upon switching off the heating it dropped back to 13.5ºC after a couple of hours. | Less time than previously to warm up; several hours to cool down. |

### A.8.3 *Observations from monitored data*

Figure 165 shows a drop in the *mean internal temperature* after retrofit; Figure 166 shows that both heated and unheated hours reduced in temperature:

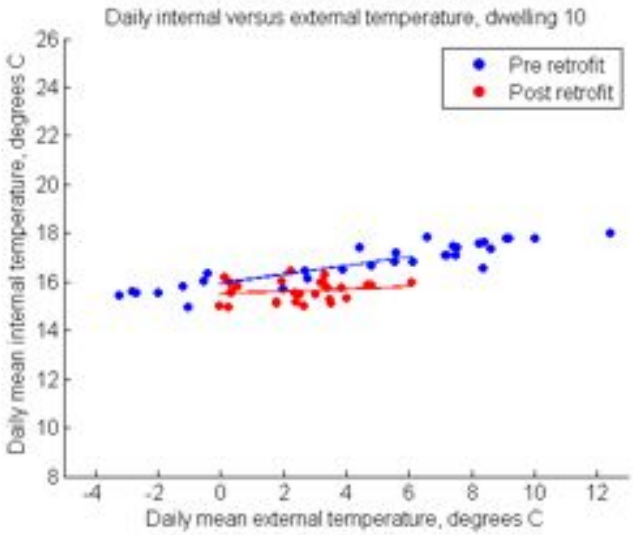



Figure 165: Dwelling 10, *M.I.T.* versus external temperature.

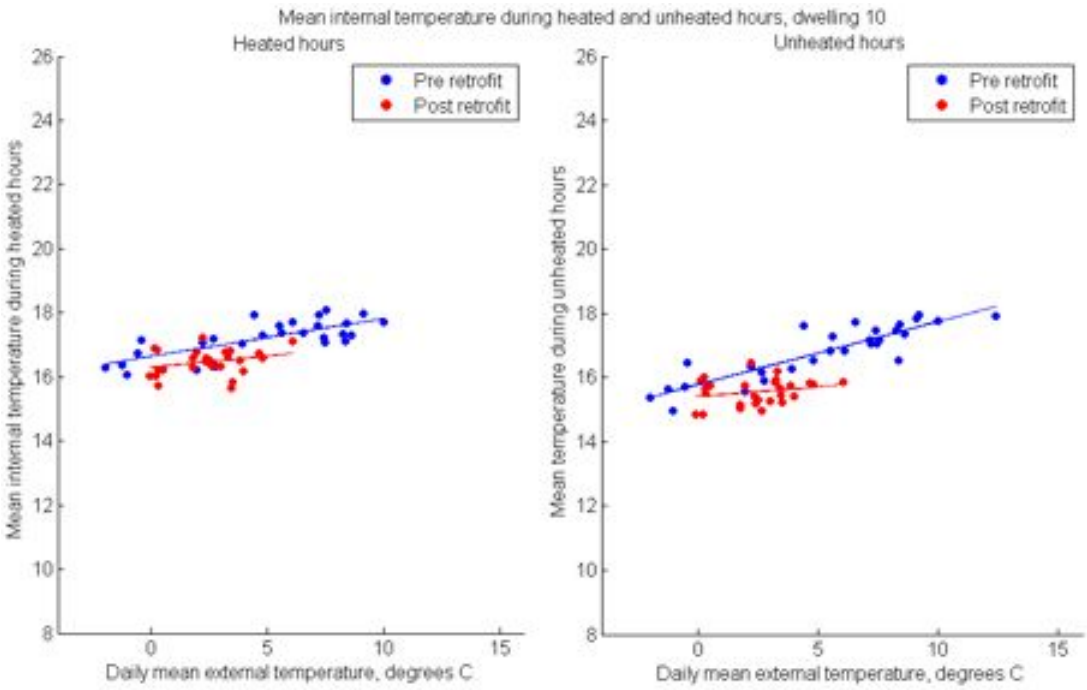



Figure 166: Dwelling 10, temperature during heated and unheated hours.

A decrease in *daily heated hours* (Figure 167) arose from the reduction in frequency of an afternoon heating period, and the elimination of any heating use outside of the morning and afternoon heating periods (Figure 168 ).

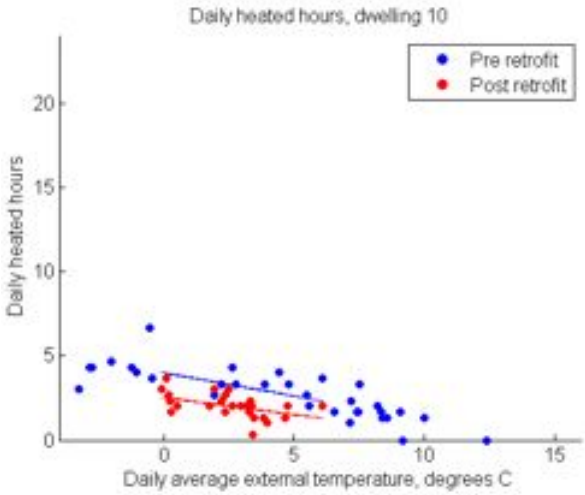



Figure 167: Dwelling 10, *daily heated hours*.

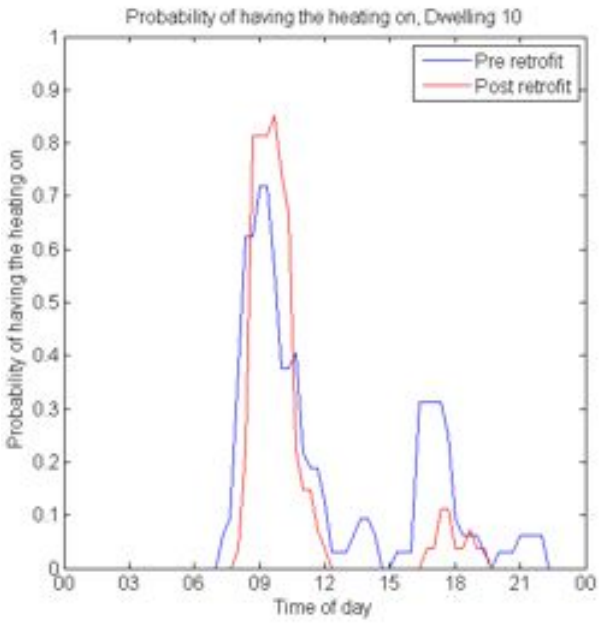



Figure 168: Dwelling 10, probability the heating is on at different times of day.

### A.8.4 *Further analysis (mixed methodology)*

#### A.8.4.1 *Why did the M.I.T. decrease?*

Upon examining the data from individual sensors in order to investigate what brought about the *M.I.T.* decrease following retrofit, it was observed that the latter can mostly be attributed to the temperature change in one room. The daughter's bedroom (bedroom 2), occupied before retrofit and unoccupied afterwards, reduced dramatically in temperature as shown in Figure 169:

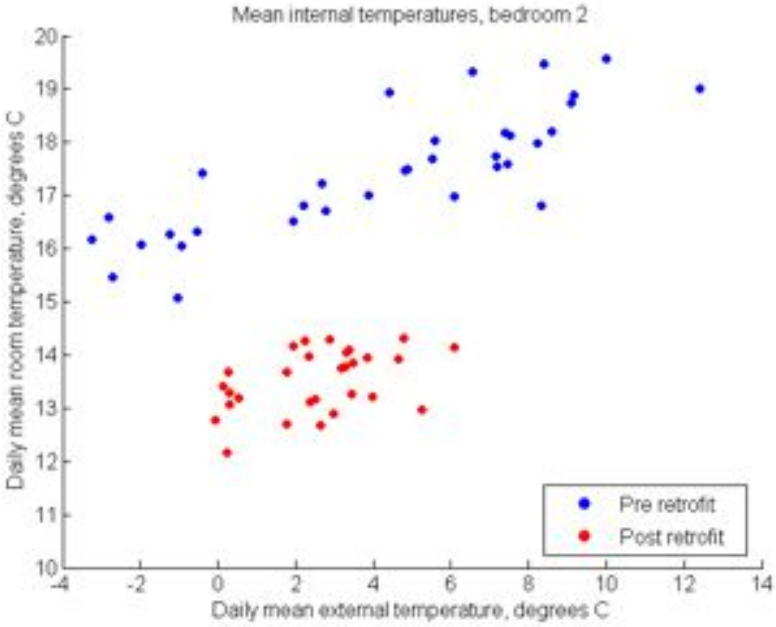



Figure 169: Dwelling 10, daily mean internal temperatures in daughter's bedroom only.

The decrease in room temperature observed in Figure 169 is 3-4°C. Even though the room went from occupied to unoccupied, and in its occupied state had been used most hours of the day and night with several electronic appliances running, this decrease still seems large: for example, it is twice the difference observed in the other case in this sample in which a room became unoccupied from one year to the next (case study 13; Section A.11)

The occupant was telephoned after the second monitoring period to ask if he had turned down the radiator or opened the trickle vent since his daughter moved out. He replied that he had not changed the radiator but may have opened the trickle vent, and that both before and after retrofit the door to that room was kept closed. The reason for the large decrease in temperature remains unresolved.

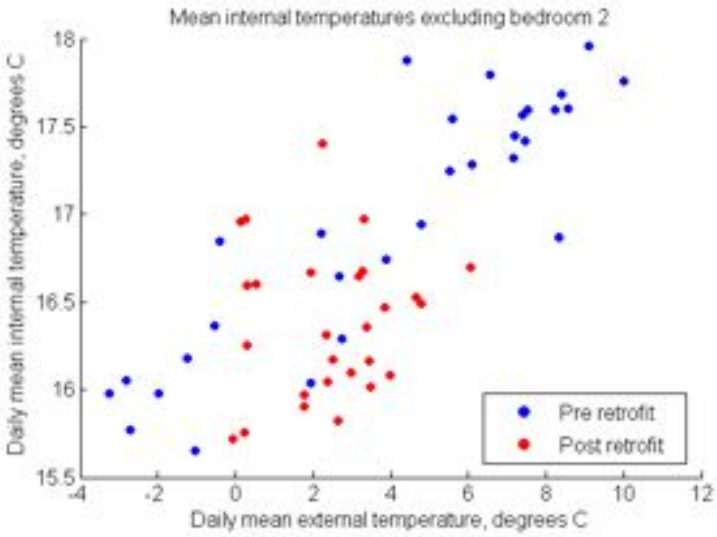



Figure 170: Dwelling 10, mean internal temperature excluding bedroom 2.

### A.8.4.2 *Tentative analysis excluding the anomalous room*

There may or may not be a justification for excluding the aforementioned bedroom from the analysis. An argument for its exclusion would be to aim to isolate the effect of the retrofit on internal temperature. The counter argument is that this room is coupled to the rest of the dwelling in terms of heat transfer and hence cannot be simply ignored.

If the daughter's bedroom (bedroom 2) is excluded, the mean internal temperature of the dwelling was very similar after retrofit to beforehand, as shown in Figure 170. Please note that the y-axis is over a smaller range than usual in this thesis.

It seems therefore that the reduction in daily heated hours by the occupant compensated more or less exactly with the natural temperature increase of the building following retrofit, resulting in an approximately constant *M.I.T.* over the process of retrofit.

### A.8.4.3 *Reduction in heating use*

The occupant's pre retrofit heating schedule comprised of an hour's heating in the morning controlled by the timer, and an afternoon heating period which appears from examining the data to also be programmed in but its exact timing changed by the occupant on about half of all days. After retrofit, there was less need for two heating periods per day, as illustrated by the following quotation:

*"With the walls being done [...] I put the heating on in the morning, comes on at 8, goes off at 9, and if it starts to get too nippy, I'll use a quilt to warm up; if it's really cold, sort of below zero*

*outside, then I'll put it on for an hour in the evening, but that's only happened 2 or 3 times the whole winter. It's only been on an hour a day for the whole winter. I'm really pleased with how my gas has gone down."* (dwelling 10, post retrofit)

From this quotation, it is the influence of the external temperature on the internal temperature, and then the occupant's perception of the internal temperature, which goes on to determine heating timing (which would then go on to determine energy use). It is shown in Section 11.2.2.2 that this mechanism appears to occur in most of the dwellings in the sample.

Furthermore, unlike other dwellings in the sample, the reduction in daily heated hours was not accompanied by an increase in *achieved demand temperature*. The thermostat was set to 16°C, a setting which was achieved both before and after retrofit. This, then, limited the temperature during heated hours.

#### A.8.4.4 *The occupant's theory of heat transfer*

The occupants of dwelling 8 and dwelling 10 both reasoned in the same manner concerning heat transfer from warmer to cooler rooms. The quotation below is from dwelling 10, the current case study dwelling:

*Interviewer: "Do you ever turn the radiators in the individual rooms off?"*

*Occupant: "No. I used to, but then I was thinking, well, you're doing that, and the heating's still got to work harder, because the cooler air from that room is getting out and cooling the rest down! So now I just leave them all on. I just let it carry on."* (dwelling 10, post retrofit)

Even with the doors to the unoccupied rooms closed, this belief still held true for the occupant. He had an awareness of heat loss, which seemed wasteful. He did not, however, have a clear way to compare this heat loss with that in the counterfactual situation, which involved leaving the heating on in an unoccupied room. Building physics would predict that the counterfactual uses more energy.

### A.8.5 *Proposed causal mechanism*

Given the above analysis, the proposed mechanism for the observed changes in monitored variables is as follows:

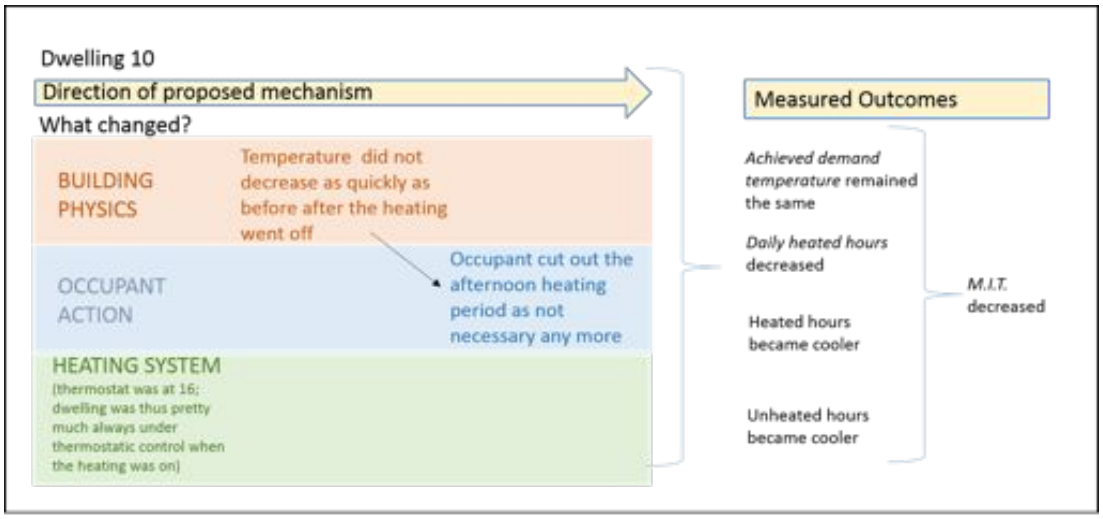



Figure 171: Dwelling 10, proposed causal mechanism.

### A.8.6 *Conclusion*

The *mean internal temperature* decreased in this dwelling following retrofit, although this is thought to be more due to an occupant moving out than the effect of the retrofit itself. Attempting to exclude this occupant from the analysis gives the result that the *M.I.T.* remained approximately constant following retrofit. This is probably because the natural temperature increase of the building was counteracted by the occupant shortening the amount of time he used the heating per day.

This is then an example of all the benefit of the retrofit being in energy saving, as opposed to increased temperature. This is rare for the sample; in most of the case study dwelling the *M.I.T.* increased (although not as a result of deliberature occupant behaviour).

## A.9 CASE STUDY 11

### A.9.1 *Context of the household*

This mid-terrace was occupied by a married couple from Zimbabwe and their two primary school aged children. At the time of the start of the study they had lived in the house for 4 years, and did not particularly like the exterior but had decorated the inside to make it smart and pleasant. The mother worked night shifts as a nurse whilst the father worked during the day, meaning that weekends were the only times they were able to spend all together as a family.

Making sure the children were warm was very important. The woman would come home from work, put the heating on, and go to bed – so that the house was warm for when the children arrived home from school. The heating system was not able to provide enough heat in the living room by itself, so the occupants put the electric fire on, which was expensive to run. To preserve warmth, instead of opening the windows the woman used air freshener in the rooms, and had clingfilmed over the extractor fan.

Although all the rooms were used for specific purposes (for example the children were sent to their rooms to do their homework), some activities could be carried out in different rooms – notably, meals were eaten in the living room if the television was on and in the kitchen if not.

The retrofit measures consisted of double glazing and external wall insulation. Although the glazing stopped the draughts, the house did not feel sigificantly warmer, and heating expenditure had not decreased. The father claimed to be putting the same amount of money on the meter as before the retrofit, and suggested that the slight decrease in heating use was cancelled out by the yearly increase in energy prices. He was aware that they may use more heating than other households.

| | |
|---|---|
| Rooms present | Living, kitchen, main bedroom, bedroom 2 (daughter's bedroom), bedroom 3 (second daughter's bedroom) |
| Rooms with complete longitudinal air temperature dataset | Hall, main bedroom, bedroom 2, bedroom 3 |
| Primary heating system | Gas central heating with T.R.V.s |
| Secondary heating system | Gas fire in the living room |
| Location of thermostat | Hall |
| Retrofit measures undertaken | E.W.I. and double glazing |
| Zone 1 *achieved demand temperature* increase | 1.2°C |
| *Daily heated hours* increase | -0.3 hours |
| *M.I.T. increase* | 1.9°C |

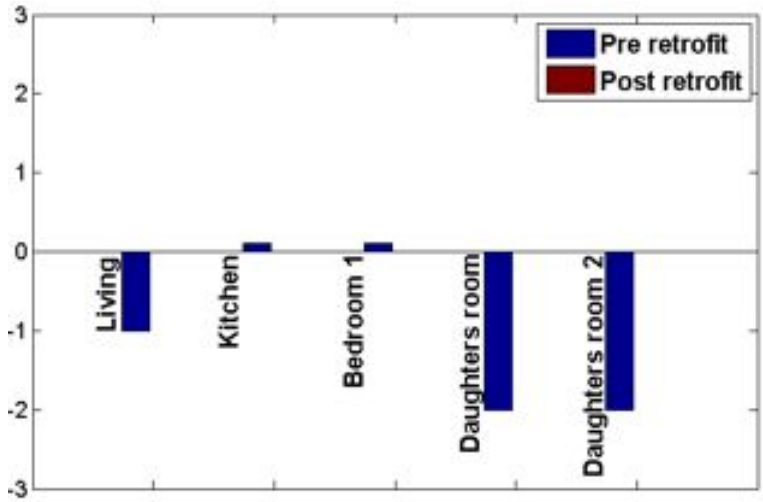
Table 35: Summary physical information about dwelling 11.

### A.9.2 *Occupant responses on standard topics*

A detailed interview was carried out at the end of the pre retrofit monitoring period with the mother of the household. However, at the end of the post retrofit monitoring period she was not available to be interviewed, and her husband was far less willing than her to talk to the author, resulting in limited qualitative data being collected after retrofit.

Table 36: Dwelling 11, occupant responses to standard topics

| **Theme** | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How is heating switched on/off | Press 'on' and 'off' at the programmer. | <data not obtained> |
| Heating timing | Off at night, on in the morning when the mother returned from her night shift, to warm the house for the children arriving home from school. | <data not obtained> |
| Thermostat | Did not know what it was set at. | <data not obtained> |
| Radiator valves | On max; never adjusted. | <data not obtained>. |
| Secondary heating | Gas fire in living room used if the occupants felt cold in there. | <data not obtained> |

| | | |
|---|---|---|
| Other related factors that changed apart from the works | <data not obtained> | |
| Temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Hopes/expectations of works (pre); opinion of what changed after the works (post) | Not much understanding of what was going to take place - something to do with the heating system. | The works did not make much of a difference to the temperature or heating use. |
| What constitutes energy saving | Knew that the fire cost a lot to use. | Seemed to think that internal insulation would have been more effective, but gave no clear reason for that. |
| Perception of change (or lack of) in own heating behaviour | Thought they were spending the same amount on heating as last year, although energy prices had gone up 6%. | |
| Perception of how long it takes to warm up and cool down, and difference after retrofit | Warm up: not sure but it was warm by the time the children got home from school (5 hours after it was switched on). Cool down: not sure, since everyone was in bed or out by then. | Never thought about. |

### A.9.3 *Observations from monitored data*

This is one of the dwellings in which it was not especially meaningful to fit a line through the plots of daily mean internal temperature over a given range of external temperature, given that there were not many days in which there were external temperatures common to both monitoring periods (Figure 172). However this was carried out nonetheless as is the basis of calculation of quantities such as *M.I.T. increase*.

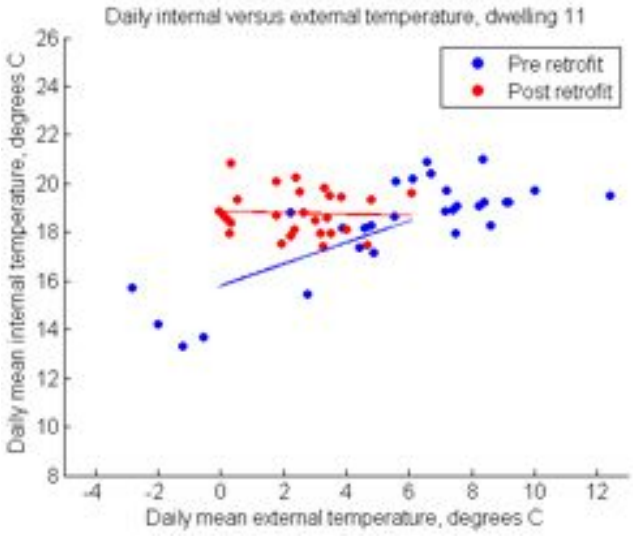



Figure 172: Dwelling 11, daily *mean internal temperatures*.

Daily use of central heating in this dwelling was very variable, as shown in Figure 173. There did not appear to be a noticeable change in *daily heated hours* following retrofit.

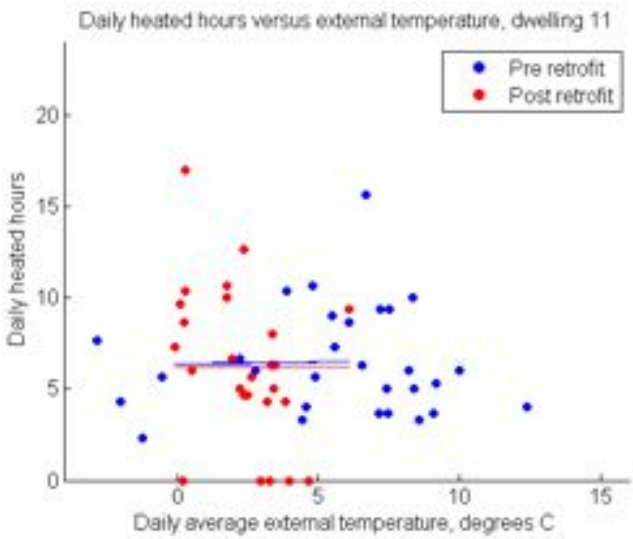



Figure 173: Dwelling 11, *daily heated hours*.

Heating behaviour is clearer to understand if plotted as a probability across the day, as in Figure 174:

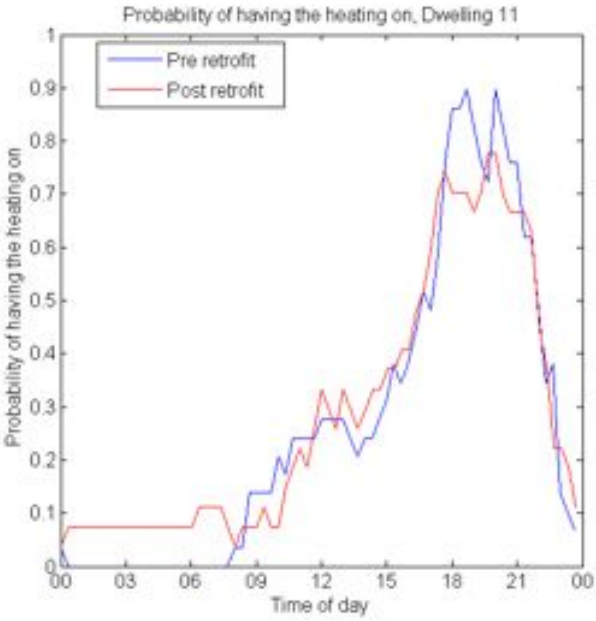



Figure 174: Dwelling 11, probability the heating is on at different times of day.

From Figure 174, the only changes after retrofit were the introduction of a small amount of heating at night and a slightly lower probability of the heating being on at the peak, around 7 p.m.

One observed difference following retrofit was a decrease in the *inter-room temperature gradient*, as shown in Figures 175 and 176:

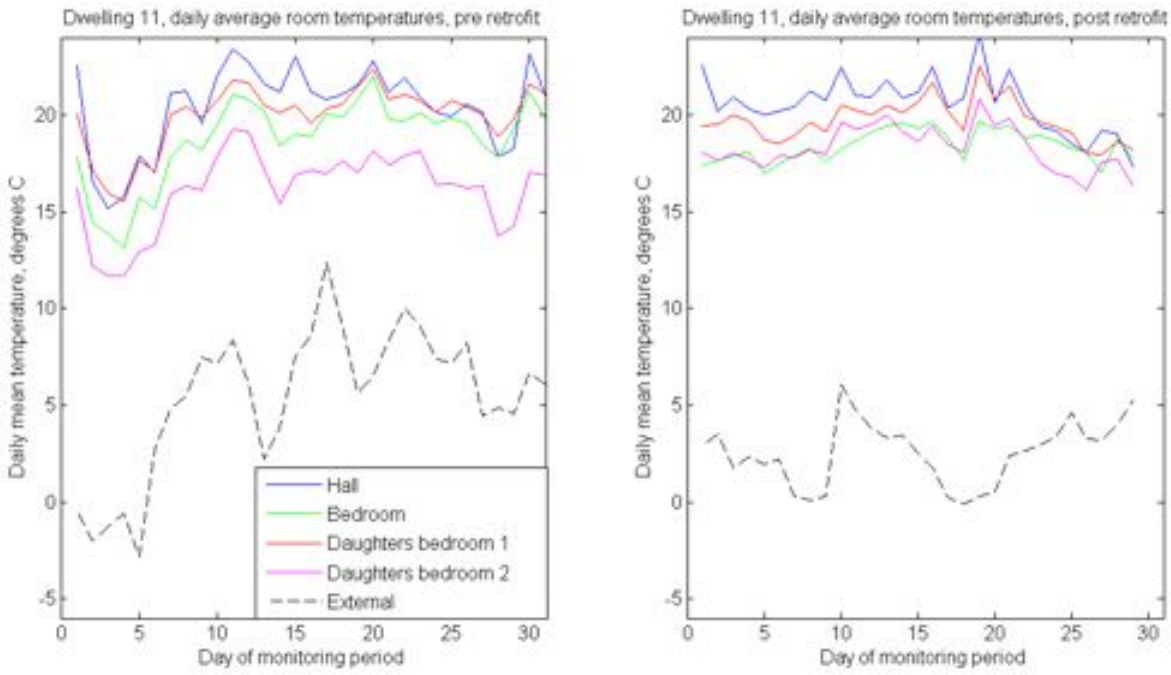



Figure 175: Dwelling 11, temperatures in individual rooms over the monitoring periods.

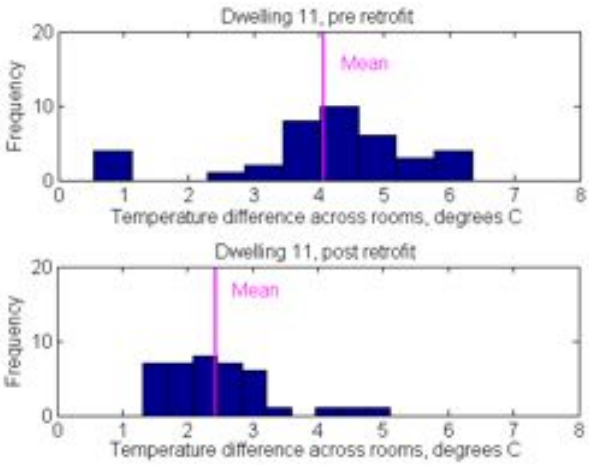



Figure 176: Dwelling 11, histograms of *inter-room temperature gradient*.

A second observed effect was a reduction in the rate of cooling, as shown in Figure 177:

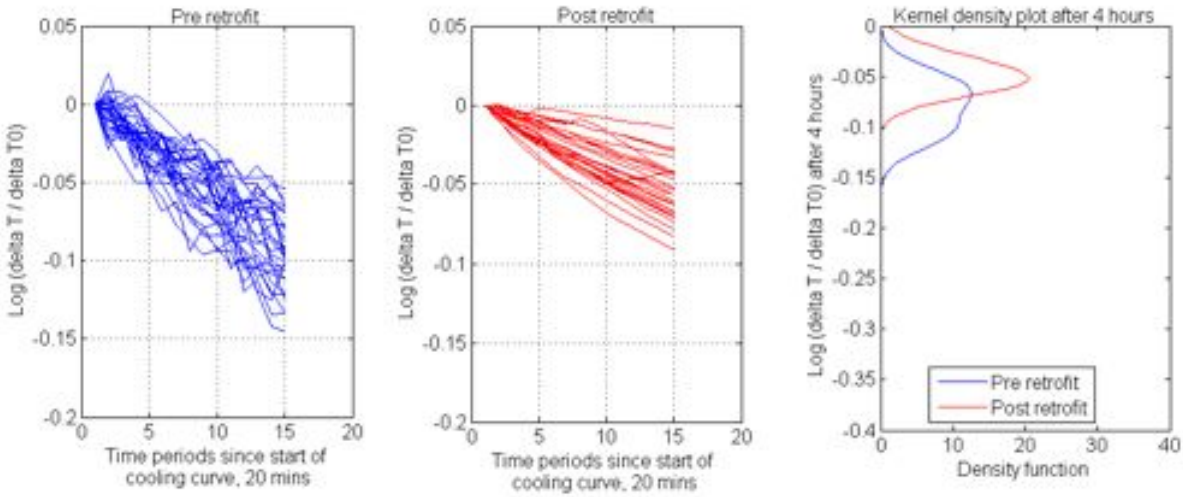



Figure 177: Dwelling 11, night cooling.

Applying the procedure described in Section 7.10 to find the thermal time constant before and after retrofit yields 63 hours and 100 hours respectively. These results seem large compared to the only other known empirical measurement of this (Jez Wingfield 2013, pers. comm.) although the latter is not published.

### A.9.4 *Further analysis (mixed methodology)*

#### A.9.4.1 *Ensuring that the dwelling was warm for the children*

The heating in this dwelling was switched on a long time before the children came home from school, so that the house was warm when they arrived back. However, the time the heating was switched on was not determined according to how long the dwelling actually took to warm up, but according to what time the mother came home from her night shift (in the morning), as she went to bed afterwards:

*Interviewer: "How long do you feel it takes to warm up, when the heating goes on?"*

*Occupant: "I'm not sure now. Cos what I normally do is switch them on then I go to bed."*

According to this, much of the daily heating use would occur when the children were out and the mother was asleep (however, as Figure 174 shows, the monitored data suggests that this behaviour did not occur every day).

As with other dwellings in the sample, the thermostat in this house was set at 30°C and as such the heating was not controlled by it. This is an example of a combination of priorities (making sure the children do not experience discomfort) and a non-optimal way to control the heating system (not using the timer, present in the kitchen, which could have switched on the system whilst the occupant was asleep - combined with the thermostat being set high) limiting the potential energy savings from the retrofit. However, since energy data was not collected, the energy use outcome of proposed interaction between occupants, the heating system and the dwelling can only be known from what the occupant reported: that little energy appeared to have been saved following retrofit.

#### A.9.4.2 *Alternatives to ventilation*

The threat of being cold was preventing the occupant from opening the windows during the pre retrofit winter:

*Interviewer: "Do you open the windows?"*

*Occupant: "Sometimes, but not at this time of year.*

*Interviewer: "Do you ever think about letting fresh air in this room?"*

*Occupant: "Yeah, or I use air fresheners so I don't have to open the windows!"* (dwelling 11, pre retrofit)

Plotting the monitored range of twenty-minutely relative humidity yields a band between 50% and 70% (Figure 178). This could be considered bordering on too high to prevent mould growth and other allergens. Section 10.7 calculates the effect of retrofit on R.H. in all of the dwellings to observe to what extent the efficiency measures mitigated the effect of infrequent window opening.

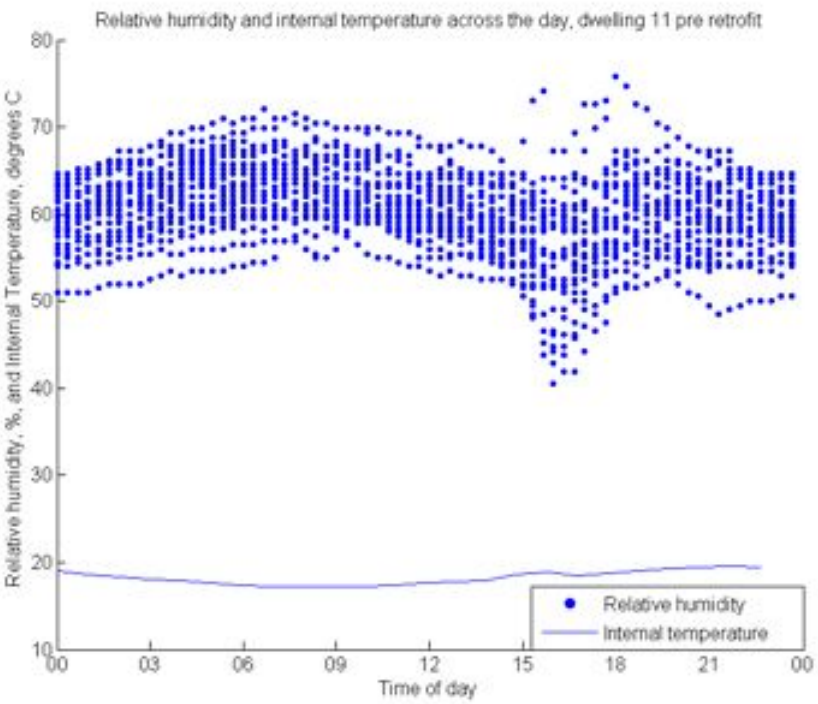



Figure 178: Dwelling 11, relative humidity pre retrofit.

### A.9.5 *Proposed causal mechanism*

Since the monitored data does not reveal a change in any aspect of occupant behaviour following retrofit, the proposed mechanism only involves the response of the building fabric:

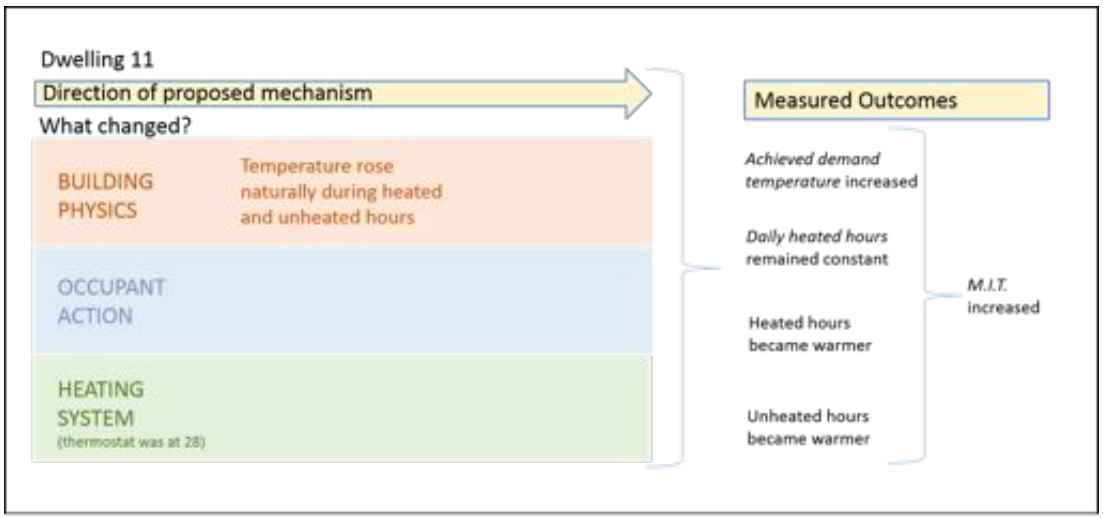



Figure 179: Dwelling 11, proposed causal mechanism.

### A.9.6 *Conclusion*

Although in this dwelling there was little occupant-reported information on the effect of the retrofit and as such the monitored data must be relied upon, several points can be made. Firstly, the efficiency measures did not seem to provide the occupants with an opportunity to cut down on their daily heated hours, unlike in many of the other dwellings across the sample. There was an increase in *mean internal temperature*, a slowing down in the cooling rate and a decrease in the *inter-room temperature gradient*, but the occupant briefly interviewed post retrofit was not satisfied.

This case study highlighted a couple of themes important to occcupants but not necessarily anticipated by researchers: the preheating of the dwelling before the children arrived home from school (combined with an inefficient heating control strategy so that this was carried out several hours in advance), and a reluctance to ventilate a cold dwelling adequately depsite knowing that the air quality was poor.

## A.10 CASE STUDY 12

### A.10.1 *Context of the household (different occupants pre and post retrofit)*

#### A.10.1.1 *Pre retrofit*

This occupant was a single man who had recently retired from being a photographer. He had a keen interest in other cultures, had spent time in India, and preferred hot places to cold ones. He appeared to have a strong social network and a level of education higher than that of many of the other residents.

His daily routine involved carrying out tasks around the flat in the morning, going out between about 12 and 6, and then on some evenings entertaining guests back at the flat. He made a half-joking comment that going out for a large part of the day cut down on heating use.

Since the flat was very exposed, and the occupant liked to maintain a warm temperature in the living room, he used 4 heat sources in that room: central heating and 3 secondary sources. In his bedroom he did not mind a cooler temperature, and was happy to stay in bed and read to save on heating. In this way his hobby (reading) was combined with saving money. However, in terms of getting up properly, he did not like to do so until the flat was warm. Therefore he put the heating on for a while before getting up.

He was looking forward to the energy efficiency measures, since he had been to a friend's house where the fuel bills had dropped significantly as a result of them.

#### A.10.1.2 *Post retrofit*

A new household had moved in by the time of the post retrofit monitoring period. They were originally from Swaziland but had recently moved to England from Canada. One reason for this was that Canada was too cold, so they had come to England to start their family. They had a six-month-old baby; the mother stayed at home looking after him while the father worked for a pharmaceutical company. They had moved into the area to save money, although they were not on an especially low income: the reason they had been housed in the estate was due to the baby.

Most aspects of life at home revolved around the baby. This greatly affected the household's heating behaviour: the flat was kept very warm. The windows were only opened for a short amount of time at once; solar gain was appreciated when possible but the

curtains had to be shut if the baby was asleep. There were too many variations in their day for a timer to be used to control the heating.

The occupants appreciated that the flat retained heat fairly well, and that they had solar panels which helped with the electricity bill. However, their demand for instant heat at certain times was not satisfied by the central heating, so they put the fire on whilst they were waiting for the radiators to warm up.

Although the mother used to work for an electricity company and was very aware of which appliances use energy and approximately how much, the baby came first, so only after his needs were met could thought be given to saving energy.

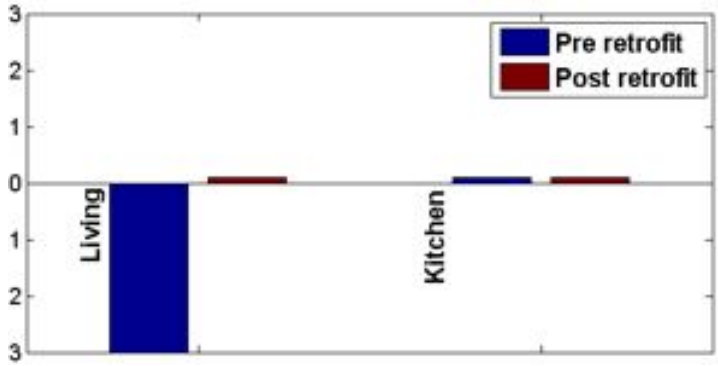
| | |
|---|---|
| Rooms present | Living, kitchen, bedroom |
| Rooms with complete longitudinal air temperature dataset | Living, kitchen, hall, bedroom |
| Primary heating system | Gas central heating with T.R.V.s |
| Secondary heating system | Gas fire in the living room. The pre retrofit occupant also had a halogen heater and an electric fan heater taken between the living room his bedroom. |
| Location of thermostat | Hall |
| Retrofit measures undertaken | E.W.I. and double glazing |
| Zone 1 *achieved demand temperature* increase | 2.3°C |
| *Daily heated hours* increase | -1.8 hours |
| *M.I.T. increase* | 2.4°C |

Table 37: Summary physical information about dwelling 12.

### A.10.2 *Summary of occupant comments on standard topics*

Table 38: Dwelling 12, occupant responses to standard topics.

| Theme | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How is heating switched on/off | At the programmer. Manually except if he knew he has to get up at a certain time, in which case he set it to 30 mins beforehand. | At the programmer, manually. |
| Heating timing | A short period in the morning and longer one when returning home around 6 p.m. | A morning heating period and two evening periods |
| Thermostat | Apparently broken | Set at 28-30°C |
| Radiator valves | All on max; even then there was not enough heat | All on max. |
| Secondary heating | 3 extra sources used in the living room; turned off gradually as the radiators warmed up, but one of them left on as radiators were not adequate by themselves. | Gas fire used whilst the radiators warmed up. |

| | | |
|---|---|---|
| Other related factors that changed apart from the works | The occupants | |
| Temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Perception of how long it took to warm up and cool down | Warm up enough to 'take the edge off': half an hour. Cool down: half an hour. | Warm up: 30 minutes. Cool down: 3-4 hours. |

### A.10.3 *Observations from monitored data*

In this dwelling, there was a fairly clear increase in *M.I.T.* between the two monitoring periods, as shown in Figure 180:

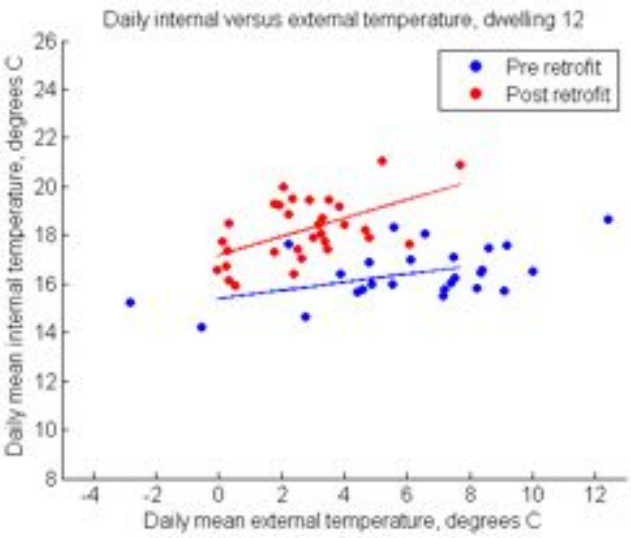



Figure 180: Dwelling 12, *mean internal temperature*.

Despite a change of household, central heating use over the day remained approximately the same (Figure 181):

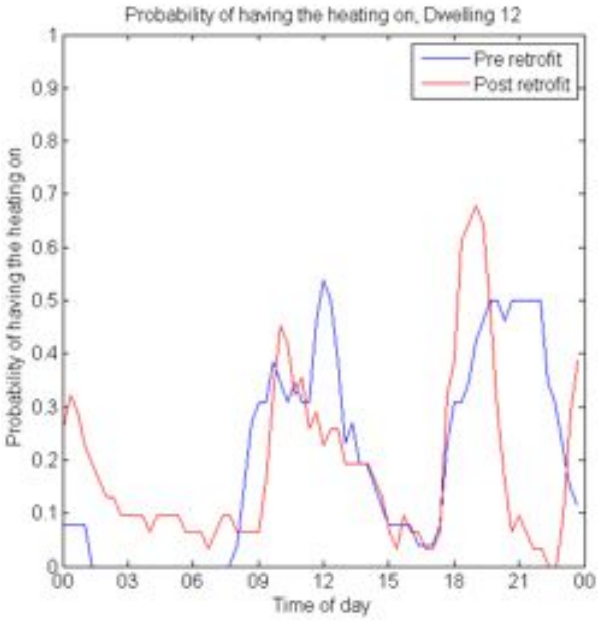



Figure 181: Dwelling 12, probability the heating is on across the day.

However, the role of secondary heating changed between the two monitoring periods/sets of occupants. An example week from each one will be used below to demonstrate this. Figure 182, from before retrofit, displays data from the living room radiator and one of the secondary heat sources (the halogen heater). It can be seen that the secondary source is used on top of the primary heating, often for the duration of the heating period. However, Figure 183 illustrates that during the post retrofit monitoring period the secondary heating (this time the gas fire) was generally used for one timestep (20 minutes) or less, at the start of the period of central heating. This will be futher explored in the next section.

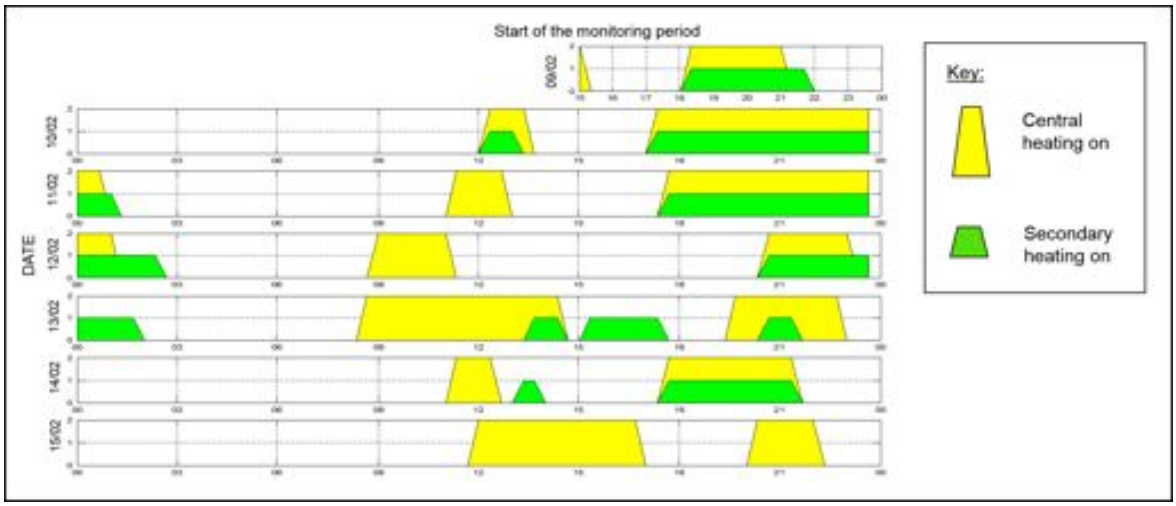



Figure 182: Dwelling 12, example week of primary and secondary heating system use, pre retrofit.

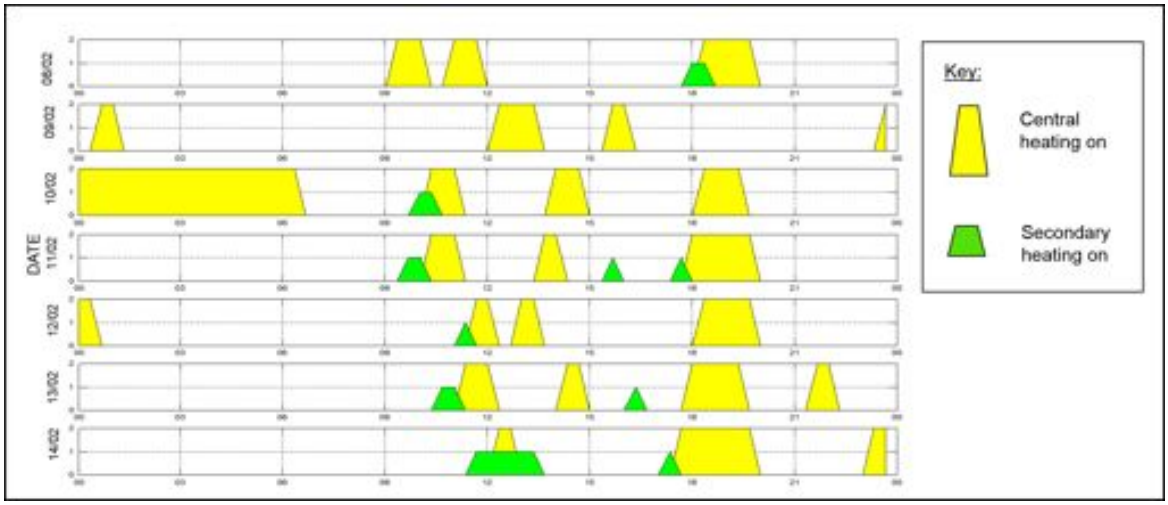



Figure 183: Dwelling 12, example week of primary and secondary heating system use, post retrofit.

Overall, the effect of the efficiency measures was such that a reduction in *daily heated hours* (Table 37) and in secondary heating use still enabled a higher *mean internal temperature* to be achieved after retrofit than before.

### A.10.4 *Further analysis*

#### A.10.4.1 *Role of secondary heating*

Further to the use of one secondary heat source described above, the pre retrofit occupant was the only case in the sample where multiple sources were used at once (althouth only one was monitored). The central heating along was not sufficient:

*"It just takes the edge off."* (dwelling 12, pre retrofit).

He described how he built up the heat using three extra sources:

*Occupant: "It does take quite a bit to heat up – I have to have all the heating on – the central heating, the gas fire, the halogen, and the hot air one that's now in the bedroom."*

*Interviewer: "So four sources of heating you have at once."*

*Occupant: "I have to have them all on at once to heat the room, then I can start turning them off again. It takes that much to heat it."*

*Interviewer: "So say you came in here, you'd put the central heating on…"*

*Occupant: "Then put the gas fire on, then I'd put the halogen on right next to me [..then the electric one...] in the floor, in centre of the room. And that'll take about half an hour to warm the room, then I can turn them off gradually as the room warms up."* (dwelling 12, pre retrofit)

In some of the case study dwellings, single-room secondary heating was used as an alternative to whole-house central heating, and as such the former heating strategy would be cheaper than the latter even if it were electric and more costly to run per unit of delivered heat. However, in this dwelling the secondary heating was supplementary. Therefore, on top of whole-house central heating, the occupant was paying for a further gas source and two electric sources.

The post retrofit occupants used the gas fire less than the previous occupant, and used no supplementary electric sources, despite having a high demand for heat to keep their baby warm. This is an example of extra $CO_2$ and financial savings not normally considered when modelling retrofit.

#### A.10.4.2 *Energy saving as a second priority*

The post retrofit occupants seemed fairly aware of household energy use:

*"...when I was in Canada I used to work for the electricity company, so I knew what made the electric go up or down."* (dwelling 12, post retrofit)

However, it was clear that their top priority was not optimising internal conditions for cost/energy saving, but for the baby's needs:

*"Because of the baby, you just go with what he needs, it's not like you can have a choice in the matter."*

The meeting of these needs affected the heating and ventilation strategy. Specific examples were as follows:

- Thermostat: *"Right now, because of the baby, we have it at 28 I think."*
- Ventilation: *"Maybe we'll have the windows open for a few hours in a day, but if it gets too cold then obviously for the baby we have to close them."*
- Solar gain: *"[this room] seems to keep the heat in quite a bit, especially with the sun [...] It's just that if he has to sleep I have to close the curtains!"*
- Use of heating at times they normally would not: *"But because of the baby we need to keep the house warm a lot, so we need to have the heat on for quite a bit at night cos that's when it's really cold."*

In Section 11.4.1.4, there is a discussion of the implication of the priority of the (primarily thermal) needs of the children on the impact of energy saving programmes.

### A.10.5 *Conclusion*

In this dwelling, a change of occupancy occurred at around the same time as the retrofit. The new occupants used the central heating less, and the secondary heating much less, and yet a higher *achieved demand temperature* and *mean internal temperature* were observed. However it is not known to what extent change in window opening may have contributed to the increased *M.I.T.* following retrofit as there is no monitored data to investigate this (the pre retrofit occupant reported leaving the windows open when

he was out, which would have cooled down the flat and rendered it more difficult to warm up, perhaps contributing to his use of 4 heat sources in the living room).

The post retrofit occupants prioritised the needs of their baby. This actually did not lead to an extremely high demand for heat: the post retrofit standardised *M.I.T.* was 19.2°C, compared to a national average of 18.3°C[1]: a difference of only 1°C. However, the occupants gave several example of where their demand for heat was increased due to the presence of the baby.

1 Using the same method as Section 11.4.2.2, that is, comparison to EFUS data by standardisation to the same external temperature

## A.11 CASE STUDY 13

### A.11.1 *Context of the household*

This ground floor flat was occupied by a woman in her fifties and her grown-up son. They had been living there for almost 20 years. During the pre retrofit monitoring period the woman was on disability benefits and her son worked at the local Co-op. They liked the flat, and had been living there quite happily until shortly after the first monitoring period when the woman's disability allowance was cut and the son lost his job.

Security concerns meant that someone always had to be in the flat. Normally it was the woman, since she only went out once or twice per week. If both her and her son were in, her son would be in his room on his computer. In the first year of the study she would have been sitting in the kitchen; by the second year she used the living room as the main living space as she had redecorated it. For her, there was no difference between weekdays and weekends. She got up early, wandered around tidying and doing different tasks throughout the day or sat using her laptop, cooked a meal in the evening and watched some television.

It was difficult to determine how cold the woman felt in the flat – she mentioned suffering in winter but also not minding the cold. One hope she had for the effect of the retrofit was that the new glazing would cut out the noise from the estate. Her son had his own coping strategy for avoiding the cold – to wrap up in a dressing gown and never open the windows.

Although the rooms felt warmer to them in the winter after the retrofit, their mood had worsened due to her income cut and his struggle to find work. They shared their incomes together, and he looked out for her. They had made huge savings in energy use since they had only had the heating on 4 or 5 times so far that winter. She would only put it on if her hands got cold if she was sitting still.

The windows had been kept closed before retrofit and open the year after – but that was not to do with the efficiency measures - it was to do with the cats.

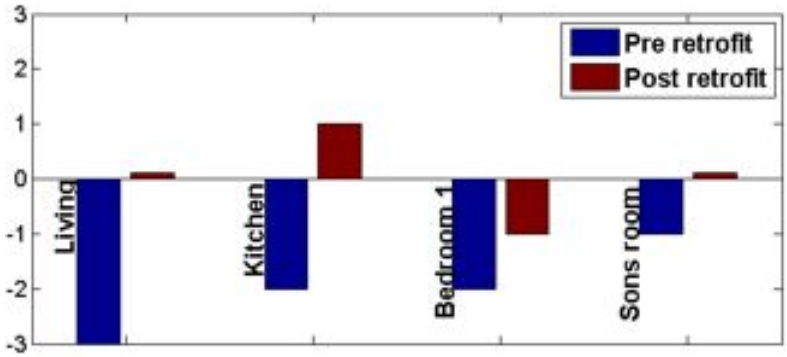
| | |
|---|---|
| Rooms present | Living, kitchen, main bedroom, bedroom 2 (son's bedroom) |
| Rooms with complete longitudinal air temperature dataset | Living, kitchen, hall |
| Primary heating system | Gas central heating with T.R.V.s |
| Secondary heating system | Gas fire (never used), halogen heater. |
| Location of thermostat | Hall |
| Retrofit measures undertaken | E.W.I. and double glazing |
| Zone 1 *achieved demand temperature* increase | 0.5°C |
| *Daily heated hours* increase | -7.9 hours |
| *M.I.T. increase* | -0.9°C |

Table 39: Summary physical information about dwelling 13.

### A.11.2 *Summary of occupant comments on standard topics*

Table 40: Dwelling 13, occupant responses to standard topics.

| **Theme** | **Pre retrofit** | **Post retrofit** |
|---|---|---|
| How was heating switched on/off | Press 'on' and 'off' at the programmer. | Press 'on' and 'off' at the programmer. |
| Heating timing | No pattern - just put on when she felt like it. | Heating had only been on 4-5 times in the winter so far. |
| Thermostat | Thought she did not have one. | Had been shown what it was and told to keep it on 20°C. |
| Radiator valves | On max; never adjusted. | On max; never adjusted. |
| Secondary heating | Occasionally used a halogen heater if it got extremely cold. | Never used. |
| Other related factors that changed apart from the works | Income decreased and son lost his job so was in the dwelling more hours of the day. | |

| | | |
|---|---|---|
| Temperature during winter (-3 = much too cold, 3 = much too warm) |  | |
| Hopes/expectations of works (pre); opinion of what changed after the works (post) | Worried about summer overheating. Hopeful about noise reduction. | Quieter, less heating needed, warmer rooms. |
| What constitutes energy saving | Knew that the fire cost a lot to use. | Since she had a prepayment meter she knew quite well which appliances use a lot of electricity. She had an awareness that new radiators would be more economic but was not sure in what way. |
| Perception of change (or lack of) in own heating behaviour | She was aware that she had dramatically reduced her heating use. | |
| Perception of how long it takes to warm up and cool down, and difference after retrofit | Warm up: 30-60 mins. Cool down: 30 mins. | Warm up: same as last year. Cool down: 90-120 minutes. |

### A.11.3 *Observations from monitored data*

It can be seen from Figure 184 that the *mean internal temperature* decreased slightly following retrofit:

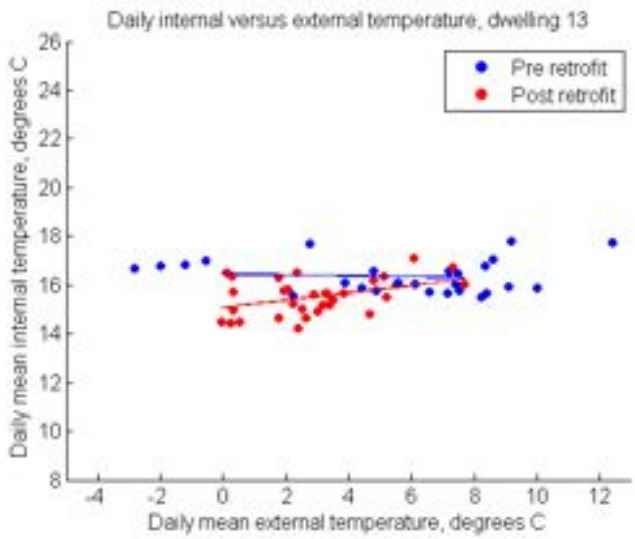



Figure 184: Dwelling 13, *mean internal temperature*.

The above decrease in *M.I.T.* was likely to at least partly have come about due to a decrease in *daily heated hours*. If a line is fitted through the latter through the process used in the rest of this thesis, it is highly influenced by four particular data points in the top left; see Figure 185. The resulting mean change in *daily heated hours* is -7.6 hours. This should be interpreted cautiously in the light of the small number of data points determining its gradient.

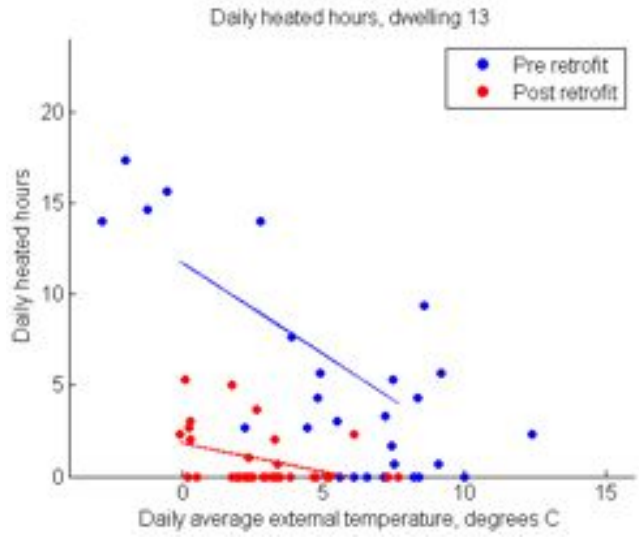



Figure 185: Dwelling 13, *daily heated hours*.

The nature of the reduction in heating use is investigated in Figure 186. It can be seen that heating during the night was completely eliminated after retrofit, and that the

afternoon and evening heating periods reduced in likelihood. However, even before retrofit, the probability of the heating being on at any given time of day was 0.5 or less.

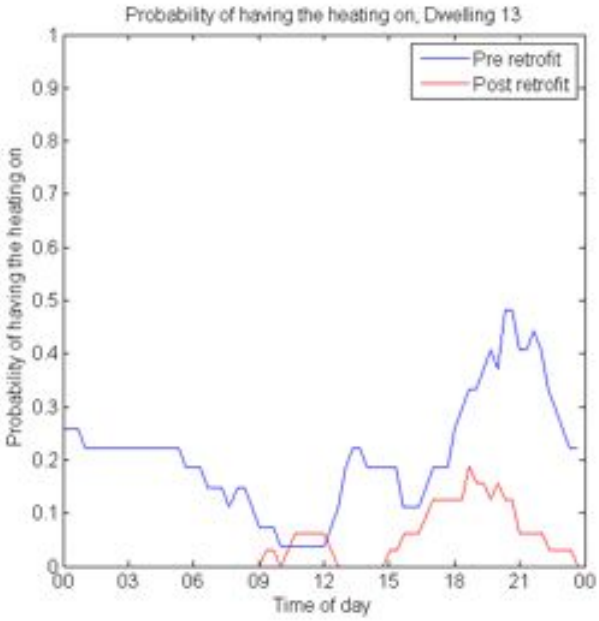



Figure 186: Dwelling 13, probability the heating is on by time of day.

### A.11.4 *Further analysis (mixed methodology)*

#### A.11.4.1 *Decrease in M.I.T.*

It was clear from the post retrofit interview that the occupant was well aware of her reduction in heating use since the previous year:

*"Last year we had to have the heating on all the time, but this year we haven't; we've only had it on a couple of times."* (dwelling 13, post retrofit)

Being able to use less heating was one effect of the retrofit that she was expecting when she was interviewed before it took place:

*Interviewer: "What are you expecting will change when you have the work done?"*

*Occupant: "That it'll get warmer. We won't have to suffer in the winter. And it'll cut down on the heating as well."* (dwelling 13, pre retrofit)

The retrofit was unfortunately accompanied by a cut in the income of both herself and her son.

*Occupant: "I used to get a hundred and ninety something a fortnight, now I get 120".*

*Interviewer: "That's a massive difference then. So how have you adapted to that new situation"?*

*Occupant: "I don't know. I don't know how I've done it. I really don't. If it wasn't for my mum and my daughter and my brother helping us with say £5 here and £5 there, I don't think I would've lasted this long. Even with my depression tablets, it's got us both down. He lost his job at Poundland, and he has nothing so far, so that's getting him down as well."* (dwelling 13, post retrofit)

At no point during the post retrofit interview did she link her cut in income and the reduction in heating use. The author can suggest that this is why she only had the heating on a handful of times over the 33 days of post retrofit monitoring period, but there is not adequate evidence to know that this was the main reason. The occupant herself thought that the reduction was due to the increased comfort brought about by the retrofit; furthermore she made no mention of heating the property less than she desired.

Despite the occupant's perceived increase in comfort, the mean internal temperature in fact reduced, such that its post retrofit value was 15°C. The range of internal temperatures in each monitoring period is shown in Figure 187:

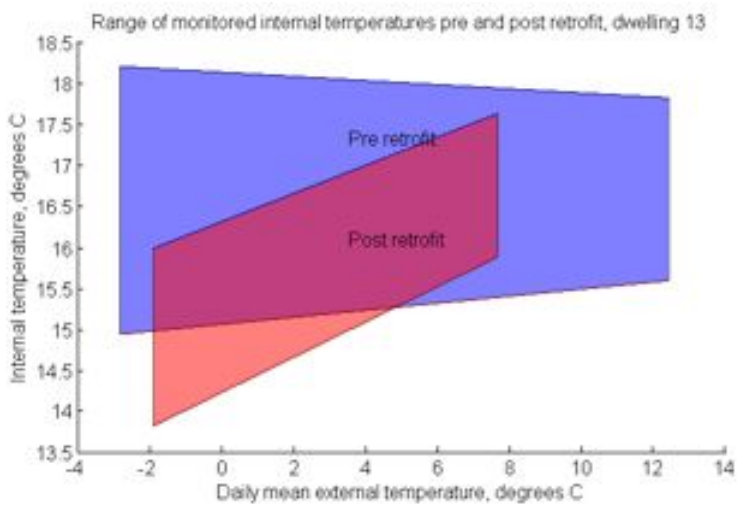



Figure 187: Dwelling 13, representation of the range of temperatures present within the twenty-minutely temperature data.

The potential health effects of living in a dwelling at less than 16°C, described in Section 3.2.1, are a concern for certain groups of the population. This occupant was in her fifties

so not in the high risk age group but she was suffering from multiple health problems already.

However, another factor in the decreased internal temperature may have been the (self-stated) change in window opening behaviour of the occupant. During the pre retrofit monitoring period, her cats had been housebound and so the windows could never be opened. The year after, the cats were regularly let in and out. This highlights the fact that to understand what actually changed over the two monitoring periods, a wider perspective than just heating use must be taken.

### A.11.5 *Proposed causal mechanism*

Given all of the above, the proposed causal mechanism following retrofit is given in Figure 188. The likelihood of this being the correct explanation is then discussed in Section A.11.5.1.

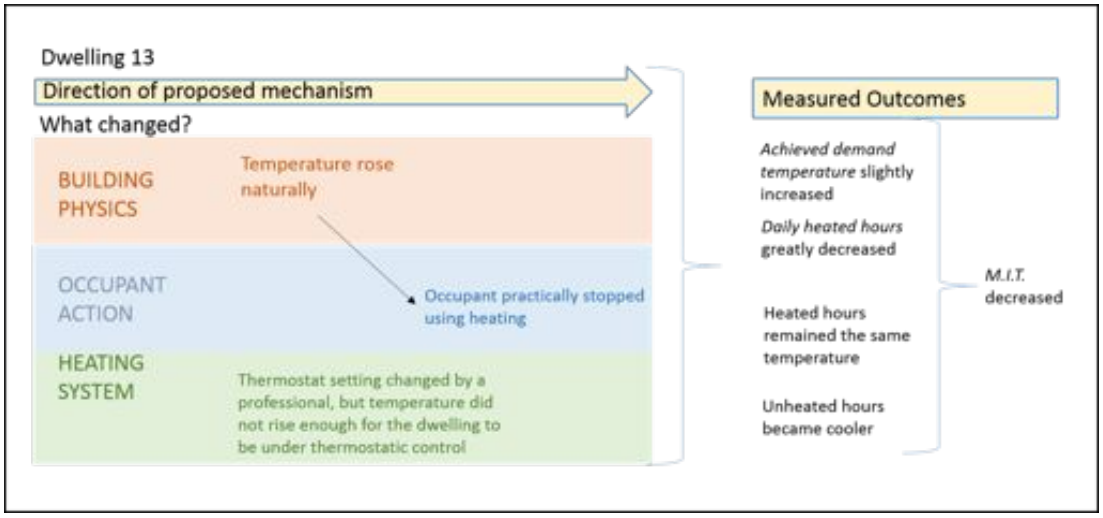



Figure 188: Dwelling 13, proposed causal mechanism leading to observed outcomes.

#### A.11.5.1 *A note on validity*

From the occupant's point of view, the insulation and double glazing had caused internal conditions to be comfortable enough such that heating was no longer needed. Even though the physical data indicates that the result of this (and perhaps increased window opening) was a temperature decrease, and thus it was proposed in Section A.11.4.1 that an income cut was possibly influential in the occupant decreasing her heating use

to such a large extent, it is clear from the interview data that the occupant was not reporting dissatisfaction and seemed to feel warm enough in the retrofitted dwelling. It is important to take factors such as income into account but also to not project an interpretation of what happened onto the situation when the occupant did not give evidence that this was the case.

### A.11.6 *Other interactions*

#### A.11.6.1 *Ventilation*

This occupant was not alone in misunderstanding the use of trickle vents and their relationship to window-opening (there is a wider discussion of this in Chapter 10.7). Below is an extract from the post retrofit interview:

*Occupant: "...it gets really steamy in here now, compared to what it did last year...I think it's having the double glazing windows, and I haven't opened the gap at the top. There's like a gap at the top you can open and shut."*

*Interviewer: "Did they explain anything about that?"*

*Occupant: "No, they just said, ventilation is to open them, and when you don't want the ventilation, shut them. But I have the window open anyway."*

*Interviewer: "How often?"*

*Occupant: "At least 4 or 5 times a week."*

*Interviewer: "So for you, you think, I've got the window open anyway; why would I do the ventilation?"*

*Occupant: "It does let some draught in. I was in the living room, and I had to ask my son to close the vent in the living room, cos it was getting really cold in there."*

In this interview extract, the occupant was replacing what is known in technical language as background ventilation with occasional window-opening (purge ventilation). The manner in which occupants are 'supposed to' operate buildings is to use both - continuous background ventilation combined with window-opening to purge moisture and odours - but it seems that few people knew this in the sample. In this case, since the trickle vents were thought to be causing a cold draught, they were closed by the occupant and replaced by occasional window opening.

### A.11.7 *Conclusion*

In this dwelling, the *mean internal temperature* reduced after retrofit by 0.9°C (±1°C). However, the occupant felt more comfortable and was highly satisfied with the energy efficiency measures.

*Daily heated hours* decreased; it is not possible to conclusively state the magnitude of the change but the limited data suggests -7.6 hours. The occupant did not explicitly link the income cut she reported to the change in heating use although the former could have contributed.

An 'ethical dilemma' of the nature first introduced by Critchley et al. (2007) exists here: the dwelling was colder than is normally regarded as acceptable but the occupant seemed to have chosen to cut down on heating use. These authors make the point that although occupant behaviour appears to be a free choice, if an occupant is struggling for money then perhaps there is no choice. The effect of the low temperature on humidity and then mould growth could furthermore be exacerbated by the lack of continuous ventilation in this property; the latter arising as the occupant did not know the conventional purpose of trickle vents.

# B

## INTERVIEW SCHEDULES

UCL ENERGY INSTITUTE

Understanding the interactions between occupants, heating systems and building fabric in the context of retrofit of social housing PhD project of Jenny Love

**Interview schedule: March 2012. Pre-retrofit.**

***BRIEFING (in living room)***

- Explanation of what form the interview will take. Reassurance that there are no right or wrong answers.
- Make it clear that they can either decline to answer individual questions or withdraw at any time.
- Reiteration that the interview will be recorded, and that a walkthrough will be conducted. Permission for this should be sought.
- Explanation of what my partner will be doing at the same time (repeat photos, measurements, taking down the sensors)
- Confidentiality statement: anonymity, use of data, to whom it will be shown, destruction of data.
- Do you have questions before we start?

***SECTION 1: BACKGROUND, OCCUPANCY, PRACTICES***

***Intro/background:***

Could you tell me a bit about yourself, such as how long you've been living here and what you do?

- What do you like about the house/flat? What do you dislike?

Could you tell me about the others who live here?

- (if children:) How old are they? Are they at school today?
- Do they feel the same way as you about the house/flat?

***About occupancy of the house in general:***

So, I would guess that you're out the house {…X period every day Monday to Friday….}?

- Can you tell me about the other times you leave the house?
- What about weekends?/days you're not working?
- What about the other people in the family – could you tell me about when they're in and when they're out?

***About how time is spent in the home:***

Now, would you mind telling me a bit about how you spend your time when you're at home?

- Could you talk about the morning? Do you do the same things every day or does it vary?
- Do you do that in {X room}?
- (if the level of routine is very low) What are some of the things you might do? Do you watch TV? Cook? What do you spend most of your time doing?
- What time do you and your family normally go to bed?
- At weekends, what do you spend your time doing? Would that be in the {X room}?

You said that {X other person} was in the house during {X period}. Can you say a bit about how he/she spends time here?

- Does he/she do things with you or are you normally doing separate things?
- What do you do together? Eat/watch TV?
- What do you do separately?

***SECTION 2: WALK-THROUGH***

OK, it'd now be great if you could show me and tell me about each room, apart from the bathroom. We'll start here, since we're here.

Could you tell me about how you and your family use this room?

- How much do you / the others use this room?

- Can you describe how you feel about the room? Do you like being in here?

Please could you show me on this scale (show comfort card scale) how the room feels in winter? Do you know if the others feel like this?

- (If too warm/much too warm:) What do you do to cool down? Explore use of fans, opening windows, portable air conditioning.
- (If too cool/much too cool:) What do you do to warm up? Explore use of secondary heaters, turning up the thermostat, turning up the TRV. Is this what you always do? How do you feel about doing this? What is the effect/does it work for you? Does that heat the whole room or a particular bit of it? Do you ever have to move around to go near the heat?

Do you feel that having the heating on makes a big difference to the temperature in here?

(Point at the TRVs): Do you ever use these? Why/why not?

Which (if any) windows in this room do you open? What about the other people?

- Could you tell me under what circumstances you might open this window? And why? (To dry clothes, to get rid of condensation, to let fresh air in)

Do you keep doors open, closed, or does it not matter? Why?

Is it draughty in here?

Do you ever think about letting fresh air in?

Do you have mould? Do the walls get wet?

***SECTION 3: HEATING AND BILLS***

***About heating behaviour and temperature***

We've touched on heating already in each room – could you talk more about how in general you heat the house?

- How do you tell the heating to come on? How do you tell it to go off?
- (if not them:) So it's someone else who sets up the heating? Do you ever change it?
- Where are the controls that you use for the heating? (go to them)
- How easy is it for you to access these controls?
- (if it is them who controls the heating:)Could you show me what you do with this?
- Is it set to a particular temperature?
- Do you tell the heating to do come on differently in different rooms?
- I saw you have a thermostat in {X room}. Do you ever use it? What do you use it for? (+ demo?) How often do you use it?
- [if they imply that their heating follows a pattern] So if I've understood you correctly, you have the heating on for {X period} and {X period} in the week, and {X period} at the weekend….
- Do you do it differently when you have guests round? Either guests who are staying with you, or people here for a few hours? Does that cost you a lot more? Do you mind doing that? Do you ever have concerns that they might not be warm enough? Which room(s) do they go in? Do you ever want the house warmer for them then you would have it for you? Why?

- Is the heating ever on at night?

Do other people in your household have different preferences for how the heating is used?

Is there someone else it would be good for me to ask the same questions about the heating?

On a cold night, when the heating goes off, do you feel that the house cools down quickly or slowly?

On a cold morning, when the heating goes on, do you feel that the house warms up quickly or slowly?

Where do you think the heat leaks from/to?

Thinking back to around the time I first came, when it snowed, was your home less comfortable than usual? Did you do anything extra to stay warm that you haven't mentioned yet? (to jog their memory)

On the whole, how do you feel about the heating in this house?

***About temperature gradient:***

About the house as a whole: you gave different rooms different scores on the colour chart earlier, so it seems that you feel that some rooms are warmer than others?

- Is that a good thing or not a good thing? Why?
- Which rooms are warmest? Why? Which are coldest? Why? Is there much of a difference?
- Do you mind that some rooms are warmer than others? Do you think this affects which rooms you use?

***How do they react when it gets cold?***

If you are cold in your home what effect does that have on your life in general?

***About impact of cold on social-ness, intra-and inter-household – only to be used if they've said the relevant statements to lead into it :***

(if they have said that they all have to stay in the same space:) If it's cold and therefore you're all in the {X room}, as you said before, how do you think being there affects you and your family?

- Do you mind that, or do you like it?
- Does that make it feel crowded?

- In the {X room}, do you all tend to stick around the fire/heater?

***Bills***

Do you know how much you spend on your gas bill? And your electric bill? Do you know how much it is in relation to your income? (Not much? About what you expect? A lot? Too much?)

How do you feel about spending this much on your heating?

- Does it affect what you spend on other things? If you want you can tell me more….

How do you pay for your bills (prepayment meter, direct debit)?

***SECTION 4: CESP***

***First source of information***

How did you find out about that you were going to have works done on your house?

- When did you find out?
- Who told you? How?

***Professionals***

What information did [the RSL] give you? Have you heard anything from other professionals, like [the construction company] or [the energy company]?

- What did they say about specifically what's happening to your home?
- What did [the RSL] say is the purpose of the works?
- When you found out, how did you feel about it?
- Did you want the work to be done? Were you offered a choice?
- Are there things you think they should have informed you more about or were you satisfied with what they told you?

***Other tenants***

Have you talked to anyone around here who has already had the work done? What have they said about the effect so far?

Have you been to anyone's home who has had the work done? What did you think?

***Own expectations***

What are you expecting will change when you have the works? What are you hoping?
- Save money?
- Warmer?
- Both?

Can you say how you formed this expectation?

- Is it from what you've seen so far? What you've heard?

**EXTRA QUESTIONS FOR THOSE WHOSE PROPERTY IS ALREADY BEING RETROFITTED**

Next year I'm going to ask a lot about what effect the works have – I'm not going to ask too much now since the works aren't completely finished yet, but it's still helpful to me to ask you a few things.

***The process***

Tell me about what they've done so far. Do you know what they've got left to do?

- What's it like living in the property whilst the works are going on? Have there been any problems during the installation work?
- Did they explain what they were doing? Were you involved at all? Did you want to be or not?

***About its effect so far***

Could you talk about whether the works have made any difference so far:

- Is there anything you particularly like about the property now?
- Is there anything you particularly dislike now?
- Are there any new problems since the works?
- Does the house now have any draughts?

Could you tell me how you feel about the temperature now – is there any difference to before?

- Are there any rooms which have become much warmer?
- Are there rooms which don't feel different to before?

Has anything changed about the way you use the rooms in your home?

***Evaluation of me***

The last question is about the sensors you've had in your home for the last month or so – how did you feel about them being there?

***To conclude***

That's all my questions, but before we finish,

Do you want to comment on anything else to do with how you feel about your home?

Do you have any questions for me?

***SWITCH OFF TAPE and thank them***

UCL ENERGY INSTITUTE

Understanding the interactions between occupants, heating systems and building fabric in the context of retrofit of social housing PhD project of Jenny Love

**Interview schedule: March 2013. Post-retrofit – for those tenants who were here pre-retrofit**

***BRIEFING (in living room)***

- Explanation of what form the interview will take – this year the topic is change from last year. Reassurance that there are no right or wrong answers. There are some repeat questions from last year and some different ones.
- Make it clear that they can either decline to answer individual questions or withdraw at any time.
- Reiteration that the interview will be recorded, and that a walkthrough will be conducted. Permission for this should be sought.
- Explanation of what my partner will be doing at the same time (repeat photos, floorplan, taking down the sensors)
- Confidentiality statement: anonymity, use of data, to whom it will be shown, destruction of data.
- Do you have questions before we start?

***SECTION 1: BACKGROUND (changes since last year, things I should be aware of)***

Last year you were telling me about how you work as a …./ how you used to work but don't any more…. – since last year has this changed at all?

What are the main changes in your life /your family's life over the last year?

How has it been living in this area in the last year?

***SUMMARY OF MY INTERPRETATION OF LAST YEAR'S INTERVIEW***

I'm going to just go over what I thought you said about how you use the house and the heating last year, so that you can see if you think that's a fair summary of what you thought about the house and the heating last year.

***Works***

What exactly did you have done to the house?

***About occupancy of the house in general:***

Since this time last year, do you think you are in and out of the house at the same times? Have you changed your routine at all?

- What about workdays/What about weekends?/days you're not working?
- What about the other people in the family – could you tell me about when they're in and when they're out?

***About changes in how time is spent in the home:***

- It seemed from last year that you spent most time in the [….] room – is that still true? What are some of the things that would make you leave the [….] room? What do you like doing in the […] room?
- What does [X person] do while they're at home? Do you do things together or separately?
- Are there rooms you use differently this year compared to last year?

***SECTION 2: WALK-THROUGH***

OK, like last year we'll walk around the house and you can tell me about each room, if that's OK.

Could you tell me about how you and your family use this room?

- How much do you / the others use this room?

- Can you describe how you feel about the room? Do you like being in here?

Please could you show me on this scale (show comfort card scale) how the room feels this winter? Do you know if the others feel like this?

- So how comfortable is this room compared to winter last year? What do you think the main reason is? (explore temperature, humidity, draughts)
- How do you keep warm in here now?
- How did the room feel in summer? Was it different to previous summers? How did you deal with it?

Do you feel that having the heating on makes a big difference to the temperature in here?

(Point at the TRVs): Do you ever use these? Do you feel the need to use them?

Do you feel that since last year you open the windows more, less or the same?

- Could you tell me under what circumstances you might open this window? And why? (To dry clothes, to get rid of condensation, to let fresh air in)

Do you keep doors open, closed, or does it not matter? Why? Has this changed at all since last year?

Is it draughty in here now?

Do you ever think about letting fresh air in?

[if there was mould last year] How has the mould been recently? How is it compared to last year?

Do you use extra heating like an electric heater or a fire?

Why do you heat this room?  Has this changed since last year?

***SECTION 3: HEATING BEHAVIOUR***

Now could you talk about how you use the heating now you've got the insulation?

- Before I think you [heating periods, thermostat – i.e. what they DID] Has this changed at all?
- You used heating for [why they did it] . Has this changed since you've had the works done?
- Do you tell the heating to do come on differently in different rooms?
- Do you do anything differently when you have guests round?

- Is the heating ever on at night?

When there was snow, a couple of weeks ago, how was the temperature in the house?

Do other people in your household have different preferences for how the heating is used?

When the heating goes off, do you feel that the house cools down quickly or slowly? Have you noticed any difference in this timing since last year?

When the heating goes on, do you feel that the house warms up quickly or slowly? Have you noticed any difference in this timing since last year?

Where do you think the heat leaks from/to?

Do you ever turn individual rooms off? (if no) Do you always have heating in all of the rooms? Is there a reason why you heat them all?

On the whole, how do you feel about the heating in this house? Is it adequate?

***About temperature gradient:***

Last year I think you felt that some rooms were warmer than others, and it seems from the chart that this year […] – do you feel there is a big difference between the temperature in different rooms? Is the difference bigger, smaller or the same as last year?

- Is that a good thing or not a good thing? Why?
- Which rooms are warmest? Why? Which are coldest? Why? Is there much of a difference?
- Do you mind that some rooms are warmer than others? Do you think this affects which rooms you use?

***About cold/lack of:***

[if it has got warmer] What effects has having a warmer house had on your life in general? (prompts: sleep? Guests? Children? Mood? Health?) Has it had any negative effects?

[if it hasn't got warmer] What do you think they could have done differently? What would have made it warmer?

Does anyone in your household use rooms differently this year? (explore social-ness)

***Bills***

Do you know how much you spend on your gas bill now? And your electric bill?

How does this compare to last year for you?

Do you pay in the same way as you did last year?

Do you know how much it is in relation to your income? (Not much? About what you expect? A lot? Too much?)

Do you mind saying what your income is? Is this the same as last year?

How do you feel about spending this much on your heating?

- Does it affect what you spend on other things? If you want you can tell me more.
- Have there been other changes in your spending since last year?

What energy company are you with? Has this changed recently?

***SECTION 4: CESP***

***The process***

Tell me about what they did when they were here.

What's it like living in the property whilst the works are going on? Were there any problems during the installation work?

Did they explain what they were doing? Were you involved at all? Did you want to be or not?

Did someone come and give you energy efficiency advice? Did they make an appointment with you first? Can you tell me what they said? Did you take their advice? Tell me how you feel about the visit in general? Do you feel like you understand how to save energy? (tell me why you found that difficult)

If you were experiencing this again, what could they do to make you feel better about it?

If someone were going to explain to you about how to save energy, how would you like them to do it? (in your home/elsewhere, demonstration, how they would explain it)

***SECTION 5: EVALUATION OF ME***

I asked you this last year but want to ask relating to this time: how was it having the sensors in your house?

How did you find being part of the study in general – the recruitment, phone calls, arranging times for me to come round, having me and my colleague in your home? Is there something we could have done differently?

Do you want to know how to save energy – I can come back not as a researcher and we can have a proper chat about it in detail.

UCL ENERGY INSTITUTE

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**Interview schedule: March 2012. Post-retrofit – for those tenants who were not here pre-retrofit**

***BRIEFING (in living room)***

- Explanation of what form the interview will take. Reassurance that there are no right or wrong answers.
- Make it clear that they can either decline to answer individual questions or withdraw at any time.
- Reiteration that the interview will be recorded, and that a walkthrough will be conducted. Permission for this should be sought.
- Explanation of what my partner will be doing at the same time (repeat photos, floorplan, taking down the sensors)
- Confidentiality statement: anonymity, use of data, to whom it will be shown, destruction of data.
- Do you have questions before we start?

***SECTION 1: BACKGROUND OCCUPANCY, PRACTICES***

***Intro/background:***

Could you tell me a bit about yourself, such as when you moved in and what you do?

- What do you like about the house/flat? What do you dislike?

Could you tell me about the others who live here?

- (if children:) How old are they? Are they at school today?
- Do they feel the same way as you about the house/flat?

***About the old house:***

Can you tell me a bit about the house/flat you lived in before?

- Was it bigger or smaller than this one?
- What did you like about your old house? What did you dislike?
- Was it warmer or colder than this one?

***About occupancy of the house in general:***

OK, let's go back to talking about this house. I would guess that you're in/out the house {…X period every day Monday to Friday….}?

- Can you tell me about the other times you leave the house?
- What about weekends?/days you're not working?
- What about the other people in the family – could you tell me about when they're in and when they're out?

***About how time is spent in the home:***

Now, would you mind telling me a bit about how you spend your time when you're at home?

- Could you talk about the morning? Do you do the same things every day or does it vary?
- Do you do that in {X room}?
- (if the level of routine is very low) What are some of the things you might do? Do you watch TV? Cook? What do you spend most of your time doing?
- What time do you and your family normally go to bed?
- At weekends, what do you spend your time doing? Would that be in the {X room}?

You said that {X other person} was in the house during {X period}. Can you say a bit about how he/she spends time here?

- Does he/she do things with you or are you normally doing separate things?
- What do you do together? Eat/watch TV?
- What do you do separately?

***SECTION 2: WALK-THROUGH***

OK, it'd now be great if you could show me and tell me about each room, apart from the bathroom. We'll start here, since we're here.

Could you tell me about how you and your family use this room?

- How much do you / the others use this room?

- Can you describe how you feel about the room? Do you like being in here?

Please could you show me on this scale (show comfort card scale) how the room feels in winter? Do you know if the others feel like this?

- (If too warm/much too warm:) What do you do to cool down? Explore use of fans, opening windows, portable air conditioning.
- (If too cool/much too cool:) What do you do to warm up? Explore use of secondary heaters, turning up the thermostat, turning up the TRV. Is this what you always do? How do you feel about doing this? What is the effect/does it work for you? Does that heat the whole room or a particular bit of it? Do you ever have to move around to go near the heat?

Do you feel that having the heating on makes a big difference to the temperature in here?

(Point at the TRVs): Do you ever use these? Why/why not?

Which (if any) windows in this room do you open? What about the other people?

- Could you tell me under what circumstances you might open this window? And why? (To dry clothes, to get rid of condensation, to let fresh air in)

Do you keep doors open, closed, or does it not matter? Why?

Is it draughty in here?

Do you ever think about letting fresh air in?

Do you have mould? Do the walls get wet?

Do you use extra heating like an electric heater or a fire?

***SECTION 3: HEATING AND BILLS***

***About heating behaviour and temperature***

Could you think back to your last house - how did you heat it?

- How did you tell the heating to come on? How did you tell it to go off?
- Was it set to a particular temperature? [Did you have a thermostat?]
- Did you tell the heating to come on differently in different rooms?
- Did it come on automatically?
- Why was it particularly that time of day you wanted to have the heating on?
- Did you also use other types of heating in any rooms, like a fire or a fan heater?
- Were you in and out at the same sort of time as in this house?

Now could you talk about how you heat this house?

- How do you tell the heating to come on? How do you tell it to go off?
- (if not them:) So it's someone else who sets up the heating? Do you ever change it?
- Where are the controls that you use for the heating? (go to them)
- How easy is it for you to access these controls?
- (if it is them who controls the heating:)Could you show me what you do with this?
- Is it set to a particular temperature?
- Do you tell the heating to do come on differently in different rooms?
- I saw you have a thermostat in {X room}. Do you ever use it? What do you use it for? (+ demo?) How often do you use it?

- [if they imply that their heating follows a pattern] So if I've understood you correctly, you have the heating on for {X period} and {X period} in the week, and {X period} at the weekend….
- Do you do it differently when you have guests round? Either guests who are staying with you, or people here for a few hours? Does that cost you a lot more? Do you mind doing that? Do you ever have concerns that they might not be warm enough? Which room(s) do they go in? Do you ever want the house warmer for them then you would have it for you? Why?
- [If they have not already said] What is the trigger for you turning the heating on? [coming in, feeling cold…]
- What month did you turn it on?

- Is the heating ever on at night?

Is the house warmer or colder than where you lived before/than you expected?

When there was snow, a few weeks ago, how was the temperature in the house?

Do other people in your household have different preferences for how the heating is used?

Is there someone else it would be good for me to ask the same questions about the heating?

On a cold night, when the heating goes off, do you feel that the house cools down quickly or slowly?

On a cold morning, when the heating goes on, do you feel that the house warms up quickly or slowly?

Where do you think the heat leaks from/to?

Do you ever turn individual rooms off? (if no) Do you always have heating in all of the rooms? Is there a reason why you heat them all?

On the whole, how do you feel about the heating in this house?

***About temperature gradient:***

About the house as a whole: you gave different rooms different scores on the colour chart earlier, so it seems that you feel that some rooms are warmer than others?

- Is that a good thing or not a good thing? Why?
- Which rooms are warmest? Why? Which are coldest? Why? Is there much of a difference?
- Do you mind that some rooms are warmer than others? Do you think this affects which rooms you use?

***How do they react when it gets cold?***

If you are cold in your home what effect does that have on your life in general?

***About impact of cold on social-ness, intra-and inter-household – only to be used if they've said the relevant statements to lead into it :***

(if they have said that they all have to stay in the same space:) If it's cold and therefore you're all in the {X room}, as you said before, how do you think being there affects you and your family?

- Do you mind that, or do you like it?
- Does that make it feel crowded?
- In the {X room}, do you all tend to stick around the fire/heater?

***Bills***

Do you know how much you spend on your gas bill? And your electric bill? Do you know how much it is in relation to your income? (Not much? About what you expect? A lot? Too much?)

Do you mind saying what your income is?

How do you feel about spending this much on your heating?

- Does it affect what you spend on other things? If you want you can tell me more….

How do you pay for your bills (prepayment meter, direct debit)?
How does the bill in this house compare to the one in your last house? Does that influence how you use the heating?

***SECTION 4: CESP***

***Information***
Did you know that your home had insulation put on just before you moved in?
Do you know who did it? Do you know why it happened to so many houses around [the area]?
Have you met other people around here who have talked about the effect of the insulation?

Has anyone come round to give you advice on saving energy in your home?

If someone were going to explain to you about how to save energy, how would you like them to do it? (in your home/elsewhere, demonstration, how they would explain it)

***SECTION 5: EVALUATION OF ME***
How was it having the sensors in your house?

# C

## REPORT FOR THE RSL

UCL ENERGY INSTITUTE

# The impact of the CESP scheme on a set of case study households

*Jenny Love*

*August 2013*

## Contents

## Summary of key findings

The overall finding was that the physical-works component of the CESP scheme was very effective, and that the educational component of the scheme was more necessary than originally anticipated and could thus benefit from being redesigned, to maximise effectiveness.

- In 8 out of the 10 properties whose occupants remained the same over the duration of the study, the internal temperature increased after the works. The occupants reported warmer homes and some of them were absolutely delighted with the effect of the works.

- In the same properties as above, the relative humidity decreased, often from a zone bordering-on-unhealthy (around 70%) by about 10-20%, which should result in less mould and less risk of dustmites. Therefore occupants with asthma and some allergies should experience better health after the retrofit.

- In many cases, occupants felt able to have the heating on less. Use of expensive secondary heating (gas fires, electric heaters) decreased as the central heating was normally able to make the property warm enough after the retrofit.

- The three sets of new tenants in the study, who did not experience their properties pre-retrofit, were all impressed and in some cases surprised with how warm their property had been during their first winter there.

- Since it transpired that many occupants do not know how to operate a heating system effectively, it is very important that they receive informed advice, perhaps in the form of a home visit, where the occupants are *shown* an efficient manner of operation. This visit should also cover ventilation and health aspects of a refurbished property.

- The advice visits would be most well-received and beneficial to the occupants if they were carried out by a party whose incentives were not selling energy, and if they were overseen or checked by [the RSL] in terms of their content.

- Some occupants would appreciate communication of how it was decided which works would be carried out, before the start, to feel part of the process. Similarly, since some occupants did not appear to understand the purpose of the works even though they had received letters and leaflets, perhaps there is room for thought on how this could be more effectively expressed.

- It may also be beneficial to communicate to tenants how they can anticipate changing their heating behaviour after the retrofit. This may aid their understanding and choice of how to take the benefit of the refurbishment.

## Introduction

This report presents findings from a detailed study of 13 case study houses which were part of the CESP scheme, which may be of interest to [the RSL]. Firstly, the study methods are briefly described, after which the findings from monitored data in terms of temperature, relative humidity and occupant heating use before and after the works are presented. Following this, observations regarding how the occupants use their heating systems are discussed, then there is a section on the home energy advice visits. Finally, the topics of 'overcompensation' and new tenants' perceptions of the refurbished properties are raised. Recommendations are presented throughout the report and especially in the Conclusion section.

Please note that a small number of properties were studied; therefore the findings may not be typical of what happens in general. I may also have misinterpreted some of my reported findings due to either the limited number of case studies or limited access to information. I would welcome any feedback where you think this may be the case.

Finally, I am very grateful to [the RSL] for their permission to do monitoring in [the location], and for their cooperation and help where I needed information or to recruit households. I hope that this report will be helpful and am happy to answer any questions raised as it is read.

## Research methods used

13 case study households were recruited for the study through letters and an open day. Three main methods were used to gather data.

Sensors:

In each room of each property, an air temperature/relative humidity sensor was placed at about waist height, a temperature sensor was placed on the radiator and the living room fire to discern when the central heating or fire was on, and an occupancy sensor was placed on the doorframe to discern how frequently the room was used. This was all carried out twice: the first monitoring period was the entire month of February, 2012 and the second was the entire month of February, 2013, such that a cold month before and after retrofit could be observed.

Interviews:

In-depth interviews of one member of each household were carried out at the same time as the sensors were taken down, at the start of March, 2012 and 2013. Questions were open-ended and covered life at home, how they dealt with the cold, how they used the heating, their financial situation, how they used the rooms, their perception of the retrofit, and other topics.

Shadowing:

An originally unplanned but eventually important part of the research came about when the opportunity presented itself to shadow a representative from [the energy company] charged with carrying out the 'Home Energy Advice' visits, for a day.

## Findings 1: Change in temperature

The case study properties are numbered 1 to 13 below and throughout this report.

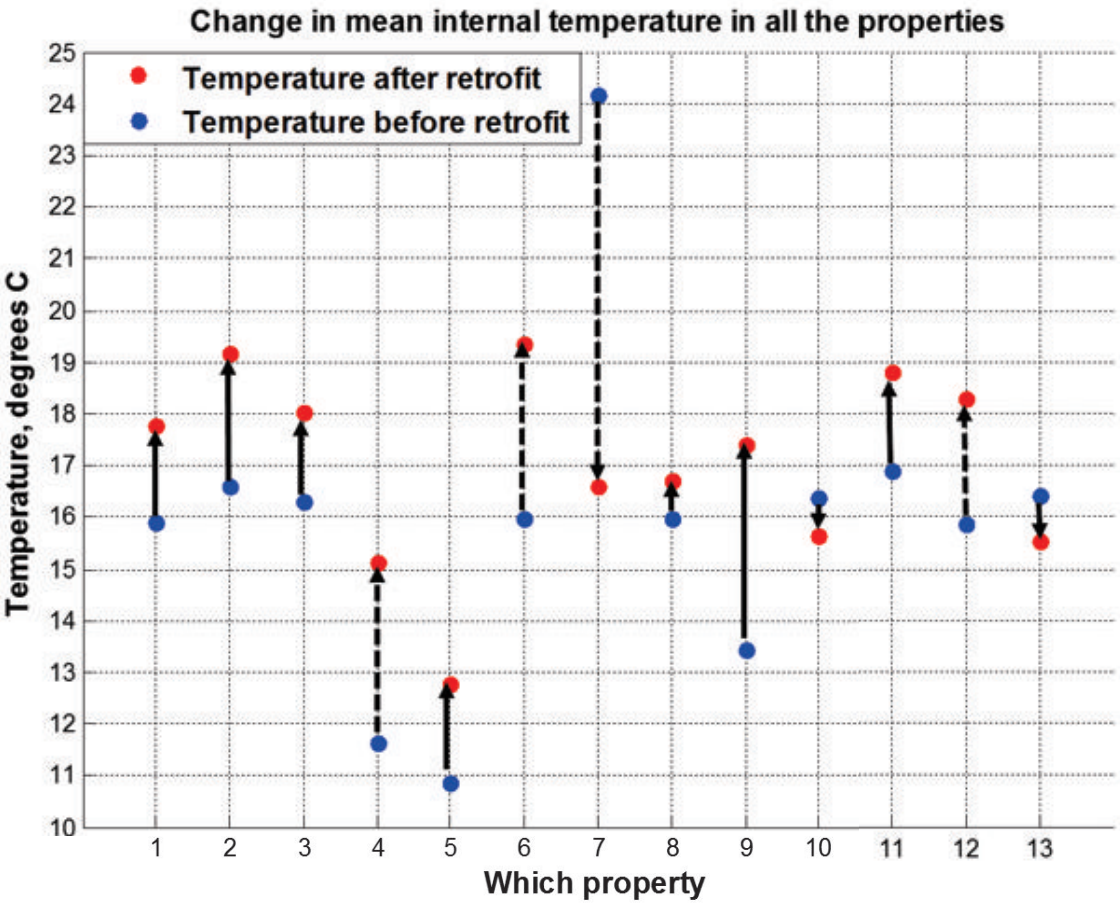



*Figure 1: Temperature change.*

Figure 1 shows initial (pre-retrofit), and final (post-retrofit) temperatures, with arrows so that the direction of change can be easily seen. Those arrows which are dashed instead of solid represent properties in which something significant happened as well as the retrofit: such as a change in occupant (properties 4,7,12) or a broken heating system being mended (property 6), in which case it is difficult to know the effect of the retrofit exactly. The effect of variation within and between monitoring periods has been taken into account here and in all other graphs in this report.

It can be seen that most properties increased in temperature after the retrofit. It was shown in separate analysis (not shown here) that this increase was mostly due to the properties keeping heat in better when the heating was switched off. In this way, the retrofit was a success.

In two of the properties (10 and 13), the temperature decreased, since the occupants turned down the heating so much after retrofit that it actually got colder, from already being fairly cold. This will be treated later in the report as it is potentially quite important.

Note that dwelling 7's initial temperature was exceptionally high since the occupants (who have since moved out) had the heating on continuously. They had learning difficulties and had not had a bill through yet, and thus seemed unaware of the implications of 24/7 heating at a high temperature on gas cost.

## Findings 2: Changes in relative humidity

Relative humidity (RH) is important since mould is known to grow best if RH is greater than 70%, potentially aggravating asthma. House dustmites also proliferate in high-RH conditions. If retrofit helps increase internal temperature, relative humidity should decrease. This theory was tested in the case study properties.

The outcomes fell into two groups: those whose temperatures increased and whose RH decreased, and those whose temperatures decreased and whose RH remained about the same but became less variable.

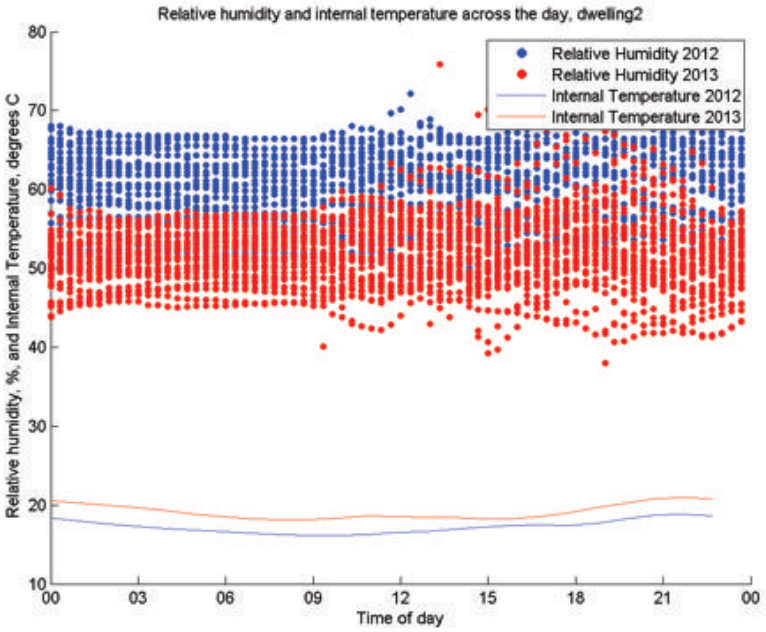



*Figure 2: Relative humidity, first type of outcome.*

An example of the first outcome is shown in Figure 2. It can be seen that the RH lowers, from a fairly high level (in fact, this house had a lot of mould problems) to a more reasonable range.

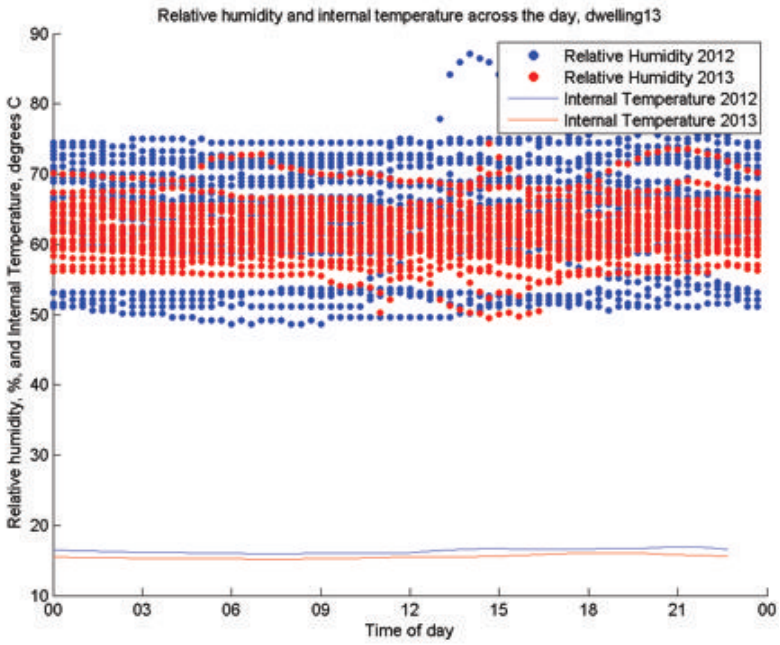



*Figure 3: Relative humidity, second type of outcome.*

An example of the second outcome is shown in Figure 3. Here, the RH is still quite high, partly because the temperature maintained is low – it decreased from the pre-retrofit level. However, the range has become less, so it does not exceed 70% as often as before. This is therefore still a positive outcome, even though it is still possible that the property will have mould problems in the future.

## Findings 3: Change in heating use after retrofit

How did people's daily heating schedules change after retrofit? The results of interviewing people about this will be presented later on, but an overview of the sensor data is given in Figure 4, which shows for most properties[1] the change in number of hours the heating was on per day after retrofit:

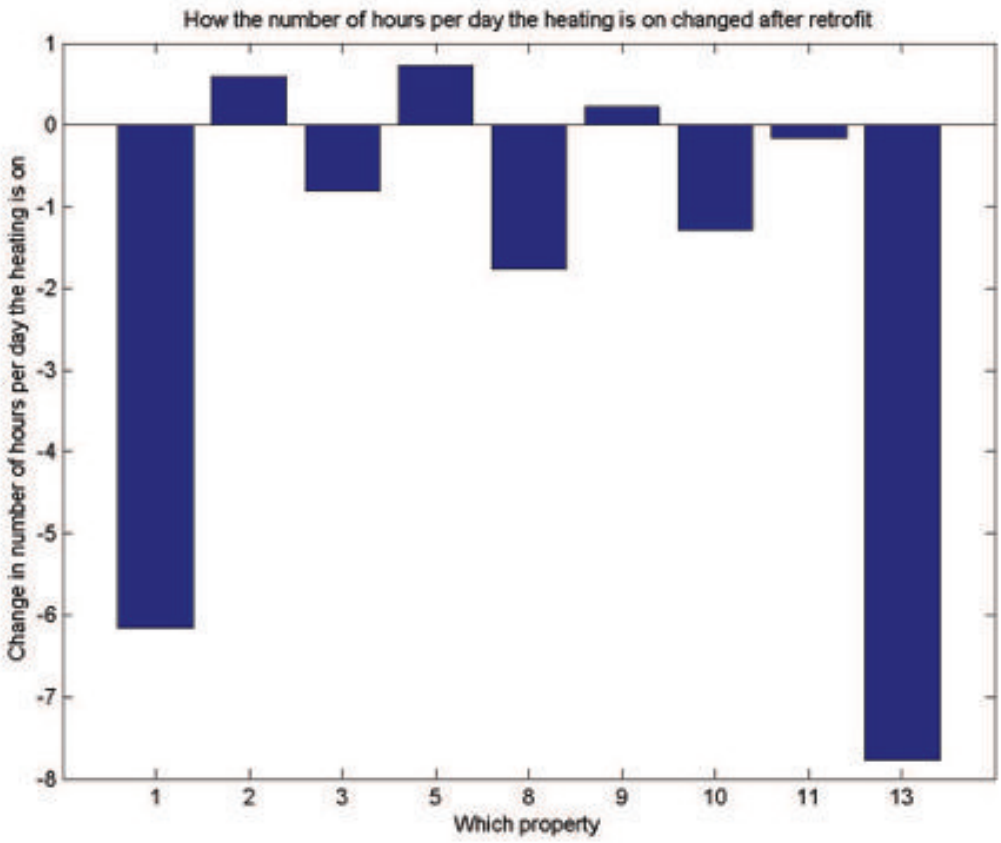



*Figure 2: change in heating use.*

It can be seen that in most properties, the occupants have been able to have the heating on fewer hours per day after retrofit, which is a positive result in terms of saving them energy.

It is worth describing what happened in those properties whose daily heating hours increased, as it was due to three different reasons.

In property 2, the occupants (a couple) still felt fairly cold after the retrofit. In property 5, the occupant had received an increase in income around the same time as the retrofit and was consciously having the heating on more because he could afford it. In property 9, the occupant was enjoying the extra warmth compared to the previous year (he now kept his flat very warm, one reason being that he did not use the thermostat to control the temperature!)

[1] Properties with a change of occupant between the two monitoring period, and property 6 in which the heating had been broken in 2012, are excluded here and in Figure 5.

## Findings 4: Overall outcomes

An 'ideal' outcome, it could be argued, is if the occupants' heating use reduced after retrofit and also those who were too cold before could maintain a higher temperature in their home.[2]

Figure 5 shows the combined results of the sections named 'Findings 1' and 'Findings 3'; that is, what happened to internal temperatures and heating use, after retrofit.

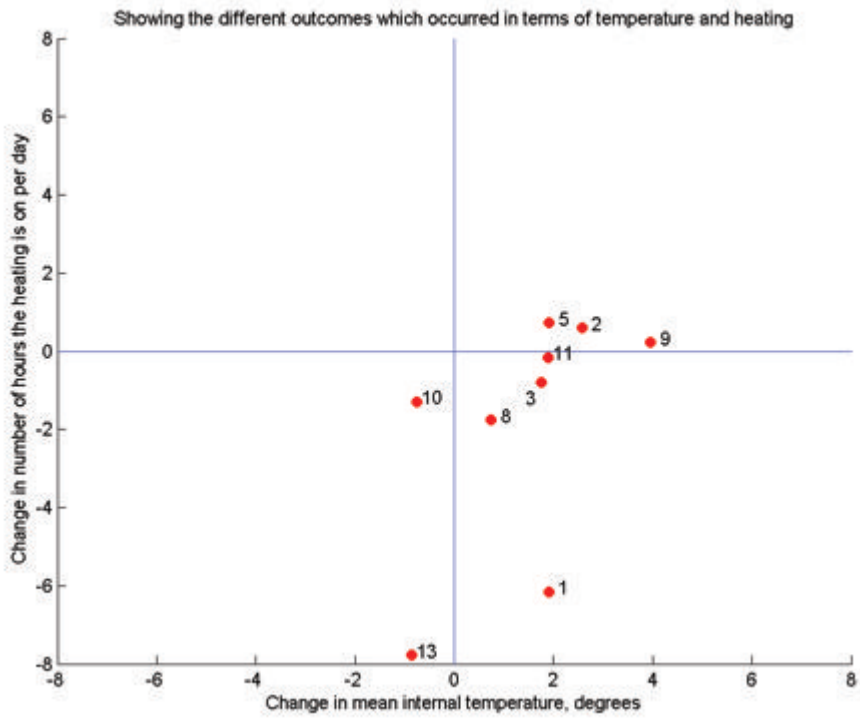



*Figure 3: overall outcomes.*

The bottom right hand quarter of Figure 5 represents the 'ideal outcome' described above: that is, after retrofit, temperature increased and heating was on less. Four properties fell into this category.

The top right hand corner represents the properties whose temperatures increased and who also used more heating after retrofit. None of them used much more heating so it is not a 'bad' outcome, but they are not saving money on their bills after retrofit.

The bottom left hand corner represents the properties whose temperatures decreased and whose use of heating also decreased. In the case of property 13, the heating use decreased dramatically, whereas in dwelling 10, a smaller reduction was enough to decrease the temperature despite the retrofit. This was for a few reasons, one being the low thermostat setting which kept a tight rein on the temperature after retrofit, unlike in some other properties. Figure 5 is shown because it illustrates the diversity in outcomes that even only 9 properties exhibit. This diversity is largely due to a combination of occupant choice/financial constraint and level of knowledge about how a heating system works.

[2] This may be different from the ideal outcome in the CESP calculator, which may be all in terms of fuel saved without allowing temperature to increase – I am not sure if allowance for temperature increase was made in the CESP calculator.

## Findings 5: How the occupants actually used their heating systems

Many people, including myself before I went into the case study houses, assume that the way people operate heating is as follows: leaving the thermostat at a reasonable setting (e.g. 20°C) to control temperature, then turning the heating on and off either using a timer or manually. However, this assumption turned out to be quite wrong in many of the case study properties, and had some implications for energy use and for the effect of the retrofit.

For example, about half of the case study households had their thermostats set on maximum (30°C). Some of them did not know what the thermostat was (one occupant thought that since it made a clicking sound when she moved it, it indicated that it was broken). Others had the idea that the thermostat needs to be set higher on colder days outside, since they thought it was a kind of valve which controlled the power of the heating system. Others thought it was an on-off switch, so turned it to max (30°C) to switch the heating on, and back to zero to turn the heating off.


*Figure 4: what a typical thermostat in the case study properties was set at.*

Most of the occupants did not use the timer on their programmer; they turned it on and off manually. In most cases this seemed reasonable; they often had more control this way. However in one case, not knowing about the existence of a timer led to quite a lot of energy waste: an occupant who worked night shifts arrived home mid-morning, and turned on the heating so that the house would be warm when the children came back from school, before she then went to sleep. A timer set to switch the heating on when she was asleep, one hour before the children came home, instead of about 5 hours, would save a lot of energy.

There were many misunderstandings about energy use caused by heating. For example, many of the tenants thought that leaving the heat on whilst they went out for a few hours uses less heat than turning it off and then on again later. Also, some of them living in larger properties thought that turning down the radiators in unused rooms used the same amount of energy as keeping them on full, as the unused room would get cooler and suck out heat from other spaces, whereas in fact they could have saved some energy by keeping unused rooms cooler and closing the doors.

There were also misunderstandings about the necessary level of ventilation in a property. One household used air freshener instead of letting fresh air in, to avoid heat loss. Another household closed all the trickle vents and occasionally opened to windows instead, hence confusing continuous background ventilation and purge ventilation, both of which are necessary but especially background ventilation. In another household the conflict between letting in fresh air and keeping in warmth led to arguably the wrong outcome: even though one occupant needed fresh air to keep down the mould as she was asthmatic, her partner would go around and close all the trickle vents.

## Findings 6: Home energy advice visits

Given that, as explained in the previous section, many occupants did not understand the components of a central heating system or ventilation techniques such as trickle vents, the home energy advice could provide an opportunity to educate occupants about the most effective way to operate the newly refurbished building and its systems.

In the CESP scheme, the visits were carried out not by [the RSL] but by [the energy company], with one consequence of this being that (as far as I am aware) communication between [the RSL] and [the energy company] on the content of the advice given to householders was minimal.

As far as I was aware (but may be wrong on this), each property undergoing retrofit was supposed to receive a home energy advice visit. Since, however, none of the case study households received such a visit, I made an arrangement to join the individual carrying out the visits for a day.

The [energy company] representative I was told was supervising the home energy advice packs and thus shadowed was an extremely helpful and kind individual who wanted to help the occupants save money on their bills and gave them good advice. He made a great deal of effort in the face of frequent rejection by occupants.

However, giving advice was not what he had specifically been told to do by [the energy company], who had given him a pre-existing tool developed possibly for another purpose.[3] The tool seemed more about data gathering than communicating personalised advice to the occupants. He had tried to ask [the energy company] what they do with the information he input, but they had not given him a response.

Even though he was very polite to the tenants, they often did not want to let him in since he was from an energy company. Indeed, in the interviews of the case study households many of them expressed resentment at companies such as [the energy company] for raising prices and simultaneously making a lot of profit. This raises a question of whether the proportion of homes accessed could be increased if such visits were carried out by a more neutral party whose incentives aligned with those of the occupants.

Some recommendations therefore for future home energy visits are as follows:

1) It is very important that tenants receive informed advice on how to use a heating system optimally given the evidence found of their misconceptions; it is even better if they are *shown* how to use their system. Given that many of them did not really read various letters about the purpose of the works, it is unlikely that the will read a paper document on the optimal use of their heating system.
2) It is also important that broader issues than just heating systems are covered, since certain occupant actions following retrofit such as extreme turning down of heating may have health implications (see the following section). Perhaps the visits could be branded as, for instance, “Getting the most out of your refurbished home”, and cover ventilation, heating, humidity and health.
3) It could be beneficial for the occupants if [the RSL] in future could either help design the advice given, or cross-check the advice being given with an independent authority to validate its content, or at least join the home energy advice visitor for a couple of visits to check how the visits are proceeding.

[3] From what I can tell, the assessment was an ‘in-home energy assessment’, described for example here: [link removed]; however no personalised report for the occupants was mentioned by the [energy company] representative. Perhaps [the energy company] posted one to each property later but the type of information one can give on paper is limited compared to actually showing the occupants how to use their system, in the context of their own needs.

4) An organisation with incentives to help the occupants reduce their energy use, and of whom the occupants do not have a prior negative opinion, carrying out the visits may make the proportion of accessible homes higher and the occupants more trusting of the advice given.

## Findings 7: Some specific phenomena to raise

### Overcompensation

As was mentioned previously, there were two properties where the temperature decreased following retrofit. Obviously it is the occupants' choice how much to use their heating, both before and after retrofit works are carried out. However, if the properties are already cold and become even colder after retrofit, there could be health consequences. If the occupants are in difficult financial situations as these were, and are looking for ways to save money, it is possible that they 'overcompensate' on reducing their heating use after retrofit, and with the resulting temperature drop could come a relative humidity increase and thus mould and dustmite growth. The relative humidity did not increase in any of the case study properties, but it could have done if the temperature decreased enough. Perhaps, then, as part of the home energy visits, as well as energy saving advice, separate advice on *minimum* recommended temperatures could be given.

### New tenants' perceptions of the retrofitted properties

Three of the case study properties had a change of occupant between the two monitoring periods. It is worth mentioning that all three of the new households were impressed and in some cases surprised by how warm their new property was.

# Conclusion

## Positive outcomes of the scheme

- In 8 out of the 10 properties whose occupants remained the same over the duration of the study, the internal temperature increased after the works. The occupants reported warmer homes and some of them were absolutely delighted with the effect of the works.

- In the same properties as above, the relative humidity decreased, often from a zone bordering-on-unhealthy (around 70%) by about 10-20%, which should result in less mould and less house dustmites. Therefore occupants with asthma and some allergies should experience better health.

- In many cases, occupants felt able to have the heating on less. Use of expensive secondary heating (gas fires, electric heaters) decreased as the central heating was normally able to make the property warm enough after the retrofit.

- The three sets of new tenants, who did not experience their properties pre-retrofit, were all impressed and in some cases surprised with how warm their property had been during their first winter there.

## What could be done for the residents whose properties were refurbished, to further increase the effectiveness of the current scheme

- It would be beneficial to know how many of the occupants with newly refurbished properties had not had an energy advice visit. Since the individual carrying them out was very good, I do not think these properties need a further visit, but I would recommend that those who did not receive a visit should get one, in which they are shown how to use their heating system in an efficient way.

- In terms of the above, it is not just advice about saving energy which is needed, but identifying those households whose buildings may be unhealthy, due to phenomenon such as overcompensation, and giving advice on ventilation and minimum recommended temperature (it may be useful to provide a thermometer).

- The advice visits would be most well-received and beneficial to the occupants if they were carried out by a party whose incentives were not selling energy, and if they were overseen or checked by [the RSL] in terms of their content.

## What could be done in future retrofit schemes

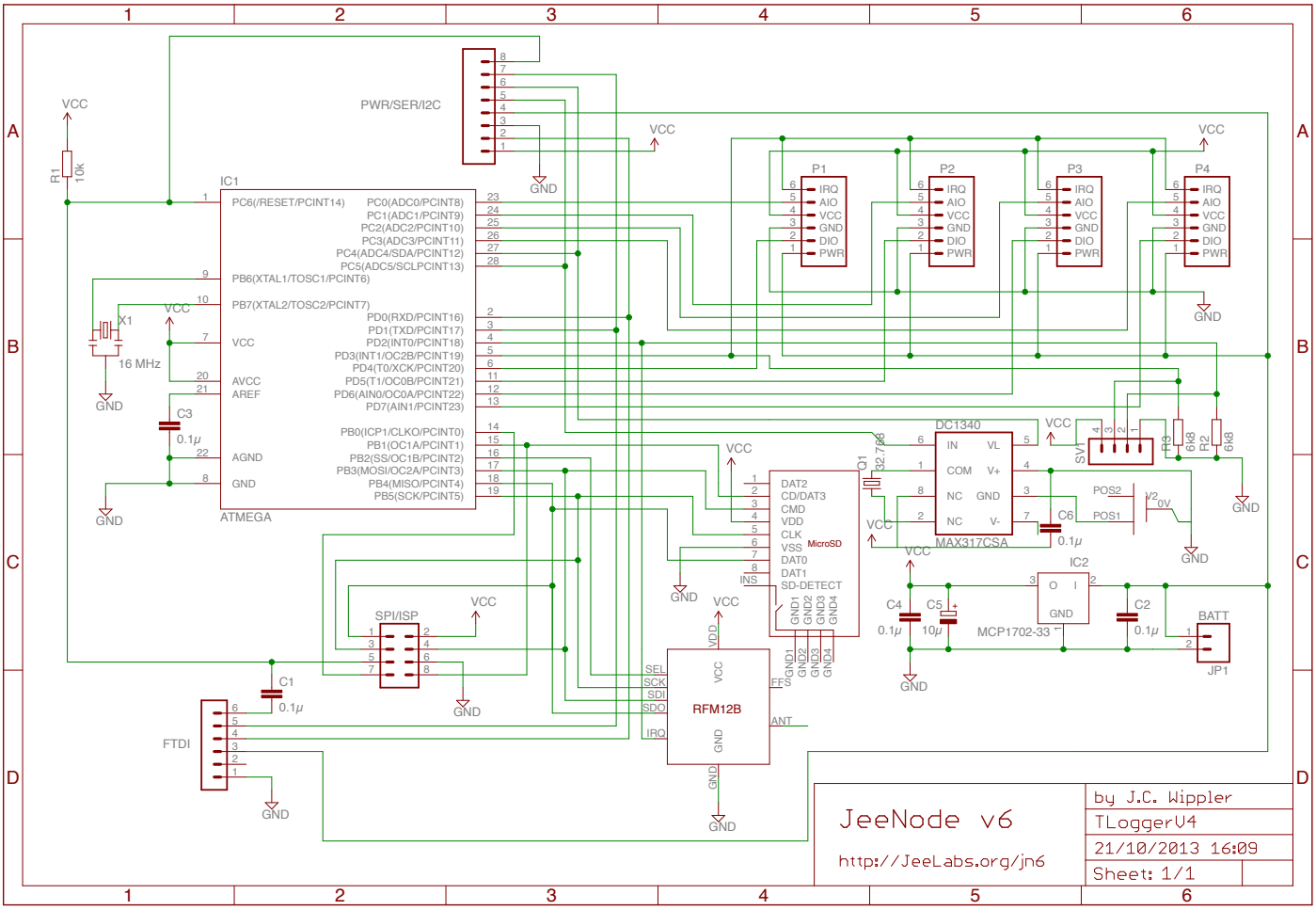
- Some occupants would appreciate communication of how it was decided which works would be carried out, before the start, to feel part of the process.

- Even though letters and leaflets had been sent, some tenants still did not seem to know the purpose of the works. I am aware that this type of communication is difficult and this is not the only CESP scheme where this happened. Since [the RSL] best knows the tenants, perhaps your experience can help devise a communication strategy which might enable more tenants to understand the purpose of the works.

- It may be beneficial to communicate to tenants how they can anticipate changing their heating behaviour after the retrofit – i.e. the more they turn down the heating after retrofit, the less their house will get warmer – or conversely, if they use the heating in the same way after as before, they will have a warmer home but might not save energy. Giving them these options up front may aid their understanding and choice of how to take the benefit of the refurbishment.

# D

# CIRCUIT DIAGRAM OF FINAL OCCUPANCY SENSOR


JeeNode v6
http://JeeLabs.org/jn6
by J.C. Wippler
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P2
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C5
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