Effects of Retrofit Insulation on Space Heating Consumption: a Case Study of a High-Rise Social Housing Building in Newcastle upon Tyne, UK

Macarena Andrea Rodriguez Beltran

Thesis presented for the degree of

Doctor of Philosophy

Newcastle University

School of Architecture, Planning and Landscape

October 2017

This page is intentionally left blank

Abstract

Different policy instruments have been applied to raise the energy efficiency in low-income and vulnerable households. However, previous studies suggested that, due to temperature take-back, occupants take part of the energy consumption saving after energy efficiency upgrades as increased internal air temperatures.

The aim of this study was to investigate the effects of retrofit insulation on space heating consumption to deepen the understanding of the temperature take-back. This study used an integrated approach to take into account the complex interactions of physical and occupants' behavioural factors; quasi-experimental and qualitative approaches. A quasi-experimental approach involved detailed internal air temperature monitoring of a sample in a high-rise building pre- and post-retrofit, and monthly space heating consumption for over a year of each flat dwelling at the retrofitted building, which was compared to a control building. A qualitative approach involved the collection of occupant responses pre- and post-retrofit.

The main findings were: 1. Following retrofit the mean internal air temperature of the high-rise retrofitted building increased +0.46˚C (22.07˚C to 22.53˚C at 5˚C external temperature) and could attain a 27% space heating saving (34% relative to a control group); 2. The effect known as saturation was taking place due to internal temperatures' reaching a maximum level of thermal comfort (~22.5°C); 3. No evidence was found that would suggest that occupants were using their homes more intensively or had changed the use of space.

These empirical findings suggested that assumptions normally made about low-income dwellings 'taking back' energy savings as increased temperatures did not accurately reflect the reality of the energy efficiency upgrades in the case study – particularly, energy efficiency retrofit upgrades that achieve saturation. The study suggested that energy efficiency measures targeting low-income dwellings designed to achieve saturation might prevent temperature take-back, and achieve both thermal comfort and low-energy use. However, a possible risk of overheating was also suggested in the non-heating season.

...to my granny

Acknowledgements

I would firstly like to thank my supervisor, Carlos Calderon for his guidance over the years of my PhD. I would like to acknowledge the support I received from the Sustainable Institute that provided funding for data loggers and gift cards. In addition, from Your Homes Newcastle staff. I would especially like to thank Tom Jarman for all his invaluable contributions.

I would also like to thank many other people, who have provided help in all kinds of disciplines, such as Tom Bradley from NAREC, Peter Kellet, Simin Davoudi, Rose Gilroy and Neveen Hamza from Newcastle University. I also wish to thank Aidan Wightman for his help in checking my English. In addition, I would also like to thank several fellow students, in particular, Montse Ferres, Javier Urquizo and Tianqi for helping me with the interviews and Najla Mansur for the poster design. It would also not have been possible without all the incredibly generous participants. I am grateful for the time and interest that they invested in the project. Last but not least, I give thanks to my family and Manos for all their support and encouragement.

This page is intentionally left blank

List of Abbreviations and Acronyms

ACE	Association for the Conservation of Energy
AS	Advanced Subsidiary
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BREDEM	BRE Domestic Energy Model
BS	British Standard
BTEC	National Award Certificate/Diploma.
˚C	Degrees Celsius
CARB	Carbon Reduction in Buildings
CERO	Carbon Emissions Reduction Obligation
CERT	Carbon Emissions Reduction Target
CESP	Community Energy Savings Programme
CSE	Certificate of Secondary Education
CI	Confidence interval
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon dioxide
CHP	Combined heat and power
CPH	Cruddas Park House
CSCO	Carbon Saving Community Obligation
DECC	Department of Energy & Climate Change
DIY	Do-it-yourself
ECF	Energy cost factor
ECO	Energy Company Obligations
EE	Energy efficiency
EU	European Union
EN	European Norm
EST	Energy Saving Trust
EWI	External wall insulation
FT	Full-time
GCSE	General Certificate of Secondary Education
HD	High density

HDD	Heating degree days
HHCRO	Home Heating Cost Reduction Obligation
HLP	Heat Loss Parameter
INCA	Insulated Render and Cladding Association
ISO	International Standards Organisation.
IT	Internal temperature
IWI	Internal wall insulation
LED	Light-emitting diode
LTHW	Low temperature hot water
m^2	Square metre
Met	Metabolic rate
mtoe	Million tonnes of oil equivalent
MW	Megawatt
NHS	National Health Service
Ofgem	The Office of Gas and Electricity Markets
PC	Personal computer
PMV	Predicted mean vote
PPD	Predicted Percentage of Dissatisfied
PT	Part-time
PWM	Position Weight Matrix
RH	Relative humidity
SAP	Standard Assessment Procedure
SHC	Space heating consumption
STBA	Sustainable Traditional Buildings Alliance
TWh	Terawatt-hour
UK	United Kingdom
YHN	Your Homes Newcastle

Publications

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

Rodriguez M, Calderon C (2017). Building fabric retrofit insulation in a UK high-rise social housing building: an appraisal of temperature take-back and energy consumption, *in process of publication*.

Rodriguez M, Calderon C (2014). Modelling approaches for retrofitting energy systems in cities: current practice and future challenges in Newcastle upon Tyne. disP: The Planning Review, 50(3), 76-89.

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1. Introduction

This chapter introduces the research problem, key terms, research context, and presents the research questions and research aim/objectives. It also describes the scope and limitations of this thesis and the research outline. Energy efficiency is one of the central objectives of the European Union Strategy 2020 to achieve energy security goals, reduce CO_2 emissions and boost economic growth (European Parliament and Council, 2012). Consequently, current UK policy has placed an emphasis and large funding on promoting energy efficiency measures so as to tackle climate change, energy security and fuel poverty concerns. The energy supplier obligations such as CERT, CESP and ECO were expected to raise the energy efficiency in low-income and vulnerable households (DECC, 2014c). ECO[1] targets, for example, focused on the lowest 15% of the UK's most deprived areas (DECC, 2012).

However insufficient consideration has been given to the implications of the "temperature take-back" and "rebound effect" on energy efficiency policy (Sorrell, 2007). Occupants may take part of the energy saving after retrofit as increased internal temperatures, particularly in dwellings occupied by low-income householders (Milne and Boardman, 2000; Sorrell, 2007). One example is the Warm Front Energy Efficiency Scheme, which had a positive health and quality of life impact (Green and Gilbertson, 2008); however, it had a negligible impact on energy saving (Hong, 2011).

Therefore, in order to avoid unintended consequences, assessing the benefits of these initiatives requires more than simply counting the number of dwellings retrofitted, the factors determining energy use in buildings need to be understood. However, to date, those factors are complex and often poorly understood

[1] This is referred to in the first version of ECO.

(Oreszczyn and Lowe, 2010). This is where studies adding new empirical evidence to deepen the understanding of the effects of retrofit insulation on space heating consumption could play a role, also shining a more critical light on how future research design could be improved. This is of even greater importance, also taking into account the higher investment needed before 2050. For example, an estimated cost for a whole house retrofit programme will range between £16,000 and £34,000 per property for at least 1,000 properties (SHAP, 2009 as cited in URBED, 2016).

Personally, this research is also important, since my main scholarly interest is in self-sufficient cities, especially in the provision of resources for urban populations with regard to energy. In this context, if we look at the pathway to meet the carbon reductions, the first step is demand reduction whilst simultaneously getting the building stock insulated. Demand reduction and building insulation measures are linked with a strong human factor component, which adds more complexity to current technical solutions to a low-carbon transition. This made me wonder if there is a real impact of current technical solutions to a low-carbon transition. This sparked my interest to research the issue of energy efficiency, as an Engineer and marketing researcher, it evoked an inspiration to study how the understanding of physical factors and behavioural factors can contribute to the low-carbon transition.

1.2. Key Terms

Since the study cuts across different fields of study, this section introduces some key terms in order to clarify some concepts that are used through the thesis. These terms are considered in greater detail in Chapter 2 (Literature Review).

Shortfall

There are several definitions that have emerged to explain the difference between the actual energy consumption saving achieved from the energy efficiency measures and the estimated saving from theoretical models. For example, this difference has been termed as the “Reduction factor” by Sanders and Phillipson

(2006) or "Shortfall" by Sorrell *et al.* (2009). The Reduction Factor[2] is defined as "*the amount by which the measured energy saving following refurbishment is less than the saving predicted from theory*" (Sanders and Phillipson, 2006, p.?).

Shortfall is defined as "*the difference between actual savings in energy consumption and those expected on the basis of engineering*" (Sorrell *et al.*, 2009, p. 1358).

The known reasons for this difference are the occupants' behaviour with the remainder due to other factors, such as inexact equations (mathematical models of heat transfer), inputs (U-values) and/or technical failures (i.e. installation, performance of equipment) (Sanders and Phillipson, 2006; Sorrell *et al.*, 2009). To avoid ambiguity in this study, the term shortfall by Sorrell *et al.* (2009) is used and is limited to residential space heating only.

Temperature take-back

There are several definitions that have emerged to explain the predicted energy consumption saving converted into an increase of internal temperature such as "comfort factor", "take-back" and "temperature take-back". Comfort factor is defined as "*the part of the reduction factor which can be identified as being caused through improved internal temperatures*" (Sanders and Phillipson, 2006, p.?[3]). Milne and Boardman for example describe take-back as "*the amount of energy taken as extra warmth following an energy efficiency improvement, expressed as a percentage of the energy which could have been saved if there had been no temperature increase*" (Milne and Boardman, 2000, p. 416).

Temperature take-back is defined as "*the change in mean internal temperatures following the energy efficiency improvement, or the reduction in energy savings associated with that change*" (Sorrell *et al.*, 2009, p. 1358).

---

[2] Sanders and Phillipson (2006) proposed that the difference between actual and predicted energy saving following an energy efficiency upgrade can be expressed as:

Reduction factor (RF) = Comfort factor (CF) + Other factor (OF).

[3] Paper without pages

The basic assumption is that only a part of temperature take-back is accounted by the occupants' behavioural change and the remainder by the physical factors (Sorrell, 2007; Sorrell *et al.*, 2009). This study uses the term temperature take-back by Sorrell *et al.* (2009) but limited to residential space heating only.

Behavioural change

There are several theories of energy consumption behaviour. Chatterton (2011) identified four theories for understanding energy consumption behaviour. Economic theories define energy as an action, in which *"consumers will adapt usage in response to price signal"* (Chatterton, 2011, p. 7). Psychological theories describe energy use on the base of "*stimulus-response mechanisms*", in which people may respond to a feedback campaign, meter readings or more information (ibid., 2011). Sociological theories propose that energy is perceived as the result of its services "*people do not directly use energy, instead we carry out a range of activities or 'practices' that lead to the consumption of energy*" (Chatterton, 2011, p.7).

Sorrell *et al.* (2009) define behavioural change as: "*the proportion of the change in internal temperature that derives from adjustments of heating controls and other variables by the user (e.g. opening windows), or the reduction in energy savings associated with those changes*" (Sorrell *et al.*, 2009, p. 1358).

However, the concept of behaviour is not limited to a set of adaptive actions (e.g. switching on/off heating, adding clothes or adjustments of heating controls). For the purposes of this thesis, the behavioural change definition by Sorrel *et al.* (2009) is suitable, since it is limited to the adaptive actions performed by occupants to adapt their environment to feel comfortable. For example, an occupant can open the windows to regulate a desired internal temperature, following retrofit.

1.3. Research Context

This section describes the key energy efficiency policies aimed at reducing carbon emissions and tackling fuel poverty in the household sector. First it reviews the

Energy Efficiency Obligations imposed on to the suppliers aimed at raising the energy efficiency in low-income and vulnerable households. The second part of this section seeks to understand better the relationship between energy efficiency policies and fuel poverty in social housing. The third part analyses the relationship between energy efficiency policies and carbon emission (or energy saving) targets.

1.3.1. Energy efficiency policies aimed at raising the energy efficiency in low-income and vulnerable households

Energy efficiency is one of the central objectives of the European Union Strategy 2020 to achieve energy security goals, reduce CO_2 emissions and boost economic growth (European Parliament and Council, 2012). The 2012/27/EU Directive set a primary[4] energy saving target of 20% by 2020 against a 2007 business-as-usual projection (ibid., 2012). In response to the Directive, the UK's government adopted a target of 129.2 mtoe[5] (saving) for final[6] energy consumption, equivalent to a 20% reduction in primary energy consumption (DECC, 2014c). From Article 7 of the 2012/27/EU Directive, which requires a cumulative final energy savings target of 1.5% relative to the average final energy consumption over the period 2010-2012, the binding target was set at 324 TWh in 2013, to comply with the 'EU Strategy 2020' (DECC, 2014c).

A total of 19 different policy measures have been used to implement the 2012/27/EU Directive (DECC, 2014c). Particularly, three supplier obligations such as the Carbon Emissions Reduction Target (CESP), Community Energy Saving Programme (CERT) and Energy Company Obligation (ECO) were expected to raise the energy efficiency of households in low-income and vulnerable households (DECC, 2014c). These three obligations were projected to contribute 167 TWh in

---

[4] Primary energy consumption is defined as gross inland consumption minus non-energy uses (European Parliament and Council, 2012).

[5] Million tonnes of oil equivalent.

[6] Final energy consumption is defined as "all energy supplied to industry, transport, households, services and agriculture" (European Parliament and Council, 2012, p.10).

energy savings, by 2023 (Table 1.1) (DECC, 2014c), meet the carbon targets in Table 1.2, and assist the fuel poor (DECC, 2011; DECC, 2012).

CERT aimed at reducing 293 mtoe of CO_2 savings by overcoming barriers to the uptake of cost-effective energy efficiency interventions i.e. insulation, heating and lighting (DECC, 2014b). CERT also required meeting at least 40% of its target to a 'Priority Group[7]' (ibid., 2014a). CERT's five years of existence (from April 2008 to December 2012) achieved 296.9 mtoe of CO_2 savings and 41% of resulted measures were provided to the Priority Group (Ofgem, 2013b). 3.9 million households received loft insulation and over 2.6 million cavity wall insulation, of these about 25% were social tenants (Watson and Bolton, 2013). See details of measures installed under CERT by type and group in Table 1.3.

CESP (Community Energy Saving Programme) was designed to reduce 19.25 mtoe of CO_2 emissions and fuel bills in the most deprived geographical areas (DECC, 2014b). CESP ran from October 2009 to December 2012 and incentivised a 'whole-house' upgrade approach, involving one or more energy efficiency measures (ibid., 2014a). Under CESP 293,922 energy efficient measures were provided to more than 154,000 low-income dwellings, of these 49% were insulation and 39% heating measures (see Table 1.4) (Ofgem, 2013a). Many of these measures were delivered through social housing providers (working in partnership with private households) (DECC, 2014b). CESP and CERT were succeeded by the Energy Companies Obligations (ECO), which was launched in 2013 (Hough and Page, 2015).

ECO (Energy Company Obligation) aimed at reducing household carbon emissions by up-taking cost-effective energy efficiency interventions which were not fully financeable through the 'Green Deal'[8], focusing on subsided measures for low-income and vulnerable households (DECC, 2012). Three obligations were imposed

---

7 Priority Group refers to "households where particular benefits are claimed and/or a household member is 70 years old or above" (DECC, 2014b, p.10).

8 The 'Green Deal' is a financial mechanism that moves responsibility onto homeowners to make energy efficiency improvements. Energy efficient measures are paid to the electricity provider in instalments, attached to the electricity bills, with a 'Golden Rule' that estimated savings must be greater than repayments (DECC, 2012).

on to suppliers under ECO: the Carbon Emissions Reduction, the Carbon Saving Community and the Home Heating Cost Reduction Obligation (HHCRO) (Ofgem, 2015). HHCRO, also known as Affordable Warmth, was intended to make heat more affordable in low-income and vulnerable dwellings (Ofgem, 2015). ECO is currently running in its second obligation period until March 2017[9] and the plan is to run for the next 5 years, from April 2017-2022, with an emphasis on tackling fuel poverty and CO_2 emissions (DECC, 2016b). Under the current ECO the Affordable Warmth obligation is exclusively dedicated to private tenure households; a further proposal aims to include energy inefficient social housing (DECC, 2016b).

As can be seen, past programmes have made progress to achieve policy goals, yet focusing on cost-effective energy-efficient measures such as loft insulation and cavity-wall insulation, so-called 'low-hanging fruit' (Rosenow and Eyre, 2014).

TWh	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	total
CERT*	2.7	5.7	9.1	9	9	9	9	9	9	9	9	8.9	8.8	8.6	116
CESP*	0	0.1	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	5
ECO				0.7	1.4	2.1	2.8	3.6	4.4	5.1	5.7	6.4	7.1	7.1	46
Total															167
Green Deal					0.2	0.4	0.5	0.7	0.8	0.9	1.1				5
Total											124				172

*(2010-2012)

Table 1.1. Estimates of final energy consumption saving by household policies in TWh. Source: based on Table 2 – '*Final energy consumption savings by year from UK policies included for Article 7 policy plan, TWh*' (DECC, 2014c)'.

9 From April 2015 until March 2017.

Scheme	Target mtoe of CO_2	Year	Target (low-income)	Target achieved mtoe of CO_2, (%)
CERT	293 (lifetime)* DECC, 2014	2008-2012	40% focused on priority group customers	296.9 (101)*
CESP	19.25 (lifetime)**	2009-2012	Specific low-income areas	16.31 (85) **
ECO 1st period	Carbon emissions reduction obligation (CERO****) (lifetime)*** Carbon saving community obligation (CSCO) – 6.8 (lifetime)*** Home Heating Cost Reduction Obligation (HHCRO) £4.2 bn***	2013-2015	Carbon saving community target focused on the lowest 15% of the UK's most deprived areas	CERO: 18.33 (131)*** CSCO: 9.87 (145)*** HHCRO £5.16bn (123)***

*(Ofgem, 2013b), **(Ofgem, 2013c), ***(Ofgem, 2015), **** a reduction of the CERO target was done by 33%, from 20.9 mtoe CO_2 to 14 mtoe CO_2.

Table 1.2. Summary of energy efficiency obligation targets for the domestic sector in mtoe of CO_2, between 2008 and 2015. Source: Ofgem (2013b), Ofgem (2013c), Ofgem (2015).

Measure type	Measures	Priority group (thousands)	Non-priority group (thousands)	Total (thousands)
Insulation	Cavity wall insulation	1,260	1,309	2,569
	Loft insulation	2,334	1,564	3,897
	DIY insulation (m^2)	18,008	94,843	112,851
	Solid-wall insulation	44	15	59
	Window glazing (m^2)	113	34,478	34,590
	Other insulation (*)	107	613	720
Heating	Other heating (control & boilers) (**)	619	977	1,596
	Other heating network (***)	3	6	9
Lighting	Compact Fluorescent Lamps	121,489	182,463	303,953
	Other lighting system(****)	112	904	1,016
Real Time Displays	Real Time Displays	761	2,239	3,000
Other	Shower regulators	1,526	8,128	9,653
	TVs	10,336	20,146	30,482
	EE. cold and wet appliances	851	3,580	4,432
	Standby savers	2,399	2,528	4,927

(*) Other insulation: draught proofing, hot water tank jackets, radiator panels (m^2) and flat-roof insulation. (**) Other heating controls and boilers: fuel switching, replacement boilers, heating controls installed and communal heating. (***) Other heating networks: ground source heat pump, air source heat pump, solar water heating and large-scale CHP. (****) Other lighting: other lighting and LEDs.

Table 1.3. Measures installed under CERT by type and group. Source: based on '*Table 4.1 The number of measures installed'* (Ofgem, 2013b).

Measure type	Measure	Number of measures	%	Measure type (%)
Insulation	Cavity wall insulation	3,000	1	49
	Loft insulation	23,503	8	
	Solid wall insulation	80,257	27	
	Window glazing (m^2)	21,779	7	
	Other insulation (*)	14,952	5	
Heating	Heating other (control and boilers) (**)	113,980	39	39
District heating	Connection to, upgrade and meter	23,732	8	8
Microgeneration	Heat pump, solar water heater	1,079	0	4
	Photovoltaic panel	11,546	4	
Energy advice package		94	0	0
Total		293,922	100	100

(*) Other insulation: draught proofing, flat-roof insulation and under-floor insulation. (**) Heating other controls and boilers: fuel switching, replacement boilers and heating controls.

Table 1.4. Measure type installed under CESP. Source: based on *'Table 1: Total number of measures delivered'* (Ofgem, 2013a).

1.3.2. Energy efficiency policies and fuel poverty in social housing

The social housing sector is one of the most important sectors in the UK, around 4.1 million dwellings (17% of the stock), of which 2.4 million dwellings are owned by housing associations and around 1.7 million owned by local authorities (DCLG, 2016a). There are different pressing issues in this sector such as low income[10], fuel poverty and unemployment. One in ten households in the social-rented tenures is classified as living in fuel poverty[11] (DECC, 2015). Fuel poverty has been linked with increased morbidity and mortality, especially among the most vulnerable groups (Wilkinson *et al.*, 2001; Institute of Health Equity, 2014). In addition, the degree of exposure to cold temperatures is linked with respiratory, circulatory and mental health problems (Institute of Health Equity, 2014).

Although fuel poverty in the social sector has decreased since 2003, particularly eight percentage points of fuel poverty in local authority housing (DECC, 2016a)[12], there is a further risk of more households in the social sector going into fuel poverty, given the increase in energy bills. However, to some extent smaller floor areas and improved energy efficiency (see Table 1.5) contribute to reduce the level of fuel poverty in this group (DECC, 2015). It is therefore important for a long-term solution to continue fostering energy efficiency measures in the social housing sector i.e. insulation and heating systems.

However, the positive impact of energy efficiency measures on fuel poverty or health (due to better living conditions provided by the increase in internal temperatures) may be decoupled from the energy saving. One example is the Warm Front Energy Efficiency Scheme, one of the main programmes to tackle fuel

---

[10] Local authority tenant incomes: £13,662. Social housing tenant incomes: £13,344. Values expressed in median equivalised AHC (after housing cost), in which incomes, mortgages and rent payments are deducted from the full income of each household. (DECC, 2015).

[11] Fuel poverty has been subject to different debatable redefinitions; the last definition is that fuel poverty is calculated under the low-income/high-costs indicator (Hills, 2012). The previous 10% indicator was very sensitive to energy prices, bringing people living in large inefficient homes into the fuel poverty statistics, who were reasonably well-off (DECC, 2015).

[12] Housing belonging to local authorities or social landlords has an ‘above-average energy performance’ compared to other households since it has been much more likely to get energy-efficiency improvements (Palmer, J. and Cooper, I. (2013) *United Kingdom housing energy fact file 2013*. [Online]. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/345141/uk_housing_fact_file_2013.pdf (Accessed: 15/10/2017).

poverty among the low-income and vulnerable households (Green and Gilbertson, 2008). The Warm Front Scheme had a positive health and quality of life impact (Green and Gilbertson, 2008); however, it has a negligible impact on energy saving (Hong, 2011). This is explored in more detail in a later section (2.4).

Tenure	2011	2012	2013
Social	63.4	64.7	65.6
Privately rented	55.6	57.3	58.8
Owner-occupied	55.7	57.5	58.7

Table 1.5. Average energy efficiency rating by tenure 2011-2012. Source: based on *'Table 2.3: Average SAP 12 ratings by tenure, 2011–2012'* (DECC, 2015).

1.3.3. Energy efficiency policies and CO_2 emissions targets

Despite the measures installed or provided to households in Tables 1.3 and 1.4, there is concern as to whether the energy efficiency policies can meet the energy-saving goals. The identified issues could be divided into two categories: retrofit uptake and predicted energy saving. It has been noted that the retrofit uptake has been less than needed, indeed since 2013 there is a slow-down in the rate of installation of energy efficiency upgrades in buildings (Energy and Climate Change Committee, 2016). Although there is still an energy-saving potential for dwelling insulation and heating measures of 54TWh, between now and 2020, it implies that millions of homes need to be insulated (DECC, 2014c). 7.3 million solid wall, 5.1 million cavity wall, 7.4 million loft insulation and 20.1 million floor insulations, among other measures, are shown in Table 1.6 (ibid., 2014b).

The impact of retrofits on energy saving has been less than predicted, particularly in low-income and vulnerable households. To date, insufficient consideration has been given to the implications of the temperature take-back and rebound effect on energy efficiency policy (Sorrell, 2007). However, there is a growing awareness that normative models, such as the one used to account for the energy saving from energy efficiency policies, do not represent the actual energy saving. The difference between the actual saving achieved from the energy efficiency measures and the estimated one from theoretical models has been termed *shortfall* (Sorrell *et al*., 2009). This shortfall can be attributed to occupant behaviour with the remainder due to other factors, such as technical failures (i.e. installation, performance of equipment) and poor engineering estimates of potential savings. Particularly in household heating, the term temperature take-back has been used to explain the predicted energy consumption saving converted into increases of internal temperature.

It has been established that standard physical models overestimate the energy savings from energy efficiency improvements in household heating systems by one half or more in low-income households (Sorrell *et al.,* 2009).

Insulation measures	Number of houses (million)
Solid wall insulation	7.3
Cavity wall insulation	5.1
Loft insulation	7.4
Floor insulation	20.1
Double glazing	19.2
Insulated, energy-efficient doors	11.1
Draught proofing (draught stripping)	1.9
Reduced infiltration (foam, strips, sealant use)	23.7

Table 1.6. Remaining number of houses with potential for insulation measures (million). Source: based on '*Table 1: Remaining potential for measure within UK housing stock*' (DECC, 2014c)'.

For example, the impact of the Warm Front Scheme had a negligible impact on energy saving (and consequently carbon emissions) (Hong, 2011). The author reported that following the energy efficiency upgrades the internal air temperature increased by 1.6°C and fuel consumption increased by 12% (Hong, 2011). Several researchers (such as Hong *et al.*, 2006; Oreszczyn *et al.*, 2006; Hong, 2011), have suggested that occupants may take part of the energy saving after retrofit as increased internal temperatures. Particularly, it was noted that temperature take-back is usually higher in dwellings occupied by low-income householders (Milne and Boardman, 2000; Sorrell, 2007). It is therefore very important to understand the factors determining energy use in buildings, as this lack of knowledge is a concern in the achievement of energy and carbon emissions policy goals. However to date these factors determining energy use in buildings are complex and often poorly understood (Oreszczyn and Lowe, 2010).

1.3.4. Summary of research context

The European Union Strategy 2020 has influenced the UK's energy efficiency policies in the household sector. The policy reviewed in this section identified particularly three energy efficiency supplier obligations aimed at raising the energy efficiency in low-income and vulnerable households. Despite the measures installed under the three energy efficiency supplier obligations and the Warm-front scheme, concerns have been noted that they have been insufficient to meet the energy-saving targets. One of the reasons is the insufficient consideration given to the implications of the temperature take-back and rebound effect on energy efficiency policy (Sorrell, 2007).

Occupants may take part of the energy saving after retrofit as increased internal temperatures, particularly in dwellings occupied by low-income householders (Milne and Boardman, 2000; Sorrell, 2007). One example is the Warm Front Energy Efficiency Scheme, which had a positive health and quality of life impact (Green and Gilbertson, 2008); however, it had a negligible impact on energy saving (Hong, 2011). It is therefore very important to understand the factors determining energy use in buildings, as this lack of knowledge is a concern in the achievement of energy and carbon emissions policy goals. However, to date, these factors determining energy use in buildings are complex and often poorly understood (Oreszczyn and Lowe, 2010).

1.4. Research Questions

The following research questions are stated to explore the effects of retrofit insulation on space heating consumption to deepen the understanding of the temperature take-back.

- How do internal air temperatures change following an imposed building fabric retrofit insulation?
- How does space heating consumption changes following an imposed building fabric retrofit insulation?
- Which interactions between occupant behavioural factors and physical factors may account for space heating consumption change?
- Why do internal air temperatures change afterwards?

These Research Questions are situated within the current research assumptions and main theoretical approaches (see Chapter 2 Literature Review). The first and second Research Questions are based on the premise that temperature take-back after retrofit exists and can be observed (Chapter 2). Concerning this premise, previous quantitative studies have measured the temperature take-back, which is usually higher in low-income dwellings, as those are often not warm enough for occupancy (Milne and Boardman, 2000; Sorrell *et al.*, 2009) (Section 2.4).

Having included in the previous research questions the change of internal air temperatures and space heating consumption following building fabric retrofit insulation, the third Research Question is based on the premise that the physical and occupant's behavioural factors seem to form a complex system (Lowe *et al.*, 2012; Love, 2014), in which temperature take-back is accounted for by the physical factors and the remainder by the occupant's behavioural change (Hong *et al.*, 2006; Sanders and Phillipson, 2006; Sorrell, 2007) (Section 2.4). However, to date, the factors determining energy use in buildings are complex and often poorly understood (Oreszczyn and Lowe, 2010). Trying to catalogue the types of interactions that occur following retrofit insulation, this study includes changes in the use of space.

A fourth Research Question was added at the end of the study to include the insight gained through the face-to-face interviews to understand why those outcomes occurred. Indeed, this "why" question tries to understand why internal air temperatures change afterwards. Together, these four Research Questions describe the extent to which retrofit insulation may impact on space heating consumption in a high-rise social housing building.

1.5. Research Aim and Objectives

The aim of this study is to investigate the effects of retrofit insulation on space heating consumption to deepen the understanding of the temperature take-back, in which occupants take part of the energy saving after energy efficiency upgrades as increased indoor temperatures, through an empirical study. The objectives of this study are as follows:

1. To examine the effect of energy efficiency upgrade on energy consumption for space heating using a method of analysis that quantifies the change of the energy service – internal air temperature;

2. To examine the effect of energy efficiency upgrade on energy consumption for space heating using a method of analysis that quantifies the change of the energy input – space heating consumption;

3. To identify occupant responses that can explain the effect of the energy efficiency upgrade on energy consumption for space heating.

1.6. Scope and Limitations of the Thesis

This thesis is an investigation of the effect of building fabric investments on space heating consumption in a high-rise social housing building. In order to understand this effect, the change of space heating consumption along with the changes in internal air temperature are measured, as current thinking argues that energy service is the most relevant output of a system (Sorrell, 2015). In addition, the link between physical and behavioural factors is observed in response to the installation of energy efficiency measures through the change in the use of space, and the insight gained from the occupants tries to understand why internal air temperatures change afterwards.

The study area was limited to the retrofit project at the Cruddas Park House (CPH), as it was the only project managed by the social housing association 'Your Homes Newcastle'[13] which had secured retrofit funding[14] at the time of the survey (February 2014). The CPH building underwent specific insulation type – external solid wall insulation and double glazing of windows. Therefore, the study results obtained need to be considered under this scope. The results of this study are indicative of the effect of building fabric investments on space heating consumption in a high-rise social housing; other dwellings or other types of retrofit insulation are not considered. It is noted that generally every building is different either in design, construction, or operational characteristics. Ultimately, this research might shine a more critical light on how future research design could be improved and may lead to recommendations which can be used as a basis for larger studies which can inform energy policies.

1.7. Structure of the Thesis

This thesis is structured in the following way (see Figure 1.1).

Chapter 1 'Introduction' introduces the research problem, research context, and presents the research questions and research aim/objectives. It also describes the scope and limitations of this thesis and the research outline.

Chapter 2 *'Literature Review'*. The literature review is divided into two parts. The first part introduces the building retrofit under the current paradigms. Indeed, it explains the building retrofit motivation and cost-benefit evaluation strategy for upgrading domestic buildings in the UK. In addition, it also reviews the thermal

[13] Your Homes Newcastle is the housing association responsible for managing council homes on behalf of Newcastle City Council.

[14] ECO funding to develop other retrofit projects was cancelled and support (interviewers) from YHN to undertake the survey was revoked.

performance metrics used to describe the energy efficiency upgrades of dwellings such as U-value and SAP. Moreover, it reviews the causes that might create discrepancies between energy-modelling predictions and actual energy saving pre- and post-retrofit such as: miscalculation of physics-based models, technical failures, occupant factors and temperature take-back, therefore introducing in this section the temperature take-back concept. Following this, the main research assumptions related to temperature take-back and energy consumption are reviewed.

The second part of this chapter reviews theoretical approaches that might be used to explain how occupants might respond to the introduction of energy efficient measures in the domestic sector: economic, engineering/physics-based model approaches and thermal comfort models. This part of the chapter also reviews work in this area undertaken by previous researches using a quasi-experimental approach and presents the rationale for the selection of the quasi-experimental and qualitative approaches used in this study.

Chapter 3 'Research methodology' describes the research methodology for this study. Firstly, an overview of the research strategy '*intervention design'* (Creswell, 2015), adopted to address the Research Questions, is presented. Intervention design strategy is an advanced mixed method that comprises a quasi-experimental design and qualitative method. Secondly, the chapter describes the case study and its justification. The study comprises two high-rise social housing buildings located in the Riverside Dene Area of Newcastle upon Tyne, UK: Cruddas Park House (CPH), the target building, and The Hawthorns, the control group building. The chapter also describes the sampling approach, building physical characteristics, socio-demographic characteristics. Finally, this chapter describes how validity is addressed in this case study and how ethical considerations are taken into account in this case study.

Chapter 4 'Data Collection' provides a summary of the research methods used to collect the evidence used in this research. The research methods for data collection such as detailed monitoring, meter readings, structured questionnaire, self-completion diaries and follow-up interview, and semi-structured questionnaire are described and justified. In addition, the implementation of the research methods is explained. This chapter also describes the data analysis steps and the metrics constructed to answer the Research Questions in Chapters 5, 6 and 7. Finally, this chapter describes the main limitations of the research methodology.

Chapter 5 'Results part 1: Internal Air Temperatures and Space heating Consumption'. First, this chapter presents the findings of the impact of the energy efficiency retrofit interventions on changes in internal air temperatures in the target building. Secondly, the chapter shows the findings of the impact of the energy efficiency retrofit interventions on changes in space heating consumption of the target building relative to the control group building.

Chapter 6 'Results Part 2: Interactions between Occupant Behavioural and Physical Factors' presents the findings of the interaction between behavioural and physical factors through the changes in the use of space and thermal comfort perception.

Chapter 7 'Results Part 3: Why internal air temperatures change afterwards?' is devoted to gain qualitative insights to explain the change of internal temperatures after retrofit insulation.

Chapter 8 'Discussion' brings together all the result chapters and discusses the findings in comparison with the main assumptions reviewed in Chapter 2. It reflects on the theoretical and practical methodological limitations so providing a critical light on the methodology and ways for improving it.

Chapter 9 'Conclusion' starts with a summary of the thesis and brings this thesis to a close by summarising the key findings, contribution to the knowledge and it draws out the main recommendations for future studies and projects.

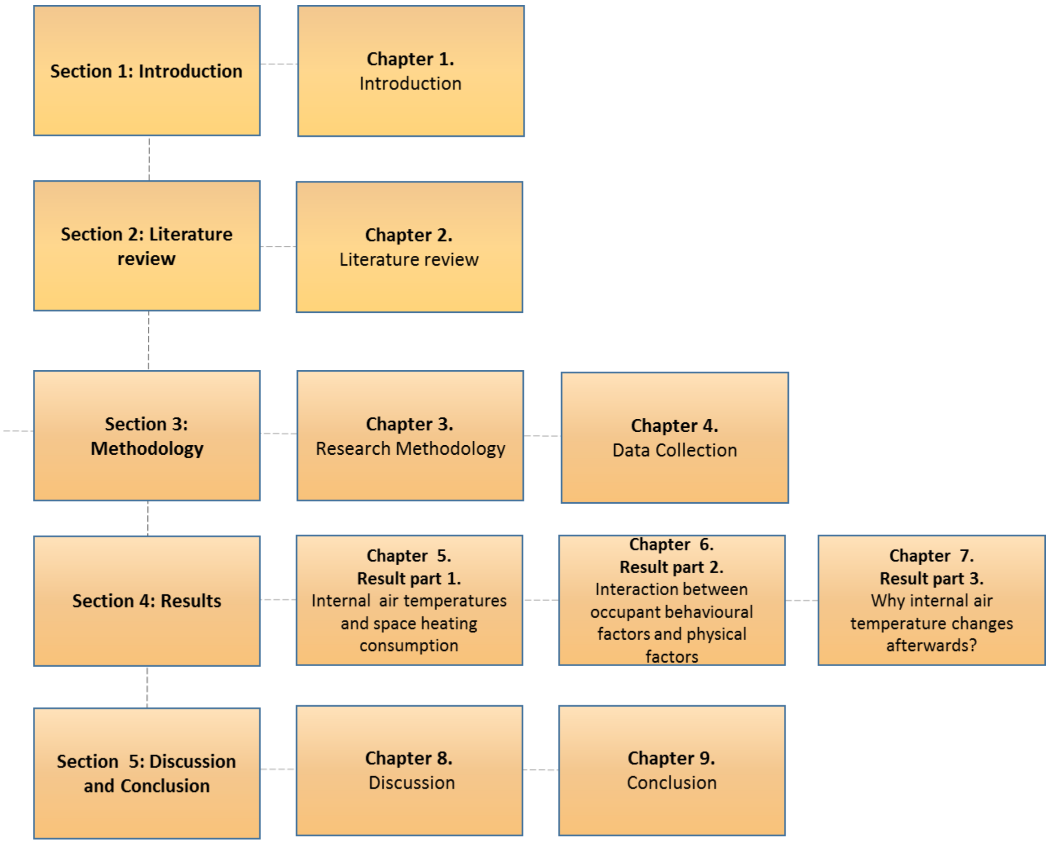


Figure 1.1. Structure of the thesis

1.8. Summary

This chapter first introduces the research problem and explains some key terms in order to clarify some concepts that are used through the thesis. Secondly, it reviews the current energy efficiency policy and outlines the research questions and research aim/objectives to understand the effect of building fabric investments on space heating consumption in a high-rise social housing building. This chapter also describes the scope, limitations and structure of the thesis, which is structured into five sections that comprise nine chapters.

Chapter 2. Literature Review

2.1. Introduction

This chapter is divided into two parts. The first part introduces the building retrofit under the current paradigms. Indeed, Section 2.2 explains the building retrofit motivation and cost-benefit evaluation strategy for upgrading domestic buildings in the UK. In addition, Section 2.2 also reviews the thermal-performance metrics used to describe the energy efficiency upgrades of dwellings such as U-value and SAP. Section 2.3 reviews the causes that might create discrepancies between energy-modelling predictions and actual energy saving, pre- and post-retrofit, such as: miscalculation of physics-based models, technical failures, occupant factors and temperature take-back, therefore introducing in this section the temperature take-back concept. Section 2.4 presents the main research assumptions related to temperature take-back and energy consumption. Thus, in this chapter current research assumptions are presented and summarised so as to provide a context for the study's research questions and results.

The research assumptions are broken down into the following six stages:

- Energy consumption saving and temperature take-back;
- Temperature take-back and low-income dwellings;
- Temperature take-back and saturation effects;
- Temperature take-back and CO_2 savings;
- Temperature take-back, and the relationship between physical factors and occupant behaviour;
- Temperature take-back and occupant behaviour in the retrofit context.

The second part of this chapter (Section 2.5) provides a summary of the main theoretical approaches that might be used to explain the reason for temperature take-back in the domestic sector such as: economic, engineering/ physics-based model approaches and thermal comfort models. This part of the chapter also reviews work in this area undertaken by previous research by using a quasi-experimental approach and presents the rationale for the selection of the quasi-experimental and qualitative approaches used in the current study.

2.2. Building Retrofit

This section firstly provides a review of the building retrofit motivations. Secondly, this section reviews the main building retrofit insulation strategy for upgrading domestic building in the UK. Thirdly, this section reviews the retrofit insulation for building envelopes, revising the internal and external insulation available for each wall type. Following this, thermal performance metrics used to describe the energy efficiency upgrades of dwellings such as U-value are revised in Section 2.2.4. Finally, Sections 2.2.5 and 2.2.6 examine the existing building regulations when renovating existing residential dwellings in England and the compliance mechanism for building retrofit under SAP 2012.

2.2.1. Building retrofit motivations

The primary motivation for domestic retrofit insulation is to reduce CO_2 emissions. In the UK, more than 25% of the CO_2 emission are attributed to domestic energy use, in which energy for heating is by far the biggest contributor (Palmer and Cooper, 2012). Retrofit insulation is particularly important in the UK because most of the residential buildings were constructed before 1980 with relatively low levels of energy efficiency (Sweatman and Managan, 2010). England's housing stock comprised 23.4 million dwellings in 2014, of which the social housing stock is made up of over 4 million dwellings (17% of the stock); approximately 2.4 million owned by housing associations and 1.7 million owned by local authorities (DCLG, 2016a). The housing stock is made up of a range of diverse housing types and sizes, of which 6% of the social housing stock are high-rise flats (DCLG, 2016b).

According to the Association for the Conservation of Energy (ACE), the UK's dwellings stock is one of the most energy inefficient stock in Europe, performing poorly in how much heat they lost through their walls, floors, roofs and windows (U-value) (ACE, 2013; ACE, 2015) and with the largest components of older buildings (Buildings Performance Institute Europe, 2011). The average SAP rating of the dwelling stock was 62 in 2015 (moderate SAP rating Band D). Although from 1996 to 2015 the average SAP rating of the dwelling stock has improved 45 points (DCLG, 2017b), the large majority of the dwellings are still under the reasonable standard of energy efficiency SAP rating Band C. Moreover, approximately 5 million of dwellings in England are still rated with a poor SAP Rating below 54 (SAP rating Band E, F, G) (DCLG, 2017a). (See SAP rating in Table 2.8 in p.42).

The second motivation for domestic retrofit is to increase the energy security through reduced space heating demand. The third motivation is the reduction of fuel poverty, caused by the combination of inefficient dwellings, high energy cost and low income. However, the ability of energy efficiency upgrades (including building retrofit insulation) actually to deliver real reductions in space heating consumption (hereby CO_2) and fuel poverty has not been always achieved, particularly in low-income dwellings (see more in detail in Section 1.3).

2.2.2. Building retrofit insulation strategies

Retrofit insulation strategies aim to reduce space heating consumption through the reduction of thermal transmittance of building envelopes (i.e. external walls, floor and roof areas, etc.). Previous retrofit schemes had been implemented through a cost-benefit strategy, which in many cases had led to focus on energy-efficient measures such as loft insulation or cavity wall insulation, so-called ‘low hanging fruit’ (Rosenow and Eyre, 2014).

A cost-benefit strategy considers energy efficiency upgrades for which the payback period does not exceed the predicted energy efficiency measure’s lifespan. For example, Shorrock *et al.* (2005) reviewed the potential for energy saving investments applied to a typical 3-bedroom semi-detached house in the UK. The study estimated that loft insulation to 300 mm, with less than 150 mm of insulation already in place, and cavity wall insulation might have payback periods that do not exceed the predicted energy efficiency measure’s lifespan (low and high capital costs), therefore justifying the capital investment based on the energy saving calculated with high and low capital costs of wall insulation.

A cost-benefit strategy tends also to maximize the capital investment, hereby many energy efficiency measures, such as loft insulation to 300 mm (currently 70 mm or 100 mm) or solid wall insulation are not desirable under this strategy, calculated with high capital costs. For example, the solid wall insulation payback period ranges from 9 to 22.5 years, a long-term payback. These data are shown in Table 2.1.

	Capital Cost (£)		Annual savings (£/year)	Lifetime (years)	Lifetime saving (£)	Payback period (years)	
Retrofit measure	low[1]	high[1]				low[1]	high[1]
Loft insulation to 300 mm (currently 0 mm)	138	273	86.2	30	2586	1.6	3.2
Loft insulation to 300 mm (currently 50 mm or less)	137	254	38.21	30	1146	3.6	6.6
Loft insulation to 300 mm (currently 70 mm)	103	223	15.5	30	465	6.6	14.4
Loft insulation to 300 mm (currently 100 mm)	86	211	11.26	30	338	7.6	18.7
Loft insulation to 300 mm (currently 150 mm)	69	199	5.39	30	162	12.8	36.9
Loft insulation to 300 mm (currently 200 mm)	35	170	2.7	30	81	13.0	63.0
Cavity wall insulation (pre-1976)	300	325	80.1	40	3204	3.7	4.1
Cavity wall insulation (post-1976)	300	325	47.1	40	1884	6.4	6.9
Solid wall insulation	1309	3272	145.6	30	4368	9.0	22.5

[1] Low and high estimates of the capital costs of measures

Assumptions: No grant available. Take back: 30% of the energy savings. Payback calculations: simple return on investment calculation.

Table 2.1. Pay-back period for energy saving investments in the UK applied to a typical 3-bedroom semi-detached house. Source: Shorrock *et al.* (2005)

This cost-benefit strategy, combined with a slow-down in the rate of the installation of energy efficiency upgrades in buildings from 2013 onwards, has created a real challenge for meeting energy efficiency targets. Energy efficiency measures will tend to be less viable under a cost-benefit decision, as the ‘low hanging fruits’ have already been picked. For example, there is a high remaining potential for cavity wall insulation, loft insulation and solid wall insulation; however, a large proportion is considered hard-to-treat or unfillable. According to BEIS (2017) there are approximately 5.4 million homes across the UK without cavity wall insulation, 1.3 million of these are hard-to-treat homes. 8.1 million uninsulated lofts[15], of these, around 2.3 million are hard-to-treat or unfillable (ibid., 2017). Unfillable cavities mean the loft would be hard/costly to insulate or cannot be insulated (ibid., 2017).

Approximately one-third of properties have solid walls in the UK, which are also considered hard-to–treat, and the vast majority of these homes (7.8 million) have no wall insulation (ibid., 2017). See data in Table 2.2.

Energy efficiency measures	Insulated[1]	Uncertainty[2]	Remaining potential[3]	Remaining potential of which:		Total properties
				Easy to treat	Hard to treat	
Cavity wall insulation	13,291	504	5,444	4,120	1,324	19,239
Loft insulation	15,783	22	8,126	5,815	2,311	23,931
Solid wall insulation	718		7,785			8,502

1 Properties with full insulation.

2 Properties which may or may not have insulation.

3 This includes some properties with partial insulations. Not all remaining potential properties could be insulated or cost-effective to insulate.

Table 2.2. Remaining potential cavity wall insulation, loft insulation and solid wall insulation, December 2016. Source: Table 4.4, Table 4.5 and Table 4.6 from BEIS (2017).

Hard-to-treat [16] properties represent a real challenge for meeting energy efficiency targets, because they cannot be insulated in a cost-effective way

15 Lofts without at least 125 mm of insulation

16 ‘Hard to treat’ includes dwellings off the gas network, without loft and also high-rise flats. BRE (2008) *A study of hard-to-treat homes using the English house condition survey, Part 1 – dwelling and household characteristics of hard-to-treat homes*. London: Building Research Establishment Limited.

(BRE, 2008). Similarly, high-rise buildings (flats with more than six storeys), predominantly (78%) built post-war, can also be seen as hard-to-treat due to poor physical condition, lack of maintenance and lack of gas supply (BRE, 2008), in particular, buildings constructed from 1953 to 1972 (Beaumont, 2007). There are 326,000 dwellings in high-rise buildings, 4% of the total hard-to-treat stock (ibid., 2007).

2.2.3. Retrofit insulation for building envelopes

Retrofit insulation for building envelopes can be classified according to the types of wall construction; there are retrofit insulations aimed at solid-walled dwellings and cavity-walled dwellings (EST, 2010). Solid-walled dwellings usually have been built before the 1930s of masonry material with a wall width equal or greater than 9 inches (Hulme and Beaumont 2008 as cited in Milsom, 2014). External walls are made of brick, block, stone or flint without a cavity (DCLG, 2013). Cavity-walled dwellings have usually been built from the late 1920s onwards with two wall layers of masonry (brick or block) separated by a gap (a cavity) (EST, 2010)[17]. In mid-1970 the building regulations required a maximum wall U-value of 1.0 W/m2K (ibid., 2010). See the evolution of wall construction in Table 2.3.

Solid-walled dwellings

External wall insulation (EWI) and internal wall insulation (IWI) might both be suitable for solid-walled dwellings. Particularly external wall insulation might be a better option if it is desirable to keep the same internal space and improve the exterior appearance. In addition, EWI has a lower risk of moisture and condensation, and heat loss is slower than IWI. However, it tends to be more expensive than IWI and it can also have a significant impact on the appearance of the building, which may not be suitable for heritage buildings. It also has restrictions on the execution of work such as the weather. IWI tends to be cheaper;

[17] Although houses built after 1930 may have built with cavity walls.

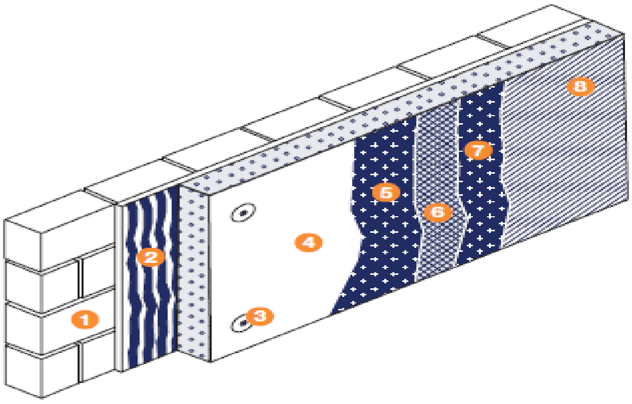
however, it might have problems with moisture build-up, condensation and cold bridges in the installation.

Time	Description
19th century	Houses walls of at least one-brick thickness Stone used for prestigious buildings or in areas where it was available.
1920s-1930s	Solid wall still dominates, but cavity wall became the accepted form of construction (cavity width 50 mm-100 mm)
1940s-1960s	Cavity width became standardised at 50 mm and mortars gradually became cement-based rather than lime-based. Also non-traditional construction (pre-cast frames, panels)
1970s-1980s	Insulation standards slowly improved. In 1972, a maximum 'U' value of 1.70 was introduced. In 1980, the maximum U value dropped to 1; this required lightweight blockwork in the inner leaf. From this period to the present day most lightweight blocks have been made from aerated concrete.
1990 onwards	Full-fill cavity-wall insulation is dominant (cavity width 50-100 mm)

Table 2.3. Evolution of wall construction in the UK. Source: based on Table 4 from EST (2010) and University of West England, 2009 (UWE, 2009).

External wall insulation (EWI)

EWI involves an insulation layer applied to the existing wall, and a protective render and/or decorative cladding (i.e. clays, stones, etc.) (EST, 2010). EWI usually is installed by a contractor (Milsom, 2014) and the system is approved by a suitable independent authority. The Insulated Render and Cladding Association (INCA) has a register of authorized contractors/systems (EST, 2010). In general, an EWI system consists of the following components: adhesive, fixing/mechanical anchors, insulation board, reinforcement base coats/embedded mesh/lath, primers and surface finishes, beads, trims and flashings (INCA, 2015). See Figure 2.1.



1) Substrate; 2) Adhesive if applicable; 3) Fixings; 4) Insulation board; 5) and 7) Base coat; 6) Embedded mesh; 8) Final finish.

Figure 2.1. Overview of an EWI system. Source: INCA (2015), pag. 6.

The main thermal layer is the insulation board in which various types of material are available such as: expanded polystyrene, phenolic, polyisocyanurate, mineral (Stone) wool/ glass wool, cork and wood fibre insulation (INCA, 2015). Table 2.4 shows the main descriptions of these insulation materials.

Material	Description
Expanded polystyrene	Lightweight, rigid, plastic foam insulation material.
Phenolic	Phenolic foam is closed cell insulation, formed by the evaporation of a high-performance blowing agent; it has good fire resistance properties, but is classed as combustible.
Polyisocyanurate (PIR)	PIR foam is closed cell insulation; it has good fire resistance properties, but is classed as combustible.
Mineral (Stone) Wool/ Glass Wool	Manufactured from molten rock or silica sand heated and blown to form thin fibres with binders and oils. Excellent fire resistant properties, classed as non-combustible.
Cork	Cellular structure which makes it a natural insulator. It has good fire resistance properties, but is classed as combustible.
Wood Fibre Insulation	Manufactured from wood chippings and natural binders. It is both vapour permeable and hygroscopic.

Table 2.4. Description of insulation materials. Source: INCA (2015)

Internal wall insulation (IWI)

There are three main techniques for IWI: insulation that can be applied with rigid insulation plasterboards[18] (Figure 2.2) or between and across a studwork frame (Figure 2.3) (fitted between battens) or a combination of both (EST, 2010; Thorpe, 2013). Rigid insulated plasterboard can achieve a high-thermal performance and may include a water vapour barrier to avoid condensation (EST, 2010).

[18] e.g. thermal insulation board such as polystyrene or polyurethane.

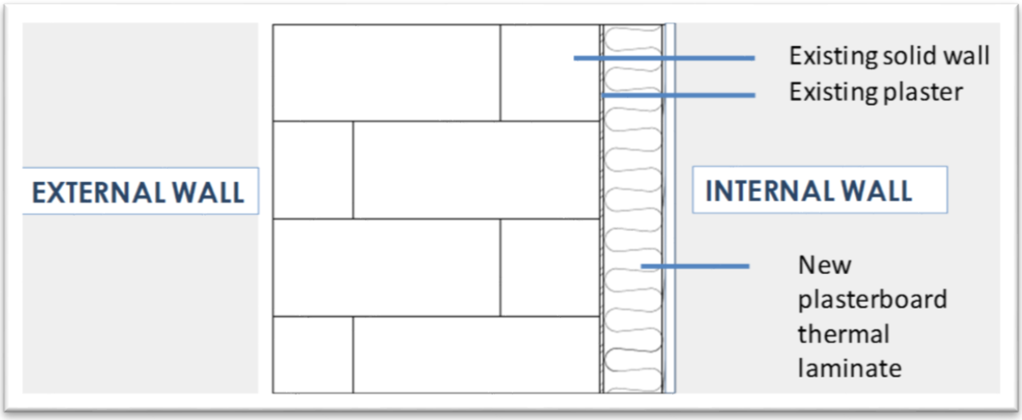


Figure 2.2. Rigid insulation plasterboard technique. Source. Based on Figure 1 from EST (EST, 2002)

The second technique, the insulation is fitted between and across a studwork frame, which can be made of timber or steel (EST, 2002). Once the insulation has been installed, a new sheet of plasterboard is then fitted to the battens (Milsom, 2014). Materials such as polystyrene, polyurethane or mineral wool (or similar) can be used to insulate (ibid., 2014). See Figure 2.3.

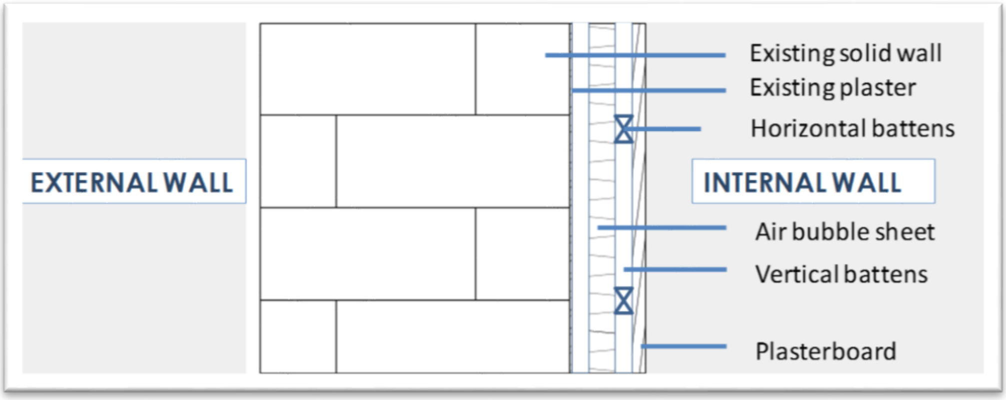


Figure 2.3. Studwork frame insulation, fixed to battens and counter-battens. Based on Figure 5 from EST (EST, 2002).

Cavity-walled dwellings

Cavity wall insulation for cavity-walled dwellings is considered the most cost-effective insulation measure (EST, 2010). Unfilled cavity walls are filled to reduce the heat loss through the walls (ibid., 2010). Materials such as blown mineral wool (rock wool or glass wool) and bonded polystyrene beads are suitable to be injected into the cavity (Milsom, 2014).

2.2.4. Building retrofit thermal performance metrics

Thermal performance of insulation materials is often represented by physical metrics such as the U-value. Thermal transmittance or the U-value can be defined as the "*Heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a system*" (British Standards Institution, 1996, p. 5). The rate of heat transfer is expressed in W/m²K (i.e. watts of heat lost per square metre per degree). U-values are used to describe the tendency of walls to lose heat. This value tells how well an element (e.g. windows, walls) insulates, thus a well-insulated wall will have a low U-value. According to ISO 7345 (British Standards Institution, 1996) the U-value is calculated using the following equation:

$$U = \frac{\boldsymbol{\Phi}}{(\boldsymbol{T1}-\boldsymbol{T2})\boldsymbol{A}} \qquad \text{Equation 2-1}$$

Where:
A = area (m^2);
T1 and T2 are the reference temperatures (K);
Φ = the rate of heat loss (W).

Although U-value measurement can be obtained by measuring the difference in temperature on both sides of the wall under steady state conditions, for existing walls a simplified procedure for U-value calculation (thermal transmittance) can be implemented for thermally homogenous or inhomogeneous layers, which may contain air layers up to 0.3 m thick and metal fasteners (British Standards Institution, 2017).

For a homogeneous layer the thermal resistance of a component is calculated as:

$$\mathbf{R} = \frac{\mathbf{d}}{\boldsymbol{\lambda}} \qquad \text{Equation 2-2}$$

Where:

R = thermal resistance of a component in m^2K/W;
d = thickness of the layer in the component;
λ = design thermal conductivity of the material.

And therefore:

$$U = \frac{1}{Rtot} \qquad \text{Equation 2-3}$$

Where:

U = thermal transmittance in W/(m2·K);
Rtot = the total thermal resistance in $m^2 \cdot K/W$.

As a wall can have different layers (i.e. brick, plasterboard, etc.) the total thermal resistance of consisting of homogeneous layers is calculated by the following expression:

$$Rtot = Rsi + R1 + R2 + ... + Rn + Rse \qquad \text{Equation 2-4}$$

Where:
Rsi = internal surface resistance; $m^2 \cdot K/W$;
R1, R2 ... Rn = the thermal resistances of each layer; $m^2 \cdot K/W$;
Rse = external surface resistance; $m^2 \cdot K/W$;

Standardised assumptions are used for U-value calculations of existing walls as published in Appendix S – SAP 2012 (BRE, 2014). For example, a 220 mm solid brick wall is assumed to have a U-value of 2.1 W/m^2K (see more detail in Table S6, BRE (2014)) and therefore an upgraded 220 mm solid brick wall will have a lower U-value. Table 2.5 provides an example of the change of U-values for an upgraded 220 mm solid brick wall using thermal laminated plasterboard or in-situ applied closed-cell insulation (typical thermal conductivity insulation of 0.035 W/mK).

Internal insulation thickness	U-values of insulated solid wall (W/m^2K)
25 mm	0.71
50 mm	0.47
75 mm	0.35
100 mm	0.28

Table 2.5. U-value of an upgraded 220 mm solid brick wall using thermal laminated plasterboard or in-situ applied closed cell insulation. Source: based on Table 5. EST (2010).

Moreover, Table 2.6 can be used as a guide to calculate U-values of upgraded walls, since it shows thermal conductivity using different insulation materials.

Material	Density (Kg/m^3)	Thermal conductivity (W/m^2K)
Mineral wool	50	0.038
Glass and mineral wool	15-30	0.040
Expanded Polystyrene Board (EPS)	16	0.038
Extruded Polystyrene (XPS)	35	0.030
Polyurethane (PUR)	30	0.025
Polyisocyanurate (PIR)	30	0.025
Phenolic foam	45	0.025
Cellular glass	120	0.04-0.05

Table 2.6. Thermal conductivity and density of insulation materials. Source: Table 1 from EST (2002).

2.2.5. Building retrofit regulations

Guidance on how to meet the thermal requirements of the building regulations when renovating existing residential dwellings in England are detailed in part L1B of Buildings Regulations – Conservation of fuel and power in existing dwellings (HM Government, 2015).

The requirement of this regulation is that:

> Reasonable provision shall be made for the conservation of heat and power in buildings by: limiting heat gains and losses – i) through thermal elements and other parts of the building fabric; and ii) from pipes, ducts and vessels used for space heating, space cooling and hot water services; ...
>
> (HM Government, 2015, p. 5).

The L1B regulation sets energy efficiency requirements where renovation work is at least 50% of a thermal element or 25% of the entire building envelope (HM Government, 2015). Renovation of thermal elements (i.e. wall, floor or roof), is either provided by a new layer or the replacement of an existing layer, but it does not include windows, doors, roof windows or roof-lights (ibid., 2015).

A new layer could include the following activities: cladding, rendering, plastering or dry-lining a thermal element, while an existing layer could be replaced by stripping down the thermal elements and then rebuilding it to achieve the thermal performance or replacing the waterproof membrane on a flat roof (HM Government, 2015).

Table 2.7 shows the minimum standards for heat loss that need to be achieved for upgrading walls, floors and roofs. For example, if the existing U-value of a wall is over 0.70 W/m^2K (the U-value threshold), the improved U-value should be equal or less than 0.3 W/m^2K for external or internal insulation (the lower the U-value the better). Nevertheless, if it is not technically, functionally or economically feasible to meet the standard given in Table 2.7, the thermal element should be upgraded to a lower possible U-value achievable within a 15 year payback. In addition, traditional and historic buildings are exempt from complying with Part L of the Buildings Regulations in situations where it would be detrimental to the character and appearance of the building.

Retrofit measures	Threshold U-value W/(m^2*K)	Target U-value W/(m^2*K)
Wall – cavity insulation	0.70	0.55
Wall – external or internal insulation	0.70	0.30
Floor	0.70	0.25
Pitched roof – insulation at ceiling level	0.35	0.16
Pitched roof – insulation at rafter level	0.35	0.18
Flat roof or roof with integral insulation	0.35	0.18

Table 2.7. Minimum standards for heat loss that need to be achieved for upgrading walls, floors and roofs in Building Regulations part L1B – Conservation of fuel and power in existing dwellings. Source: Table 3 – Upgrading retained thermal elements (HM Government, 2015).

2.2.6. Building regulations compliance/SAP

The Government's Standard Assessment Procedure (SAP) is predominantly used for assessing compliance with Part L1 of the Building Regulations (HM Government, 2015). SAP ratings range from 1 to 100, so that a rating of 100 is then converted into a letter grade from A to G (ibid., 2014). The higher values or first letters (e.g. 100 or A) represent the most energy efficiency dwellings. SAP is a physics-based methodology that gives an output of energy use taking into account of factors such as floor area, heating system and thermal performance of the fabric. SAP calculation is based on the BRE Domestic Energy Model and is consistent with the standard BS EN ISO 13790 (BRE, 2014). SAP calculates different energy ratings such as the annual energy cost, the environmental impact rating (based on CO_2 annual emissions) and the dwelling's CO_2 emission rate (BRE, 2014). See rating bands in Table 2.8.

Rating	Band
1 – 20	G
21 – 38	F
39 – 54	E
55 – 68	D
69 – 80	C
81 – 91	B
92 or more	A

Table 2.8. SAP rating bands. Source: '*Table 14: Rating bands'* (BRE, 2014).

The annual energy costs are associated with space heating, water heating, ventilation and lighting, and fewer cost savings from energy generation technologies (BRE, 2014). For example, space heating consumption is calculated by multiplying the dwelling's fuel consumption by appropriate factors (e.g. heat from biomass boilers in a community heating scheme is assumed to have a cost of 3.78 p/kWh).

The annual energy cost is converted to the SAP rating [19], which enables comparability of properties based on physical factors, which is independent of occupant behaviour (such as heating demand temperatures and heating periods), climatic inputs, the number of people in the building or ownership of domestic appliances.

As much of this thesis is concerned with determining the changes of internal air temperatures following retrofit, it is important to understand how SAP calculates the mean internal temperature. Calculation of the mean internal temperature for each month is based on pre-defined heating patterns, in which the average temperature is obtained separately for the living area (zone 1) and elsewhere (Zone 2) (BRE, 2014). The demand temperature (Th1) in the zone 1 is 21ºC and the zone

[19] ECF = deflator × total cost / (TFA + 45);
if ECF >= 3.5, SAP 2012 = 117 – 121 x log10 (ECF);
if ECF < 3.5, SAP 2012 = 100 – 13.95 x ECF
where TFA is the total floor area, m² and ECF is the energy cost factor.

2 demand temperature (Th2) assumes that it is usually cooler than zone 1, which may vary depending on the heating system (i.e. for boiler systems with radiators or under-floor heating, Th2 = 21 – 0.5 HLP[20]) (ibid., 2014).

2.3. Predicting energy saving from building retrofit insulation

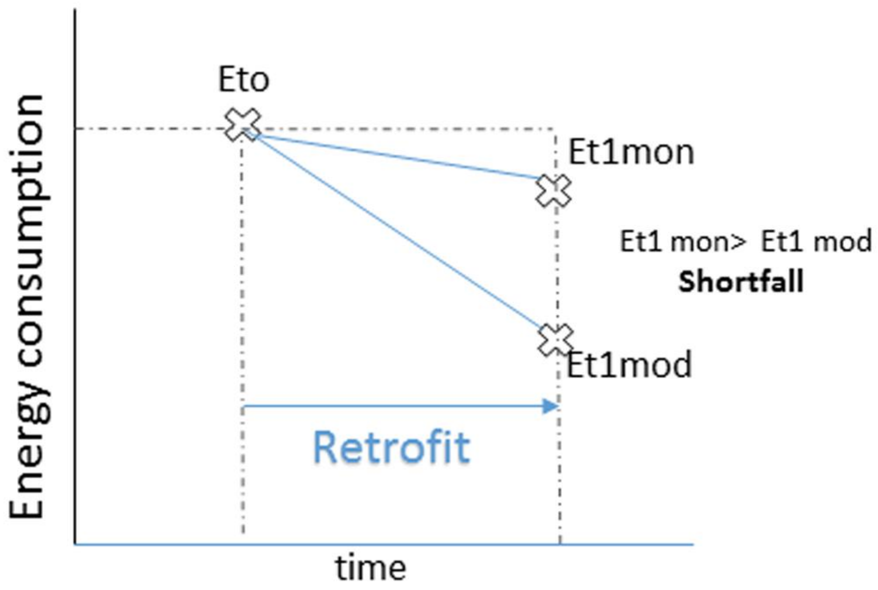
The Warm Front scheme (Hong *et al.*, 2006; Oreszczyn *et al.*, 2006; Hong *et al.*, 2009) offered one of the main insights into the shortfall in the residential retrofit programmes. The programme consisted of providing grants to vulnerable households for the installation of cavity-wall insulation, loft insulation, draught proofing and heating system. Engineering-based estimates based on BREDEM model algorithms predicted a theoretical decrease in the energy consumption of 25%-35% after the upgrade. However, the monitored space heating consumption pre-and post-intervention found that the energy efficiency measures had little impact. The authors attributed this discrepancy, between the modelled and monitored results, to errors in the monitored data or the simplicity of the model.

Errors in the monitored space heating consumption were attributed to the disaggregation of the heating consumption (space heating and non-space heating consumption) or to the use of non-utility fuel-based heating systems (not measured accurately) or to the construction of the average internal air temperatures of zone 2 (rest of the house apart of living room) based on bedroom temperature. The simplicity of the model means that the theoretical model, for predicting the energy use, simplified the occupant's behaviour. For example, the authors highlighted the ventilation rate predictions, which were assumed to be dependent on the physical characteristics of the dwellings; however, in practice, ventilation parameters depend also on internal and external temperatures.

Other factors might also be incomplete insulation filling of exterior wall and loft spaces, or a lower efficiency of the heating system compared with laboratory efficiency tests, due for example to uninsulated under-floor piping or the incorrect installation of boilers and heating controls.

[20] HLP = Heat Loss Parameter, (W/m^2K).

The difference between the actual saving achieved from the energy efficiency measures and that estimated from theoretical models has been termed shortfall by Sorrell *et al.* (2009). Figure 2.4 shows the shortfall diagram. In general, the known reasons for the shortfall are the occupant factors with the remainder due to other factors, such as equations (e.g. mathematical models of heat transfer), input parameters of the physical-based models (e.g. baseline U-values) and technical failures (i.e. installation, performance of equipment) (Sanders and Phillipson, 2006; Sorrell *et al.*, 2009).



Eto: energy consumption time 0. Et1 *mon*: monitored energy consumption time 1. Et1 *mod*: modelled energy consumption time 1.

Figure 2.4. Shortfall diagram.

This section reviews evidence about the following factors that might create discrepancies between energy modelling predictions and actual energy savings, pre- and post-retrofit:

- Miscalculation of physics-based models (mathematical models of heat transfer and input parameters of the physical-based models and Pre-bound effect);

- Technical failures;

- Occupant factors;

- Temperature take-back.

2.3.1. *Miscalculation of physics-based models*

It has been established that standard physical models overestimate the energy savings from energy efficiency improvements in household heating systems by one half or more in low-income households (Sorrell *et al.*, 2009). This review compiles evidence about three sources of discrepancy in the calculation of predicted performance compared to the actual savings pre- and post- retrofit: mathematical models of heat transfer, input parameters of the physical-based models and the pre-bound-effect.

Mathematical models of heat transfer

Physics-based models estimate the energy heating demand by using physical laws such as heat transfer. The mean rate of heat output over a period is estimated by BREDEM-12 (Anderson *et al.*, 2002) by using the following equation, which shows the balance between heat losses against gains:

$\Phi = H\,(Tint - G/H - Text)$ Equation 2-5 [21]

Where:
- Φ is the mean daily heat output from the heating system (W);
- Tint is the mean internal temperature (˚C);
- G is the mean useful gains (W) (e.g. internal gains are due to water heating, cooking, use of lights, appliances and metabolic gains, external gains are due solar gains);
- H is the specific heat loss for the dwelling (W/˚C);
- Text is the mean external temperature (˚C).

If there were no heating (heat output from the heating system) the internal temperature would be higher than the external temperature due to external and internal gains.

$G = H\,(Tint - Text)$ Equation 2-6 [22]

---

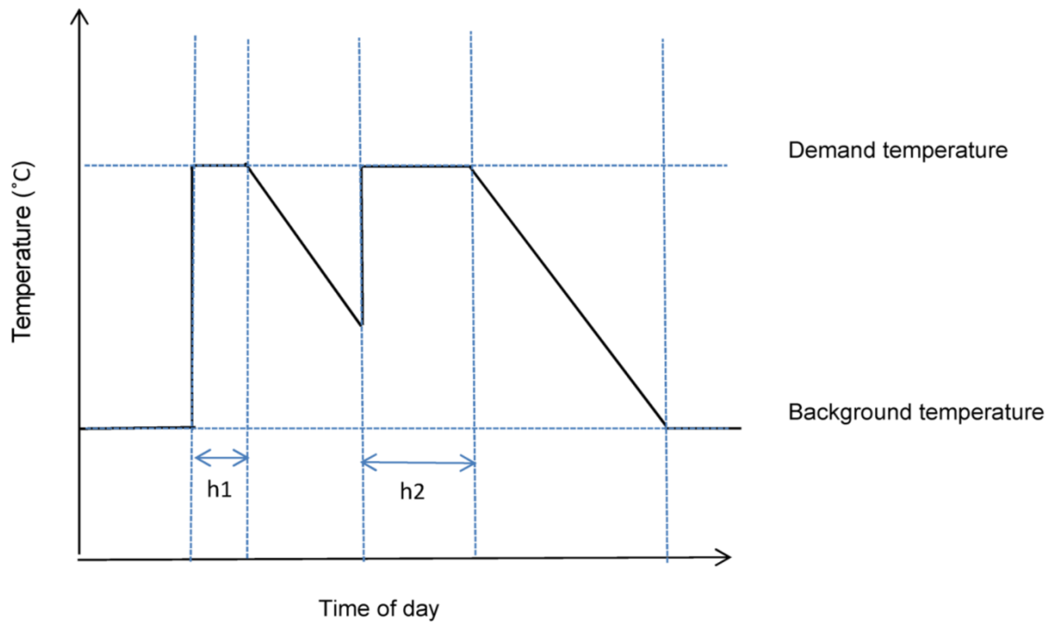
[21] BREDEM Anderson, B.R., Chapman, P.F., Cutland, N.G., Dickson, C.M., Doran, S.M., Henderson, G., Henderson, J.H., Iles, P.J., Kosmina, L. and Shorrock, L.D. (2002) *BREDEM-12 Model description: 2001 update*. Garston, Watford, UK.

[22] BREDEM ibid., 2002.

Tint = G/H + Text   Equation 2-7[23]

Space heating is needed to raise the internal temperature (Tint) to the desired internal temperature (Anderson *et al.*, 2002). In theory, with a steady state condition, the space heating needed to raise the internal temperature to the desired internal temperature should be less following building fabric, as the heat loss for the dwelling (H) decreases[24]. BREDEM will assume a fixed heating demand temperature and periods. For zone 1, the living room, the heating demand temperature (thermostat heating) is 21°C, while the heating period is 9 hours on weekdays (07:00-09:00 hrs, 16:00-23:00 hrs), and 16 hours at weekends (07:00-23:00) (Anderson *et al.*, 2002; Huebner *et al.*, 2013a). Outside these time periods the heating is assumed to be off (Anderson *et al.*, 2002; Huebner *et al.*, 2013a) (see Figure 2.5).

For estimating potential savings from retrofit interventions, the same heating demand temperature is assumed for before and after retrofit. Thus, in theory, the space heating needed post-retrofit to raise the internal temperature to the desired internal temperature should be less than pre-retrofit. Therefore, for example: gas use for home heating may be reduced by insulating the walls or roof.



[23] BREDEM ibid., 2002.

[24] Changes in the cooling rate following retrofit are not reviewed for simplicity.

Figure 2.5. Internal temperature profile used in BREDEM-based model. Source: reproduced from figure 10.1 of BREDEM-12 (Anderson *et al.*, 2002).

Therefore BREDEM's 'standardised' occupant influence assesses the building's performance independently of occupant effects (Huebner *et al.*, 2013a). In practice, however, there is not a fixed heating demand. Heating demand temperature and heating periods following retrofit may be higher or lower depending on how people actually use heating.

Input parameters

Another source of error of the physics-based models is the input parameters such as the fabric and ventilation heat loss. For example, Milsom (2014) reviewed evidence from different studies to understand how the heat is lost through solid walls. The review pointed out that the difference between predicted and experimental behaviour of walls in existing dwellings is due to erroneous representations of the baseline performance (ibid., 2014). The review highlighted that the U-value of materials determined from the current methodology and the influence of moisture content may not be able to represent the baseline performance of materials, in particular pre-1919 dwellings and traditional buildings (ibid., 2014).

Pre-bound effect

Regarding the difference between the actual savings achieved from the energy efficiency measures and that estimated from the physics-based models, Galvin and Sunikka-Blank (2013) noted that this can also be attributed to a smaller energy consumption prior to the upgrade. The authors noted that German occupants consume, on average, 30% less heating energy than predicted by theoretical models (as physical-based models); this has been termed the pre-bound effect (Sunikka-Blank and Galvin, 2012).

The pre-bound effect is defined as "*the tendency to consume less energy than the calculated rating*" (Galvin and Sunikka-Blank, 2013, p. 76). This is referred to as "*the situation before a retrofit, and indicates how much less energy is consumed than expected. As retrofits cannot save energy that is not actually being consumed…*" (Sunikka-Blank and Galvin, 2012, p. 265).

The authors particularly reported that low-income occupants, in poorly insulated dwellings, consume less energy prior to the upgrade than the predicted energy consumption using normative assumptions (Galvin, 2015).

2.3.2. Technical failures

Other factors that may cause the difference between predicted performance compared to the actual saving following retrofit insulation are the construction quality of the retrofit work (Milsom, 2014; Galvin, 2015). For example, some of the construction aspects studied are:

- Gaps in the insulation (Galvin and Sunikka-Blank, 2014), for example, the insulation gap in some areas of the walls (Hong, 2011);
- Building skills (Galvin, 2015) that may affect, for example, the specifications or the execution of details at junctions (Milson, 2014).

A significant technical error in the construction could jeopardise the achievement of the predicted saving. Both the design and the implementation of quality control systems are central to 'bridge the gap' between predicted fabric performance and actual savings.

2.3.3. Occupant factors

Occupant behaviour can be seen as "*The proportion of the change in internal temperature that derives from adjustments of heating controls and other variables by the user (e.g. opening windows), or the reduction in energy savings associated with those changes*" (Sorrel *et al.*, 2009, p.1358). Therefore, it covers occupants' adaptive actions such as opening/closing windows, putting on/taking off clothing layers, adjusting solar shading, drinking warm fluids, switching on/off heating and adjusting heating controls (e.g. adjusting thermostat controls, zoning controls, how many rooms are heated, etc.).

Occupant behaviour has an influential effect on energy consumption, therefore unrealistic occupant behaviour parameters embedded in the theoretical models might lead to a difference between the actual and the estimated energy savings from retrofit interventions. For example, standardised occupant behaviour parameters such as the use of a fixed temperature in the theoretical models for all insulation levels leads to an inaccurate predictions of energy savings, when for example, a pre-intervention internal temperature of 18°C is assumed in poorly insulated dwellings (Deurinck *et al.*, 2012). Furthermore, the ways that users achieve comfort in the houses differ from occupants, for example, opening windows to provide fresh air during winter while having the heating system switched on (Sharpe and Shearer, 2012).

2.3.4. Temperature take-back

In terms of household heating, the term temperature take-back has been used to explain the predicted energy consumption saving converted into an increase of internal temperature. Temperature take-back is defined as "*the change in mean internal temperatures following the energy efficiency improvement, or the reduction in energy savings associated with that change"* (Sorrell *et al.*, 2009, p. 1358).

Previous studies have showed the temperature take-back, especially in poorly insulated houses (Hong *et al.*, 2006; Hong, 2011; Shipworth, 2011), ranges from 0.4°C to 0.8°C (Sorrel, 2007). However, temperature take-back cannot be equated with occupant behaviour, since only a part of temperature take-back is accounted for by the occupant's behavioural change and the remainder by the physical factors. (Sorrell, 2007; Sorrell *et al.*, 2009).

2.3.5. Summary of the difference between predicted performance and actual saving

This section explained the difference between predicted performance and actual saving based on: (i) miscalculation of physics-based models due to heat-loss equations, input parameters (e.g. U-values) and lower pre-retrofit energy uses than estimated (Pre-bound effect); (ii) technical failures affecting construction quality of the retrofit work; (iii) occupant factors, in which unrealistic occupant parameters embedded in theoretical models lead to a difference between the actual and the estimated energy savings from retrofit interventions; and (iv) temperature take-back.

2.4. Research Assumptions

2.4.1. Energy consumption saving and temperature take-back

The study's primary assumption is that the reduction in energy-consumption savings through temperature take-back exists and can be observed. This is based on previous quantitative studies, for example Sorrell (2007) brought together a meta-review of 15 quasi-experimental studies of household heating consumption and concluded that the temperature take-back ranged from 0.4°C to 0.8°C. Hence, this may imply that a 1°C increase of the internal temperature led to approximately 10% of space heating consumption (Sorrell, 2007).

Oreszczyn *et al.* (2006) reported from a Warm Front Scheme study that heating and insulation measures increased internal temperatures by 1.6°C in living rooms (day time) and 2.8°C in bedrooms (night time) (under standardized external temperature of 5˚C). Hong (2011), also from a Warm Front study, reported that following the energy efficiency upgrades the internal air temperature increased by 1.6°C and fuel consumption increased by 12%. The mean standardised internal temperature varied depending on the energy efficiency measure type as follows: with full insulation by 0.73°C (95% CI: 0.26, 1.20), central heating by 2.28°C (95% CI: 1.81, 2.75) and full insulation and central heating by 3.11°C (95% CI: 2.25, 3.98)[25] (Hong, 2011) .

[25] Summarised from Table 8.3, a comparison of mean monitored standardized internal temperature ('Tmon'), p.185, Hong (2011). Full insulation criteria = full cavity-wall insulation (≥50mm) + full loft insulation (≥100mm) (Hong, 2011, p.68).

2.4.2. *Temperature take-back and low-income dwellings*

Several studies have proposed that temperature take-back is usually higher in dwellings occupied by low-income householders (Milne and Boardman, 2000; Sorrell, 2007). One suggested reason is that financial constraints would lead to low pre-intervention temperatures (Milne and Boardman, 2000). This, combined with a post-intervention increase of the internal temperature as a result of the unfulfilled demand, would lead to a higher temperature take-back. Milne and Boardman (2000) suggested that in low-income dwellings the potential energy-consumption saving is achieved when pre-intervention internal temperatures are around 19˚C-20˚C. Milne and Boardman's results are reproduced in Table 2.9, where pre-intervention temperatures are shown along with the % of theoretical energy-consumption saving achieved.

The relationship between household income and temperature take-back is not always apparent and could be also confounded by pre-intervention internal temperatures (Sorrell *et al.*, 2009). Therefore, pre-intervention internal temperatures may be the underlying factor that explains temperature take-back rather than low income.

Pre-intervention temperature (◦C)	Theoretical energy-consumption saving (%)
14	54
16	66
18	78
20	90

Table 2.9. Pre-intervention temperatures and theoretical energy-consumption savings from p.420 of Milne and Boardman (2000).

2.4.3. Temperature take-back and saturation effects

Temperature take-back may operate independently of socio-economic characteristics when internal air temperatures saturate (approaching 21ºC). Sorrel suggested that temperature take-back decreases owing to the saturation effect when pre-intervention temperatures saturate (approaching 21ºC) (Sorrell, 2007). In other words, adding more energy efficiency to the household will, at some point, when internal temperatures approach a maximum level for thermal comfort, yield lower incremental energy-consumption saving. This has been conceptualised as the saturation effect, which is defined as:

> The reduction in the pace of increase in the level of service required, as the gap between the effective level of service and the comfort level is reduced (e.g. when the effective heating temperatures reaches 22°C)
>
> (Maxwell *et al.*, 2011, p. 34).

The saturation effect does not imply that adding more energy efficiency will not decrease the energy consumption for space heating, rather it may imply that it is negligible in absolute terms.

2.4.4. Temperature take-back and CO_2 savings

Some authors have also noted that the reduction of the energy savings associated with the extra warmth obtained from energy efficiency improvement might have a detrimental influence on the cost per tonne of CO_2 saved. Jenkins (2010) estimated that a reduction of 30% of energy consumption saving through temperature take-back will lead to an increase between £3,220/tCO_2 and £14,640/tCO_2 saved.

2.4.5. Temperature take-back, and the relationship between physical factors and occupant's behaviour factor

Research studies have theorised that a part of the temperature take-back is accounted by the physical factors (i.e. building fabric retrofit insulation and heating system) and the remainder by the occupant's behavioural change (Sanders and Phillipson, 2006; Sorrell, 2007). Sorrel, for instance, estimated that temperature take-back appeared to average between 0.4ºC and 0.8ºC, of which physical characteristics accounted for nearly half and behavioural change for the reminder (Sorrell, 2007).

2.4.6. Temperature take-back and occupant's behaviour factor in the retrofit context

In the retrofit context research studies have theorised that physical and occupant behaviour factors form a complex system whose interactions change and co-evolve afterwards (Lowe *et al.*, 2012; Love, 2014). So far, not enough empirical studies have been carried out to identify interaction changes in the occupants' behaviour following fabric retrofit, as a result of temperature take-back.

Lomas (2010), based on the CaRB projects[26] reported that the evidence is not conclusive to understand the relationship between temperature take-back and occupant behaviour in houses with double-glazing and draught stripping. The increase in internal temperature can be explained by the physical fabric (as the dwelling can be more easily heated) or higher space temperatures increased by occupants (Lomas, 2010).

Other evidence has appeared from studies of how people's lives might improve following energy efficiency upgrades. They have proposed that, as a result of the 'extra warmth', occupants may adjust the use of space. Gilbertson *et al.* (2006), for example, reported that the warmer environment achieved through the Warm Front Scheme improved social interaction, wellbeing and the use of space was expanded during the cold months. Another author also has observed that, after energy efficiency upgrades, rooms became warm enough to perform different activities. Galvin and Sunnika-Blank reported that at least half of the people interviewed were

[26] Carbon Reduction in Buildings (CARB) is a socio-technical, longitudinal study of carbon use in buildings.

occupying their dwellings more intensively (Galvin and Sunnika-Blank, 2014a, as cited in Galvin, 2015).

The change in the use of space in old houses in Britain is denoted by Galvin (2015) in the following quotes:

> – "*one [household] had installed an electric heater in a loft, as this [loft] had become useable as a workroom now that the ceiling was insulated*" (Galvin, 2015, p. 17);
>
> – *"A large Victorian home with two occupants was now heated throughout in every room, and daily activities had expanded to fill most of the house. A room with a piano was used more frequently because the householder could play without his fingers 'freezing'* " (Galvin, 2015, p. 17).

For example, studies concerned with fuel poverty have suggested that people tend to turn the heating down and/or limit heating to certain rooms to minimise fuel bill expenditure (Anderson *et al.*, 2010).

Regarding other adaptive actions such as wearing more or fewer clothes when energy-efficient measures are introduced, it has been reported that the level of clothes[27] was slightly reduced with the introduction of energy efficiency upgrades (Hong *et al.*, 2009).

Regarding heating usage, Love (2014)[28] reported that thermal comfort was achieved with fewer hours of heating per day, demand temperature increased and daily heated hours shortened following retrofit.

It should be noted that further research is needed, as it is not possible to discern from the current literature whether retrofitting might change the occupants' use of

---

[27] In comparison with the control group, the mean clothing insulation level was 0.07 less in dwellings that were fully insulated and centrally heated (Hong, 2011).

[28] Study of 19 retrofitted social dwellings.

space or heating usage or other adaptive actions. Different retrofit measures need to be evaluated with different socio-economic groups.

2.4.7. Summary of the research assumptions

This section sought to understand better the several assumptions related to temperature take-back and energy consumption. In addition, it also sought to understand how occupants might respond to the introduction of energy efficient measures in the domestic sector.

This section proposed that temperature take-back exists and can be measured. This is based on evidence of other studies in which temperature take-back ranged from 0.4°C to 0.8°C (Sorrell, 2007). This section also reviewed the temperature take-back assumption in dwellings occupied by low-income householders, in which temperature take-back tended to be higher. This is based on the premise that financial constraints in low-income dwellings would lead to low pre-intervention temperatures (Milne and Boardman, 2000) combined with a post-intervention increase of temperature as a result of the unsaturated demand. The relationship between household income and temperature take-back is not always apparent and could also be confounded by pre-intervention internal temperatures (Sorrell et al., 2009). Therefore, pre-intervention internal temperatures may be the underlying factor that explain temperature take-back rather than low income. Temperature take-back may operate, therefore, independently of socio-economic characteristics when pre-intervention temperatures saturate (approaching 21ºC). This effect is known as the 'Saturation effect' (Sorrell, 2007).

Temperature take-back is accounted for by the physical factors (i.e. building fabric retrofit insulation and heating system) and the remainder by the occupant's behaviour. Indeed, in the retrofit insulation context physical and the occupant's behavioural factors are linked, forming a complex system (Lowe et al., 2012; Love, 2014). It was not possible to answer whether energy-efficient measures are likely to change the occupants' behaviour and the extent to which this might impact their energy use. Some qualitative evidence includes, but is not limited to, changes in the use of space and adaptive actions. However, the evidence is not conclusive to identify interaction changes in the occupants' behaviour following fabric retrofit, as a result of temperature take-back.

2.5. Main Theoretical Approaches

This section provides a summary of the main theoretical approaches that might be used to explain the reason for temperature take-back in the domestic sector such as: economic, engineering/ physics-based model approaches and thermal comfort models. This section also reviews work in this area undertaken by previous research using the quasi-experimental approach and presents the rationale for the selection of the quasi-experimental approach used.

2.5.1. Physics-based model approach

The physics-based model approach, also known as 'Engineering models approach' estimates the energy heating demand by using physical laws such as heat transfer. In the UK, the foremost physics-based models for estimating the residential energy demand belong to the BREDEM family (The Building Research Establishment's Domestic Energy Model) (Anderson *et al.*, 2002), forming the basis of the Standard Assessment Procedure (SAP) (Kavgic *et al.*, 2010; Huebner *et al.*, 2013a). It is also the most widely used model for estimating potential savings from retrofit interventions. BREDEM models work with a series of heat-balance equations in steady state conditions (see detail in Section 2.3.1) and other algorithms to estimate the residential energy consumption. For example, energy consumption of lights and appliances are based on floor area and the number of occupants (Kavgic *et al.*, 2010). This type of model is applied to the national and individual dwelling scales (Love, 2014).

Other physics-based models share also the BREDEM core calculation engine such as, for example, BREHOMES (Shorrock and Dunster, 1997), the UK domestic carbon model (UKDCM) (Boardman *et al.*, 2005) and DECarb (Natarajan and Levermore, 2007). BREDEM has a modular structure which gives flexibility to upgrade some parts to suit particular needs. At the national scale, engineering models have been used to evaluate the uptake of energy efficiency measures

(Shorrock and Dunster, 1997; Natarajan and Levermore, 2007), showing that the energy efficiency technologies could play a central role in delivering a reduction in the carbon dioxide emissions of the domestic sector.

This type of model is applied at the national and individual dwelling scales (Love, 2014). For instance, at the national scale this approach can be seen in the uptake of energy efficiency measures (Shorrock and Dunster, 1997; Natarajan and Levermore, 2007), showing that the energy efficiency technologies could play a central role in delivering a reduction in the carbon dioxide emissions of the domestic sector, but this is a theoretical potential, so the real potential is likely to be much less since the main drawback of the physics based approach is that it does not capture appropriately the occupants' behaviour. For example, (Sorrell *et al.*, 2009) suggested that physical models overestimate the energy savings from energy efficiency improvements in household heating systems by one half or more in low-income households.

2.5.2. Thermal comfort models

Thermal comfort is defined as the "*... condition of mind which expresses satisfaction with the thermal environment*" (Fanger, 1970, p. 13). Principally, two types of model have analysed thermal comfort: predictive (thermal physiology[29]); and adaptive models (Humphreys *et al.*, 2007). Predictive models simulate the thermal sensation of occupants based on the principles set by the heat balance in the human body. Fanger (1970) model, one of the most notable predictive models, proposes that the human body is in a state of equilibrium; the following quote describes the main principle.

> … the purpose of the thermoregulatory system of the body is to maintain an essentially constant internal body temperature, it can be assumed that for long exposures to a constant (moderate) thermal environment with a constant metabolic rate.
>
> (Fanger, 1970, p. 22).

[29] Humphreys uses the term thermal physiology to refer to predictive models.

Fanger (1970) summarises the heat balance in the following equation:

$$H - Ed - Esw - Ere - L = K = R + C \qquad \text{Equation 2-8}$$ [30]

Where:

H = the internal heat production in the human body;

Ed = the heat loss by water vapour diffusion through the skin;

Esw = the heat loss by evaporation of sweat from the surface of the skin;

Ere = the latent respiration heat loss;

L = the dry respiration heat loss;

K = the heat transfer from the skin to the outer surface of the clothed body;

R = the heat loss by radiation from the outer surface of the clothed body;

C = the heat loss by convection from the outer surface of the clothed body.

Fanger's model predicts a thermal sensation with the Predicted Mean Vote (PMV) index, which is a function of activity (kcal/hrm^2), clothing (clo), air temperature (°C), mean radiant temperature, relativity air velocity (m/s) and air humidity (mmHg). The thermal sensation prediction of thermal comfort is quantified by a 7-point scale with values ranging from -3 to +3 (cold to hot, including 0 neutral).

The recommended categories for the design of mechanically heated and cooled buildings from the International Standard ISO 7730 (British Standards Institution, 2005) are summarised in Table 2.10.

[30] Fanger, P.O. (1970) *Thermal comfort. Analysis and applications in environmental engineering*. Copenhagen: Danish Technical Press

ISO 7730 Category	Range of PMV	PPD (%)
A	−0.2 < PMV < +0.2	< 6%
B	−0.5 < PMV < +0.5	< 10%
C	−0.7 < PMV < +0.7	< 15%

Table 2.10. Range of PMV and PPD by building categorizations in ISO 7730:2005 (British Standards Institution, 2005).

A major limitation of the predictive model is that, in practice, thermal comfort is not steady; people adapt their environment to feel comfortable, especially when they have control over their thermal comfort, as in the residential arena. In the residential arena people adapt their environment to feel comfortable using a wide range of possibilities such as opening windows and curtains, drinking cold/warm drinks, switching on/off heating and so on (Peeters *et al.*, 2009). This is not to say that they cannot be useful, but rather that it should be recognised that predictive models are not entirely suitable for the prediction of thermal comfort in a domestic context. For example, evidence presented by Hong *et al.* (2009) shows that there are variations between the model and the actual thermal comfort perception.

The adaptive approach model, on the other hand, implicitly builds on the hypothesis that occupants are able to change their comfort temperature (neutral) through adjustment of actions (Nicol *et al.*, 2012). In principle, adaptive models may be applied to the domestic sector; however, empirical data have not been collected on a large scale in the domestic sector to be applicable to residential buildings. For example, the acceptable indoor temperatures for buildings is specified in the standard EN 15251:2007 (British Standards Institution, 2007) for free-running buildings in Table 2.11. However, this Standard is only applicable for free-running buildings when thermal conditions are regulated by occupants (opening/closing windows and adding/reducing clothing layers), occupants are engaged in near-sedentary physical activities (1 to 1.3met[31]).

[31] Metabolic rate

Category	Upper limit *	Lower limit *
Category I	$\Theta_0 = 0.33\ \Theta rm + 18.8 + 2$	$\Theta_0 = 0.33\ \Theta rm + 18.8 - 2$
Category II	$\Theta_0 = 0.33 \times \Theta rm + 18.8 + 3$	$\Theta_0 = 0.33 \times \Theta rm + 18.8 - 3$
Category III	$\Theta_0 = 0.33 \times \Theta rm + 18.8 + 4$	$\Theta_0 = 0.33 \times \Theta rm + 18.8 - 4$

*To upper-margins (10˚C to 30˚C) and to lower-margins (15˚C to 30˚C). Θ_0 = limit value of indoor operative temperature, ˚C. Θrm = external running mean temperature, ˚C.

Table 2.11. Limits of the comfort zones by building categorizations EN 15251:2007 (British Standards Institution, 2007) for free-running buildings.

2.5.3. Economic approach

Econometric theory explores the effect of retrofit insulation on the reduction in energy saving under the so-called '*direct rebound effect*' (Sorrell *et al.*, 2009).

The direct rebound effect is defined as

> Improved energy efficiency for a particular energy service will decrease the effective price of that service and should therefore lead to an increase in consumption of that service. This will tend to offset the reduction in energy consumption provided by the efficiency improvement.
>
> (Sorrell and Dimitropoulos, 2008, p. 637).

The direct rebound effect is calculated as elasticities of demand, in which elasticity is a relation between two variables that are changing in relation to each other (e.g. energy consumption and energy efficiency). Two empirical relationships between the rebound effect and elasticities can be identified: direct rebound effect as efficiency elasticity and as price elasticity (Sorrell and Dimitropoulos, 2008). For example, the direct rebound as a consequence of the price effect can be estimated considering exogenous fuel prices (prices that householders pay to suppliers) or endogenous (prices that consumers pay per unit of energy services). (See equations in Annex A).

This approach has several advantages such as comparability from different areas (i.e. housing, transport, heating, etc.) using the concept of elasticity (Galvin, 2015). Econometric estimates for the direct rebound effect have provided comparable results, and it is considered as a robust methodology (Sorrell, 2007). However, the rebound effect depends upon how 'behaviour' is defined by the classic economic theory: i.e. consumers make 'rational' decisions and have complete information (Johnson, 1971; Nicholson, 2005). In addition, the rebound effect accounted as price elasticity follows contestable assumptions of 'symmetry' and 'exogeneity'. Symmetry relies upon the assumption that "*consumers respond the same way to increases (decreases) in energy prices as to decreases (increases) in energy efficiency*" (Sorrell and Dimitropoulos, 2008, p. 639). Furthermore, regarding 'exogeneity', the authors reported that "*most studies also assume that any change in energy efficiency derives solely from outside the model* (i.e. energy efficiency is 'exogenous')" (Sorrell and Dimitropoulos, 2008, p. 1362). However, in contrast, if energy prices are considered *endogenous,* the effect of the direct rebound may change as, for example, a householder may choose to heat, for example, unoccupied rooms.

2.5.4. Summary of the main theoretical approaches

Temperature take-back can be explained with different theories such as the physics-based, economic and thermal comfort models. The physics-based model suggests that the space heating needed to raise the internal temperature to the desired internal temperature should be less following the building's retrofit, as the heat loss for the dwelling decreases. The heating regime relies on a fixed schedule and demand temperature. Since the point of view of economic theories, consumers decide rationally to adapt their energy usage in response to price signals (Chatterton, 2011), therefore people might rationally decide to increase their thermal comfort level following retrofit. Thermal comfort models, such as the adaptive approach model, propose that people are able to change their comfort temperature (neutral) through an adjustment of actions. However, empirical data have not been collected on a large scale in the domestic sector to be applicable to the residential building.

2.6. Researching People and Buildings

2.6.1. Quasi-experimental approach

Due to the limitations given by the perspectives reviewed (economic, physics-based model and unsuitability of the actual thermal comfort models to predict domestic scenarios), other studies have followed the so-called physical paradigm approach. The physical paradigm does not predetermine the occupant influences; it is based on physical monitoring before and after the retrofit to measure the change of energy service demand and energy input. The physical monitoring, before and after the retrofit, is compared to a counterfactual scenario. The counterfactual helps to portray what demand 'would have been' in the absence of the upgrade (Sorrel, 2015) and its value should be obtained without the use of modelling to avoid error due to model miscalculation (such as the one described in the physics-based models). This approach has been termed Quasi-experimental by Sorrel (2007).

In the wider term a quasi-experimental study involves

> …to determine if a specific treatment influences an outcome. This impact is assessed by providing a specific treatment to one group and withholding it from another and then determining how both groups scored on an outcome … that use nonrandomized designs.
>
> (Creswell, 2009, p. 12).

Several researchers have studied the reduction in energy saving through the temperature take-back by using a quasi-experimental design such as Oreszczyn *et al.* (2006), Hong *et al.* (2006), Love (2014) and Hong (2011)[32]. For example, the UK's dwelling beneficiaries of the Warm Front programme were monitored for internal temperatures in the living room and main bedroom, for 2 to 4-week periods over two winters in five urban areas (Oreszczyn *et al.*, 2006). The cross-sectional[33] study compared temperatures in households that received retrofit insulation with those that have not received it (Oreszczyn *et al.*, 2006). Love (2014) used a quasi-

[32] Only the monitored part of the study can be considered as Quasi-experimental.

[33] This study was mainly cross-sectional.

experimental design to compare internal temperatures monitored before and after retrofit insulation in 13 social dwellings. Hong (2011) used fuel consumption data collected for 3 to 4 weeks and internal temperature data collected over two successive winters from the Warm Front programme to compare the effect of retrofit insulation before and after the retrofit.

Quasi-experimental studies have been useful to quantify the temperature take-back. Sorrell (2007), who brought together a meta-review of 15 quasi-experimental studies of household heating consumption, concluded that the temperature take-back ranged from 0.4°C to 0.8°C, of which physical characteristics accounted for nearly half and behavioural change for the reminder. This may imply that a 1°C increase of the internal temperature led to approximately 10% of space heating consumption.

However Quasi-experimental studies have been subject to criticism, in which the lack of a counterfactual scenario in the research study design was a common criticism or explicitly controlling for confounding variables (Sorrell, 2007). Further, use of small sample sizes, small periods of monitoring, multiple retrofit interventions and the self-selection of participants were also showed as barriers to applying the results of these interventions to wider populations (Sorrell, 2007).

2.6.2. Quasi-experimental approach and qualitative approach

This study uses an integrated approach; a quasi-experimental approach and qualitative approach. A quasi-experimental approach is used because this research is principally interested on the study of temperature take-back following an energy efficiency upgrade, accounted without predetermining the occupant influences. Design issues pointed out by Sorrell (2007) are considered in the Methodological Chapter 4. This study also uses a qualitative approach as it is interested in what are the effects of interaction between the physical and occupant’s behavioural change on space heating consumption following a retrofit. To date, the factors determining energy use in buildings are complex and often poorly understood (Oreszczyn and Lowe, 2010). Recent studies have suggested that this complexity is underpinned by the fact that physical and occupant behavioural factors form a complex system (Lowe *et al.*, 2012; Love, 2014).

2.7. Conclusion

Building retrofit is particularly important in the UK because most of the residential buildings were constructed before 1980 with relatively low levels of energy efficiency (Sweatman and Managan, 2010). The primary motivation for domestic retrofit insulation is the reduction of space heating energy use, thereby reducing CO_2 emissions. The second motivation for domestic retrofit is increasing the energy security through reduced space heating demand. The third motivation is the reduction of fuel poverty, caused by the combination of inefficient dwellings, high energy cost and low income.

Energy efficiency of dwellings is often represented using physical metrics such as the SAP rating and U-value. Similarly, normative models used to account for the energy heating savings from energy efficiency upgrades use physical laws such as heat transfer. However, there is a growing awareness of the difference between the actual savings achieved from the energy efficiency measures and those estimated from the theoretical models. This has been termed by Sorrell *et al.* (2009) as shortfall. The known reasons for the shortfall are the occupant factors with the remainder due to other factors, such as equations (e.g. mathematical models of heat transfer), input parameters of the physical-based models (e.g. baselines U-values) and technical failures (i.e. installation, performance of equipment) (Sanders and Phillipson, 2006; Sorrell *et al.*, 2009). Particularly, in terms of household heating, the term temperature take-back has been used to explain the predicted energy consumption saving converted into an increase in internal temperature.

This chapter proposed that temperature take-back exists and can be measured. This is based on evidence of other studies in which temperature take-back ranged from 0.4°C to 0.8°C (Sorrell, 2007). The reason for the temperature take-back can be explained with the different theories revised: physics-based models; economic approach; thermal comfort models; and the physical paradigm approach.

Physics-based models propose that space heating decreases when the heat loss for the dwelling decreases. This is because of the upgrade of the building fabric and the steady state conditions of the heating regime. The heating regime relies on a fixed schedule and demand temperature**.** From the point of view of economic theories, consumers decide rationally to adapt energy usage in response to price signals (Chatterton, 2011), therefore people might rationally decide to increase their thermal comfort level following a retrofit. Thermal comfort models, such as the adaptive approach model, propose that people are able to change their comfort temperature (neutral) through the adjustment of actions (Nicol *et al.*, 2012). However, empirical data have not been collected on a large scale in the domestic sector to be applicable to the residential building.

This study uses an integrated approach: a quasi-experimental approach (physical paradigm approach) and qualitative approach. A quasi-experimental approach is used because this study is principally interested on the study of temperature take-back following an energy efficiency upgrade, accounted without predetermining the occupant influences. This study also uses a qualitative approach as it is interested in what are the effects of interaction between the physical and occupant's behavioural change on space heating consumption following a retrofit.

Chapter 3. Research Methodology

3.1. Introduction

The Literature Chapter reviewed several assumptions related to temperature take-back and energy consumption and how occupants might respond to the introduction of energy efficient measures in the domestic sector (Section 2.4). The main theoretical approaches for assessing the benefits of domestic building energy efficiency initiatives were also revised to provide a theoretical framework for this research study (Section 2.5). The literature review concludes that temperature take-back exists and can be measured. This is based on evidence of other studies in which temperature take-back ranges from 0.4°C to 0.8°C (Sorrell, 2007). The reason for the temperature take-back can be explained with the different theories revised: physics-based model; economic approach; thermal comfort models; and the physical paradigm approach

This chapter describes the research methodology, which is one of the biggest challenges in this research as it has to balance the availability of data and resources with the theoretical framework. The research strategy and its justification are explained in this chapter, in which a quasi-experimental approach is proposed to be used, because this study is principally interested in the change of temperature take-back following an energy efficiency upgrade (Research Questions 1 and 2). This study also proposes to use a qualitative approach as it is interested in which the effects of the interaction between physical and occupant behavioural changes are on space heating consumption following a retrofit, which cannot be answered purely by a quasi-experimental design (Research Question 3) and why internal air temperatures change afterwards (Research Question 4).

This chapter also discusses why a case study is desirable (Section 3.3.1) and outlines why this case study focuses on social housing (Section 3.3.2). The ‘challenges’ in finding a suitable case study in Newcastle upon Tyne are described (Section 3.3.3). Further, Section 3.4 describes the social and building descriptions of the study site. Section 3.5 describes the sampling approach. Finally, the validity and ethical considerations are described in Sections 3.6 and 3.7.

3.2. Research Strategy and Justification

An integrated approach, i.e. a quasi-experimental approach and qualitative approach, was adopted to address the Research Questions. This integrated approach has been termed as '*intervention design'* (Creswell, 2015) (see Figure 3.1).

Intervention design can be defined as to "…*study a problem by conducting an experiment or an intervention trial and adding qualitative data into it*" (Creswell, 2015, p. 43).

An intervention design is a mixed method strategy referred to as an "*integration of the data at one or more stages in the process of research*"

(Creswell, 2009, p. 212).

The mixed-method strategy has been increasingly applied in social science (Creswell, 2015) so adding a 'concurrent triangulation design' to validate the findings, and checking the different findings obtained with the different methods (Denscombe, 2014). For example, in this study, the findings obtained using occupant behavioural data (self-completion diaries, and follow-up interviews and other interviews) and physical monitoring data (heating consumption and internal temperature) are compared.

Despite its utility a 'mixed-method' strategy poses different challenges for the researcher such as the ability to deal with both quantitative and qualitative forms of research (Creswell, 2009). In addition, the 'mixed-method' strategy is scarce in the field of energy and buildings, as it integrates physical and quantitative data. Studies evaluating the effect of energy efficient measures on heating consumption tend to focus only on physical factors such as changes in internal temperature and/or energy consumption following retrofit insulation (such as Hong (2011), Hong *et al.* (2006), Oreszczyn *et al.* (2006)). In contrast are the interactions between occupant behavioural factors and physical factors that may account for space heating consumption changes have been not researched in depth.

Despite the lack of precedent of 'mixed-method' methodologies in the field of energy and building, insight can be gained from Love (2014) study which combines physical and social data. For example, the following quote by Love exemplify how data should be collected

> … data should be gathered on the influence of all these elements on each other. 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 interactions with it.
>
> (ibid, 2014, p. 91).

Furthermore, texts on combining different types of social data can still be of use here, such as Creswell (2015), and Andrew and Halcomb (2009). These latter suggested that this integration may be undertaken in the data collection, data analysis and/or data interpretation.

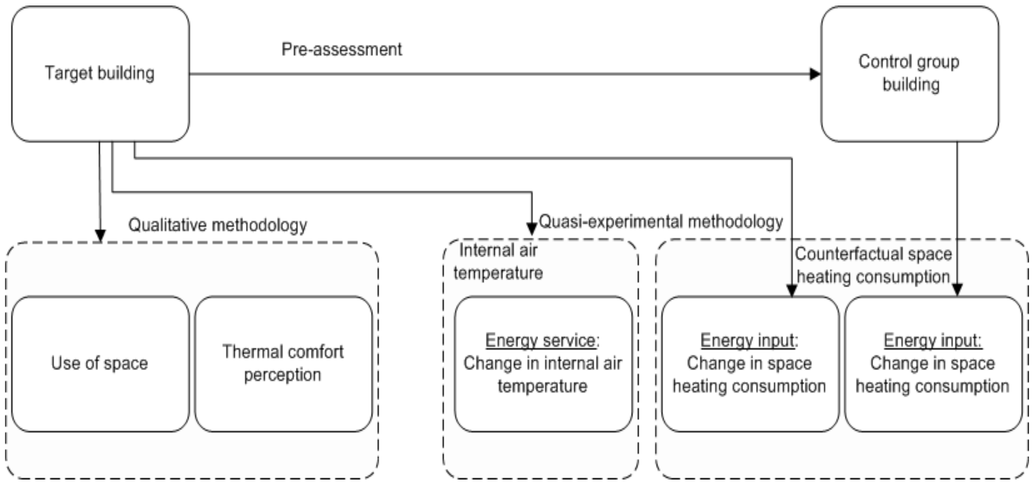


Figure 3.1. Research methodology of this study – Intervention design

3.2.1. *Quasi-experimental approach*

A quasi-experimental approach involves

> … to determine if a specific treatment influences an outcome. This impact is assessed by providing a specific treatment to one group and withholding it from another and then determining how both groups scored on an outcome … that use nonrandomized designs.
>
> (Creswell, 2009, p. 12).

Energy efficiency intervention effects using a quasi-experimental approach can be measured in two categories: measuring the change in 'energy service' or 'energy inputs' (Sorrell *et al.*, 2009). The quasi-experimental design for the measurement of the change in 'energy service' and 'energy input' in this study is represented in Figure 3.2. A review by Sorrell (2007) provides a critique of the methodologies of these types of studies, in which the lack of a counterfactual scenario in the research study design or explicitly controlling for confounding variables were common criticisms. Further, the use of small sample sizes, small periods of monitoring and the self-selection of participants were also showed as barriers to applying the results of these interventions to wider populations (Sorrell, 2007). The following paragraphs show how most of the research study design issues mentioned by Sorrell (2007) have been addressed.

Energy service

The effects of energy efficiency interventions can be measured as the change in energy service before and after an energy efficiency upgrade (Sorrell *et al.*, 2009). Indeed, current thinking argues that energy service is the most relevant output of a system (Sorrell, 2015). An energy service can be defined as the benefit that occupants get from energy-heating consumption such as thermal comfort, higher indoor air temperatures or indoor air quality (Galvin, 2015).

It could be argued that a truer reflection of the energy service being demanded is thermal comfort. However, evidence presented by Hong *et al.*'s results (Hong *et al.*, 2009) shows that the predictive models are not entirely suitable for the prediction of comfort in a domestic context. A major limitation of the predictive model in residential buildings is that, in practice, thermal comfort is not steady as people adapt their environment to feel comfortable using a wide range of possibilities such as opening windows and curtains, drinking cold/warm drinks, switching on/off heating, etc. (Peeters *et al.*, 2009). Adaptive models, on the other hand, may be suitable to measure the energy service as they implicitly build on the hypothesis that occupants are able to change their comfort temperature (neutral) through adjustments of actions (Nicol *et al.*, 2012). However, empirical data have not been collected on a large enough scale on the domestic environment for them to be applicable to residential buildings (Zero Carbon Hub, 2015) (see discussion in Chapter 2, Section 2.5.2).

Internal air temperature has been taken as a pathway towards measuring temperature take-back in retrofit insulation studies (Oreszczyn *et al.*, 2006; Love, 2014). This is because the energy service being demanded is a certain internal temperature during certain time periods through the day. Following this approach, this study measures the change in internal air temperature to provide a better understanding of the effects of energy efficiency interventions.

The energy service internal air temperature is measured before and after the retrofit in the target building, internal air temperature prior to the retrofit acts as a counterfactual scenario portraying 'would have been' in the absence of the retrofit insulation (Sorrell *et al.*, 2009). In addition, as various exogenous factors may modify the demand of energy service (Frondel and Schmidt, 2005), the research needs to control for confounding variables (Sorrell, 2007). Confounding factors might compromise the internal validity of the experiment

> In terms of the 'comparability-based' definition, confounding is said to occur when there are differences in outcome in the unexposed and exposed populations that are not due to the exposure, but are due to other variables that may be referred to as 'confounders.
>
> (Law *et al.*, 2012, p. 7).

This study addressed the confounding factors imposing the "exogeneity" (Frondel and Schmidt, 2005) by looking at populations with similar social conditions and living in buildings with similar characteristics. This means weather conditions, energy prices (the same tariff applies to each occupant supplied by the district heating network), energy supplier (occupants cannot change energy supplier as it is a district heating system), socio-economic characteristics (low-income), the type of retrofit insulation (the target building received the same energy efficiency measure), the physical characteristics (similar floor size, same location and similar building fabric) cannot be confounded with the independent variable – the retrofit building fabric.

Energy input

The effects of energy efficiency interventions can be measured through the change in ‘energy input’ before and after an energy efficiency upgrade (Sorrell, 2007). The space heating consumption before and after the retrofit is measured in the target building and a counterfactual was constructed by using space heating consumption for a control group building over the same period of time. For this counterfactual scenario (at least) two sources of errors have been identified: the energy consumption that ‘would have been’ in the absence of the retrofit insulation and without behavioural change (Sorrell *et al.*, 2009). A modelled counterfactual was not introduced to limit uncertainties introduced with the model predictions as pointed out by Sorrell *et al.* (2009). The quasi-experimental design for the energy input is represented in Figure 3.2.

3.2.2. Qualitative approach

This study seeks to understand the effects of the interaction between physical and occupant behavioural factors on space heating consumption, following a retrofit insulation. As this interaction is more complex than determining the magnitude of the change in space heating consumption or internal air temperatures, energy has been conceptualised as *“… an ingredient of the social practices and complexes of practice of which societies are composed”* (Shove and Walker, 2014, p. 6).

As Shove has pointed out about consumption of energy *"... it is bound up with routine and habit and with the use as much as the acquisition of tools, appliances, and household infrastructures"* (Shove, 2003, p. 395).

This representation of consumers and consumption are mirrored in the qualitative strategy adopted, which sees interactions between the physical and occupant factors as a consequence of everyday practices and routines.

Previous studies of how people's lives might improve following energy efficiency upgrades have proposed that as a result of the warmer environment, occupants may adjust the use of space (see Section 2.4.6). In the process of understanding how occupants may adjust the use of space, this research study proposes to study: 1) changes that may derive from the effects of retrofit insulation on the common patterns of activities (activity profile); and 2) changes that may derive from the effects of retrofit insulation on the level of activities during the time that occupants were at home (actively occupied room). In addition, as the change of the use of space was related to the warmer environment this study uses qualitative methods to understand if the energy efficiency upgrade changes the perception of thermal comfort perception and heating patterns. The methods used to collect qualitative data are explained in detail in Chapter 4, which comprises self-completion diaries, follow-up interviews and face-to-face semi-structured questionnaires. The qualitative design for this study is represented in Figure 3.3.

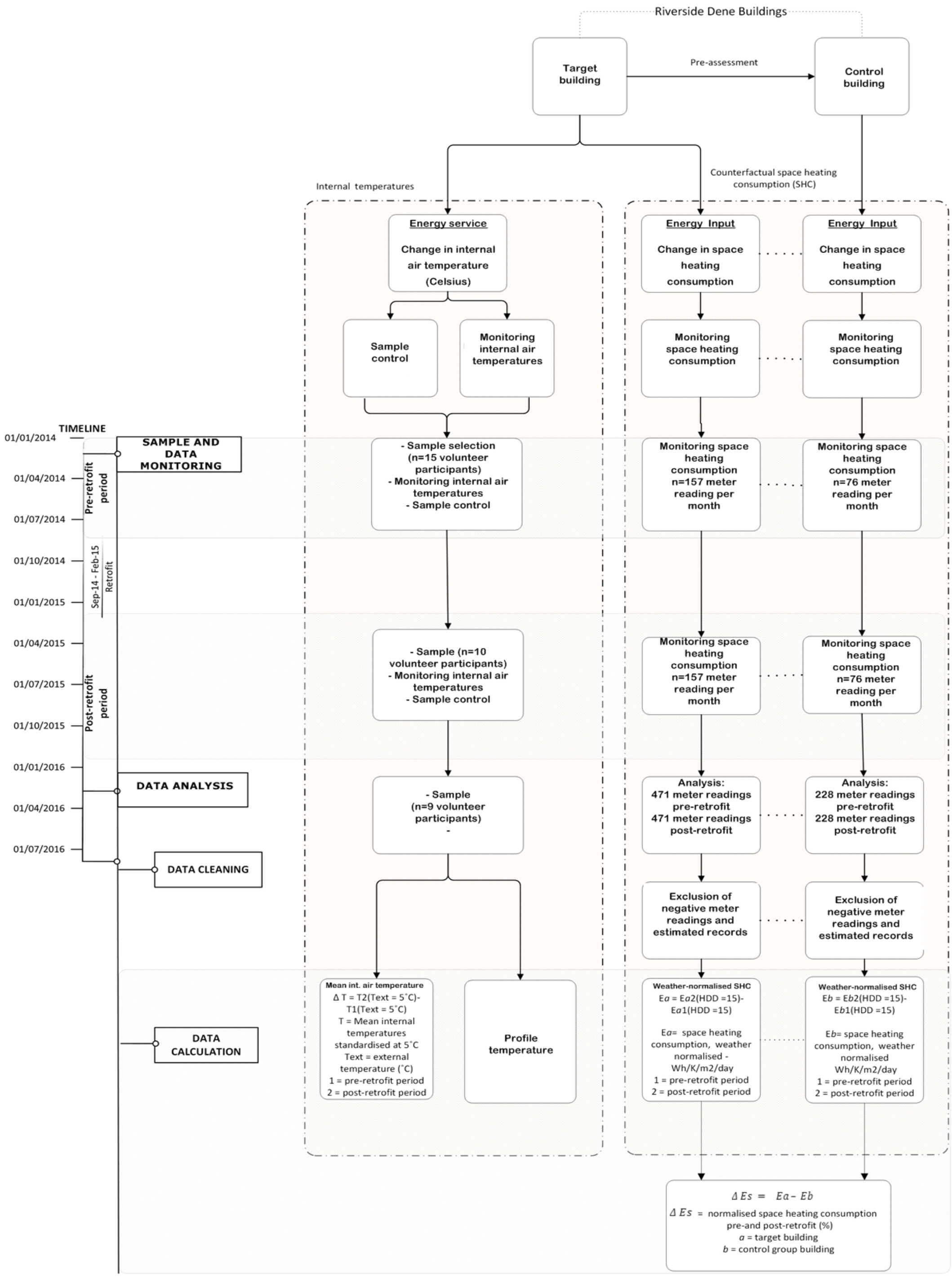


Figure 3.2. Quasi-experimental approach adopted in this study.

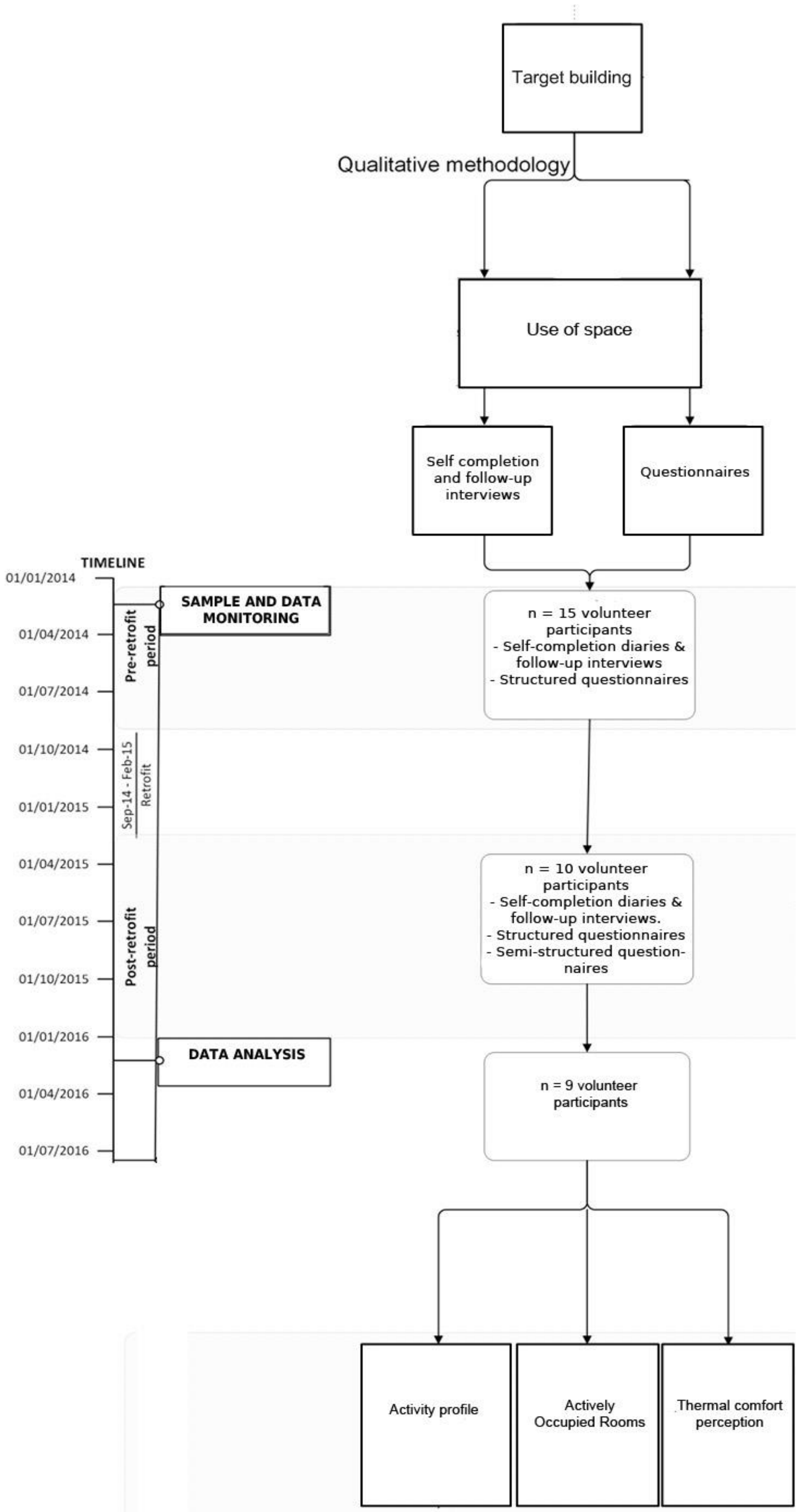


Figure 3.3. Qualitative approach adopted in this study.

3.3. Case Study

3.3.1. Why a case study is desirable

A case study is defined as "*an empirical enquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident*" (Yin, 2014, p. 16).

This research fits well with a case study research definition as it studies a contemporary phenomenon – the effects of retrofit insulation on space heating consumption – in which a case study is desirable because occupant behavioural and physical factors are linked in a complex context (see research assumption in Section 2.4). Furthermore, there is a large number of factors influencing the thermal performance of the dwellings related to the occupants, building fabric and heating system, and it is not clear what the boundaries between these factors are. This case study also fits well with the 'how' and 'why' type of research questions that investigate a contemporary phenomenon (Yin, 2014). Case study research has been well established in the social sciences (Yin, 2009) and its utility in energy and building has been more recently demonstrated by Lowe *et al.* (2012) and Love (2014). Moreover, case study research is compatible with a '*mixed-methods*' strategy (Rosenberg and Yates, 2007; Yin, 2014) and with long-term observation (Bryman, 2012). This research study has chosen a longitudinal comparison; a two-year-long empirical study on the effects of imposed retrofit insulation on a high-rise social housing building in Newcastle upon Tyne, UK.

In spite of its benefits a case study poses different challenges in terms of generalizing research findings (Bryman, 2012). However, Bryman (2012) suggested that a case study can meet the criteria of reliability, replicability and validity, and that generalization has never been the purpose of the case study method. Other challenges are resource restrictions in terms of time and cost (Yin, 2009; Bryman, 2012), which are considered in the case study research design.

3.3.2. *Appraising the effects of building fabric retrofitted insulation on social housing*

This case study focuses on social housing for three reasons: 1) the suggestion of higher temperature take-back in low-income dwellings; 2) methodological benefits; and 3) policy priority. First, the literature suggests that temperature take-back is usually higher in dwellings occupied by low-income householders (Milne and Boardman, 2000; Sorrell, 2007). Thus, internal air temperature change might be greatest in social housing and thus easiest to detect. This is because pre-retrofit unsaturated energy service demand would lead to a post-retrofit internal temperature increase. Secondly, focusing on a high-rise social housing building provides methodological benefits in avoiding biased results, and reducing extraneous factors not controlled by the researcher, as all the dwellings receive the same energy efficiency upgrade, and are influenced by the same environmental factors (i.e. external temperature, relative humidity, etc.) and also the socio-demographic variables are similar. However, this reduces the wider applicability of this research's results (see scope and limitations in Section 1.6). Third, low-income and vulnerable households have been priority groups for achieving the UK's carbon target (DECC, 2012). Consequently, it is expected that energy efficiency upgrades in social housing might contribute to reductions in CO_2 emissions and fuel poverty.

3.3.3. *Finding a suitable case study*

A suitable retrofit insulation project had to be located, from which a case study's dwellings could be conducted to study the effect of retrofit insulation on space heating consumption in a high-rise social housing building. For this purpose, at the beginning of the research, contact was made with the housing organization responsible for managing the council homes on behalf of Newcastle City Council – Your Homes Newcastle. Following the research design of Hong *et al.* (2006), the focus of this study was to conduct a quantitative cross-sectional comparison between a mixture of properties which had been upgraded recently (mostly over the past six months) and those due to receive the energy efficiency intervention. Different buildings expected to be retrofitted were visited; however, these retrofit projects were not financed. In October 2013 the researcher was also informed that interviewers available to carry out the survey, who aimed to interview a quantitative large sample size, were also cancelled. The research study was re-evaluated and the research strategy was adjusted to an intervention design strategy (Section 3.2) using a case study. The research criteria to find a suitable case study were:

- High-rise building(s) due to receive the energy efficiency intervention to take place within the non-heating period in 2014/2015;
- Access to the meter readings of the occupants during the survey, pre- and post-retrofit;
- Social housing (vulnerable dwellings);
- Access to the building to start the survey the winter before retrofit, in order to collect pre-retrofit and post-retrofit in-home practices;
- Find (a) building(s) with a large number of residents to get more chances to find at least 30 residents able to fill an activity diary for 1 week, 4 times within a year (before and after buildings receive solid wall insulation) and able to accept a 15-20 min interview and follow-up interviews to understand the diaries and collect socio-demographic data;
- Occupants that can perform their daily routine without major problems, i.e. they can perform tasks such as personal care, domestic chores and other activities.

Finding a suitable case study with the above criteria proved to be difficult, because insulation projects available with secured funding were scarce. The housing organization was extremely helpful and a new site was proposed in the Riverside Dene area, in which one of the tower buildings was due to be retrofitted in 2014.

3.4. Case Study Description

The study uses two high-rise social housing buildings located in the Riverside Dene Area of Newcastle upon Tyne, UK, managed by Your Homes Newcastle. The buildings were Cruddas Park House, the "target building", and The Hawthorns, the "control group building". The target building underwent retrofit insulation (external solid wall and double-glazing windows) from September 2014 to February 2015 (Figure 3.4).

Figure 3.4. Left image, Cruddas Park House building (target building) before retrofit insulation (March 2014). Right image, Cruddas Park House building after retrofit insulation (March 2015).

3.4.1. Socio-demographic characteristics. Riverside Dene area

The Riverside Dene project was originally a 10-block scheme and a shopping centre built in the 60s (Jones, 2013) as part of a programme of slum clearance and redevelopment (Glendinning and Muthesius, 1994). Currently, only six tower blocks remain on the site, the rest were demolished before 2011 (Jones, 2013) (see the history of the site in Annex B). The majority of the occupants living in the Riverside Dene blocks have incomes that fall below the regional average (£13,329 per year) (YHN, 2015) (Table 3.1). In addition, it is very likely that those pensioners living in the Riverside Dene buildings are retired workers with no formal qualifications (YHN, 2015) (Table 3.2).

Total net income per annum	Riverside Dene tenants (n)	Riverside Dene tenants (%)
Less than £5,199	94	18
£5,200 – £10,399	260	50
£10,400 – £15,599	111	21
£15,600 – £20,799	40	8
more than £20,800	3	3

Table 3.1. Riverside Dene area income level. Source: YHN (2015)

	UK average *	Pensioners in social rented flats	Young renters in flats
Employment status			
Employed Full-Time	100	22	110
Employed Part-Time	100	28	79
Self-employed (FT)	100	22	77
Self-employed (PT)	100	38	61
Retired	100	310	42
Unemployed and seeking work	100	40	186
Education Level			
Full-Time education	100	10	171
No formal qualifications	100	274	92
GCSE / O levels / CSE / School Certificate	100	62	101
ONC / BTEC / apprenticeship	100	80	81
A-levels/ AS levels or Highers	100	29	107
Higher education below degree level	100	55	105
Degree or higher degree	100	24	117

(*) This table is based on two sources: Northgate (YHN's housing data base) and ACORN (A Classification Of Residential Neighbourhood). The score indicates probability with 100 being a UK average.

Table 3.2. Riverside Dene area dweller characteristics. Source: YHN (2015)

3.4.2. Buildings description

The target and the control buildings share similar physical building fabric characteristics, location and heating system. Both are high-rise residential buildings built in the 60s in the Riverside Dene area in Newcastle upon Tyne. Heating is supplied by a biomass community heating system, a 750 kW biomass boiler is the primary energy source, and a 1.5 MW gas-fired boiler, and two 1.2 MW gas boilers (Armstrong group, 2012) work in peak periods of demand. The heat is distributed to the tower blocks via heating pipes, which comprise the heat network. Individual flat metering monitors the heat and then bills are based on the amount of heat used. Both buildings are under the same gas price tariff and the information recorded in both meters is automatically transmitted every month to a central database.

For the target building, the heating pipework in vertical riser ducts in the main corridors serves horizontal runs on the 6th 7th, 13th and 14th floors, which pass through the ceiling voids in the corridors then through a flat to drop vertically within the bedroom cupboard passing to the flats below. Branches tee off within the cupboard for each individual flat (see Annex C). Ducted air stub ducts supply heat to the flats, which is controlled by a heating control through an 'on/off' button (thermostat or zoned controls are not available in the target building – see Annex D). There is no heating to the kitchen or bathroom within the flats.

Unmetered heat might have been benefiting the target building flats; heat might be given off in the horizontal runs to the bedrooms and then runs vertically within in the cupboard, in turn serving the flats above and below. Thus it might also affect some of the main corridors, most likely the ones with the horizontal pipework and the corridors immediately above.

For the control group building, primary mains from the boiler house serve a heat station on the ground floor. Plastic vertical risers carry LTHW (low temperature hot water) from the plate heat exchangers up through the building. Horizontal runs pass through each flat to the local bespoke heat exchange unit in a cupboard. This unit provides heating via a plate heat exchanger and hot water indirectly via a coil running through a stored mass of hot water. Two wet-pipe systems using panel radiators supply heat to the flats, which is controlled by a programmable room thermostat (see Annex C).

After retrofit the target building was modified as follows: new external façade-wall construction with a corresponding U-value of 0.28 (W/m^2K) and new double-glazed windows with a corresponding U-value of 1.7 (W/m^2K). The system used to upgrade the walls was an external insulation render system incorporating 100 mm of HD mineral wool insulation (nominal density 140kg/m³).[34] A base coat (7 mm) and reinforcing mesh were also applied along with a top coat of silicon-resin of 1.5 mm. The windows were upgraded with 28-mm air-filled double-glazed units, which have 4 mm of inner pane, 20 mm air space between the panes and 4 mm outer pane. The window energy rating (WER) specified were band C. The air tightness was not addressed nor anything done to the heating system and controls as part of the retrofit project. Table 3.3 summarises the physical characteristics of both buildings.

Physical building descriptions	Target building	Control group
Building use	Residential	Residential
Construction year	1960s	1960s
Number of storeys	23	15
Number of dwelling units	157	76
Number of bedrooms	1 or 2	1 or 2
Floor area in m^2 (average per flat)	70	59
Energy efficiency rating before the upgrade	76 points (band C)	83 points (band B)
Wall construction (outside to inside)	Precast concrete frame with concrete infill panel	Precast concrete frame with concrete infill panel

[34] This information is based on the project specs provided by YHN, this study neither did look at fire regulations nor give recommendation about insulation system/materials.

Wall U-value (W/m^{2}K)	0.53 to 0.89*	0.30***
Window U-value (W/m^{2}K)	4.3	0.17***
Orientation	10˚ due East	10˚ due West
Completion of improving the energy efficiency	February 2015	
Heating system **		
Heat source	Primary source: 750 kW biomass community heating system. For peak demand periods: one 1.5MW gas fired boiler plant and 2 existing 1.2MW gas boiler acts a back-up serving Riverside Dean blocks.	
Heat network-pipes	Combination of a mild steel LTHW[35] heating pipework and steel pre-insulated primary with ducted air stub duct system and panel radiators.	
Heat network-pipes routing	LTHW heating pipework in vertical risers in ducts in main corridors serving horizontal runs on different floors. These runs pass through the ceiling voids in the corridors then through a flat to drop vertically within the bedroom cupboard passing to the flats below.	Plastic vertical risers carry LTHW from the plate heat exchangers up through the building. Horizontal runs pass through each flat to the local bespoke heat exchange unit in a cupboard.

(*) variable wall U-value due to uneven construction in the original façade (source: information provided by YHN). (**) Armstrong group (2012)

(***) Yu (2016)

Table 3.3. Target and control group physical building descriptions.

[35] Low temperature hot water

3.5. Sampling Approach

A convenience sample suited both the practical constraints of the study (e.g. small number of flats, limited financial resources) and the research strategy. A convenience sample was deemed the most appropriate sampling approach for addressing the research strategy '*intervention design'* (Creswell, 2015), as agreement from the participants is needed for the installation of the data loggers in their flats and to carry out the qualitative survey (self-completion diaries and follow-up interviews and other interviews). All residents of the target building were invited to participate; however, 'selection' bias can affect the sample if, for example, dwellers with a particular interest in energy consumption are more likely to participate than other dwellers. However, "*unobserved household-specific heterogeneity*" (Davis, 2008, p. 534) of the propensity to participate in the study is not affected for the propensity to adopt the energy efficiency measures, as it was imposed for all the occupants of building.

3.6. How Validity is addressed in this Case Study

Case study research can achieve integrity or rigour of validity through *'construct validity', 'internal validity', 'external validity' and 'reliability'* (Yin, 2014, p. 18). Following Yin's approach (2014), this study seeks to demonstrate validity based on previous concepts constructed by previous researchers. For example, the impact of energy efficiency on space heating is revised through specific concepts such as temperature take-back, which are related to the main objective of this research (Research Questions 1 and 2).

In addition, evidence collected from different data sources is triangulated to provide verification and validity while complementing similar data, making the results more believable. In other words, physical monitoring data (space heating consumption meter readings and internal air temperature) and occupant data (from self-completion diary and follow-up interview) are triangulated to compare the findings from both data sources.

In terms of '*internal validity'*, counterfactual scenarios are considered in the research study design for the evaluation of the changes of energy service and input, portraying what 'would have been' in the absence of the retrofit insulation (Section 3.2.1). In addition, as various exogenous factors may modify the demand of energy service (Frondel and Schmidt, 2005), the research controlled for confounding variables (see Section 4.3.1). '*Reliability'* is addressed by keeping a record of data collected (database, interview transcripts, interview notes and secondary sources) and documenting the procedure used in this study to create a chain of evidence, as can be seen in Chapter 4.

3.7. Ethical Considerations

Consent for the study was granted by the Newcastle University committee before the study was undertaken. Ethical considerations taken into account involved confidentiality and informed consent from the participants (see Annex E). A briefing meeting was carried out with each participant in order to explain: a) the purpose of the study; b) the right to participate and withdraw whenever they want; c) a guarantee of confidentiality and non-traceability in the research (as no names or flat numbers are published). In addition, at the beginning of the research study (Stage 2), a survey brochure was given to each dweller with the same information delivered verbally (see survey brochure in Annex E). A letter of consent was signed by each participant and it was explained what type of information the temperature data logger records (see letter of consent in Annex E).

3.8. Summary

This research adopts a 'mixed-methods' strategy design called 'intervention design' (Creswell, 2015) that combines quasi-experimental and qualitative approaches for answering the Research Questions. The quasi-experimental design measures the effect of energy efficiency interventions through the change in 'energy service' and 'energy inputs'.

The energy service measures internal air temperature, before and after the retrofit in the target building, and internal air temperature prior to the retrofit acts as a counterfactual scenario portraying what 'would have been' in the absence of the retrofit insulation. The energy input measures space heating consumption, before and after the retrofit in the target building, and a counterfactual scenario will be constructed using space heating consumption for a control group building, over the same period of time.

In addition, this study also seeks to understand which the effects of the interactions between physical and occupant behavioural factors are in space heating consumption, following a retrofit and why internal air temperature changes afterwards. Thus, qualitative responses to changes that may derive from the effects of retrofit insulation and change in the use of space are also studied.

This research uses a case study to understand the effects of retrofit insulation on space heating consumption. A case study is desirable due to the large number of factors influencing the thermal performance of the dwellings related to the occupants, building fabric and heating system, and it is not clear what the boundaries are between these factors. The case study research uses two high-rise social housing buildings located in the Riverside Dene Area of Newcastle upon Tyne, UK. These buildings are managed by the housing organization Your Homes Newcastle. For the purpose of this research these buildings are called the target building, and the control group building. The target building underwent retrofit insulation (solid wall and double-glazing windows) from September 2014 to February 2015 (Figure 3.4).

A 'convenience sampling' strategy was employed as volunteers are needed to carry out the study. The case study research achieves integrity or rigour of validity through *'construct validity', 'internal validity', and 'reliability'*. Ethical considerations such as confidentiality and informed consent from the participants were also taken into account in the implementation of this study.

Chapter 4. Data Collection

4.1. Introduction

Chapter 3 described the ‘*mixed-method*’ research strategy ‘*intervention design’* adopted to address the Research Questions, which combines a quasi-experimental design and qualitative methods. This strategy was chosen to analyse the effect of retrofit insulation on space heating consumption in the case study described in Chapter 3. The Research Questions are as follows:

- How do internal temperatures change following an imposed building fabric retrofit insulation?
- How does space heating consumption changes following an imposed building fabric retrofit insulation?
- Which interactions between occupant behavioural factors and physical factors may account for space heating consumption change?
- Why do internal air temperatures change afterwards?

This chapter discusses the research methods applied to collect data that allow for addressing the Research Questions. Research methods involve “*the forms of data collection, analysis, and interpretation that researchers propose for their studies*” (Creswell, 2009, p. 233). Research methods also “…*should follow research questions in a way that offers the best chance to obtain useful answers. Many research questions and combinations of questions are best and most fully answered through mixed research solutions*” (Johnson and Onwuegbuzie, 2004, pp. 17-18).

This chapter firstly discusses the data collection methods (Section 4.2), justifying why these research methods were chosen and how they were designed. Secondly, Section 4.3 describes the implementation of the data collection methods in the case study. Thirdly, Section 4.4 describes the implementation stages of the study, which was divided into eight stages in order to capture long-term patterns of physical monitoring and occupancy data in the residential building. Fourth, Section 4.5 – data analysis and construction of metrics – describes how the data collected turn from raw data into meaningful information. Finally, Section 4.6 discusses the limitations of the research methods.

4.2. Description of Data Collection Methods

This section describes the Research Methods for data collection, justifying why these research methods were chosen and how they were designed:

- Detailed monitoring (monitoring air temperature and heating consumption data);
- Structured questionnaires;
- Self-completion diaries and follow-up interviews;
- Semi-structured questionnaires.

4.2.1. Detailed monitoring

The study of changes in energy services needs recording in a high resolution of time series of internal air temperature data and space heating consumption data in order to observe changes pre-and post-upgrade. Data loggers are needed to collect air temperature accurately, although all data loggers have sources of errors, which can be limited by placing the data logger away from direct sources of heat and light, as suggested by ISO 7726:2001 (British Standards Institution, 2001). In addition, an uncertainty in the source due to sensor characteristics could be mitigated by following the guides provided by ISO 7726:2001 (British Standards Institution, 2001). The guidelines suggest a sensor response measuring range (10˚C – 40 ˚C) with an accuracy (required ± 0.5˚C and desirable ± 0.2˚C) for a 90% response time. Moreover, data loggers can be calibrated in a thermal chamber under known conditions (for example, set at 20˚C and 50% relative humidity).

Regarding space heating consumption data, ideally heat meters installed on the meters or on the heaters, which provide a high-time-resolution analysis of heating usage (switch on/off), are needed to collect SHC. However, this equipment tends to be very expensive. Another option is the meter readings. Meter readings have several sources of errors; SHC often needs to be collected from different fuel sources such as electricity and gas, and then disaggregated from the other energy consumption data. For example, gas consumption might record both space heating consumption and hot water data. Disaggregation through modelling is open to bias, because of the assumptions that need to be made about the consumption (e.g. different space heating consumption and hot-water gas in summer time compared to winter time) such as in Hong (2011). This source of error can be mitigated if different meter readings measure space heating and water heating.

4.2.2. Structured questionnaires

Structured questionnaires are needed to:

1. Identify the demographic profile of the respondent household and to characterize the population of the target building (e.g. family size, sex, age, household composition, occupation and education);
2. Identify the ownership and use of secondary heating during the retrofit process;
3. Describe the thermal comfort perception before and after the upgrade.

The design of the thermal comfort perception questionnaire was designed to understand how warm or cold they feel in their living room using five items of thermal comfort-related perception. Items used a 5-point Likert scale (for example 1= Very cold, 2 = cold, 3 = neutral, 4 = warm, 5 = Very warm) (Annex E). Other thermal comfort-related factors, that it might be related to, were also asked such as level of draught, level of noise (external noise), external appearance of the building and level of health (related to cold–diseases).

Structured questionnaires enable households to be surveyed with relative ease but they are limited in the amount and type of information that can be collected. For this reason, practices and routines were surveyed using self-completion diaries and follow-up interviews.

The structured questionnaires can be seen in Annex E.

4.2.3. Self-completion diaries and follow-up interviews

Different research methods have been used by previous researchers to capture the use of space, for example, the use of longitudinal self-completion diaries reported by other researchers to explore day-to-day adaptive actions of thermal comfort that enable predicting energy consumption in office environments (Langevin *et al.*, 2013). Langevin *et al.* (2013) monitored adaptive activities such as switched-on/off heating, drinking cold/warm drinks and closed/open windows.

However, there is no perfect technique; this means that there is a trade-off between viability, reliability and invasion of privacy. For example, one of the more intrusive methods to study the use of space is filming participants at their place, which is exposed to bias to know what really happened in the absence of the camera; this has been described as the ‘Hawthorne Effect’ (Parsons, 1974; Wickström and Bendix, 2000; Gale, 2004; Schwartz *et al.*, 2013). On the other hand, the least intrusive technique would perhaps be to carry out an interview, in which how an occupant uses the space may not be accurate, because of the bias of the interview as a technique. Acknowledging these limitations and after the evaluation of different methods, this study sought to capture only the general routine of the occupants from the diaries. There are also practical reasons why self-completion diaries and follow-up interviews were desirable in the context of this study, such as being less intrusive, cheaper and a more suitable solution than filming or using sensors.

Self-completion diaries were chosen because they are principally based on the premise that “we can analyse and learn about when, where and what energy-related activities occur in a household context and by whom (and in what social context) they are performed” (Ellegård and Palm, 2011, p. 1921). This along with the premise that “people can talk about their practices” (Hitchings, 2012), was used to support the use of follow-up interviews.

These premises can be tested with the concurrent triangulation design applied to this study in which self-completion diary data, follow-up interviews, internal air temperature and space heating consumption data were used to check the findings. Triangulation has often been conducted on other mixed method researches to enhance the credibility of the findings (Bryman, 2012).

Self-completion diaries and follow-up interviews have limitations such as 'risk of honest forgetfulness' in which participants fail to remember the scheduled response times or fail to have the diaries at hand (Bolger *et al.*, 2003, p. 594). For example, a participant commented on the first follow-up interview that her TV was always switched on in the background during the time when she was at home. She did not know how to include this 'activity', because it is not a leisure activity by its own, rather she used it to feel companionship.

Another example is the level of consciousness of the practices, this may indicate that participants are not necessarily conscious about all their daily practices and some activities could have been missed. For instance, a participant commented that he had not realised what his life routine was until he started to complete the diaries.

In addition, the 'risk of retrospection error' (Bolger *et al.*, 2003, p. 594), in which participants may fill in the diary at the end of the day and some activities could have been missed or deliberately fabricated to complete missed entries. Both the 'risk of honest forgetfulness' and 'risk of retrospection error' may lead to 'uncertain compliance' (Bolger *et al.*, 2003). The use of follow-up interviews can be used to verify information on household practices, obtaining additional information to complement the self-completion diaries.

Self-completion diaries were designed specifically for this study by including activities in which an individual might perform at home, based on the concept of previous diary surveys used in transport studies (Doherty and Miller, 2000). The self-completion diaries contain time-based diaries with 'fixed-time schedules' (Bolger *et al.*, 2003) to capture the heating schedule and hourly activities that are centred around the person's daily life and during one week.

In order to test the design a pilot study was undertaken in January 2014 (see Annex G). Ideally, this pilot would had been tested with the sample group; however, a small sample size prevented testing it with the participants. The pilot was carried out with Newcastle PhD students, although they have different socio-demographic characteristics, the expert input given by Newcastle University PhD students was worth it. This pilot primarily led to the questionnaire being shortened, and the structure of the activity survey sheet was amended (Annex G). In addition, in order to collect heating usages, a heating schedule diary was added in the final version of the self-completion diary which is shown in Annex E.

The PhD students were asked to fill in the diary survey and evaluate it, they also were interviewed after the completion of the survey with a semi-structured questionnaire in order to collect information about the survey design such as length, style, clarity of the language, instruction information and understanding of the activity diaries. For a simplified analysis it was proposed that the PhD students only fill in the diary for one day, on an average weekday routine, in winter season and exclude activity diaries for family members.

The final version of the self-completion diary can be seen in Annex E.

4.2.4. Semi-structured questionnaire

Semi-structured interviews were chosen to:

1) Identify any other relevant changes to their domestic environment that may affect energy consumption during the retrofit process (i.e. change of employment status, family members, health conditions);

2) Capture the perception of the retrofit insulation and its process. The final interview aimed to address some of the socio-technical issues surrounding the perception of the effect of retrofit insulation and its process. The script explored the predetermined themes as follows, whilst still allowing for the emergence of unanticipated themes:

- Use of main heating and secondary heating;
- Thermal comfort perception;
- Ventilation;
- Infiltration;
- Unanticipated themes.

Semi-structured questionnaires can be seen in Annex E.

4.3. Data Collection Method Implementation

This section describes the implementation of the research methods for data collection, represented in Figures 3.2 and 3.3.

4.3.1. Monitoring internal air temperature and external air temperature

Internal air temperatures were monitored at 30-minute intervals before and after the retrofit, by placing data loggers in the participant's living room. Gemini Tinytag data loggers (Table 4.1) were placed away from direct sources of heat and light. Internal air temperature data were monitored in the living room (Figure 4.1). As internal air temperatures are strongly influenced by external meteorological conditions, external air temperatures were monitored and collected using a Gemini data logger installed on the roof of the target building, set at 30-minute intervals (Table 4.1).

Data logger specs	Tinytag Plus 2 (external temperature)	Tinytag Transit 2 (internal temperature)
Model	TGP-4017	TG-4080
Temperature range Min/ Max:	-40°C/+85°C	-40°C/+70°C
Sensor type	10K NTC Thermistor (Internally mounted)	10K NTC Thermistor (Internally mounted)
Reading resolution	0.01 °C or better	0.01 °C or better
Logging Interval	1 sec to 10 days	1 sec to 10 days

Table 4.1. Gemini data logger specs. Source: Tinytag (2016)

Figure 4.1. Target building floor plan and data logger location

4.3.2. *Meter readings (gas consumption for space heating and hot water, and electricity consumption)*

A dataset of monthly gas consumption from each flat in the target building (157 flats) and control group (76 flats) was provided to the researcher by the housing association. These data were automatically transmitted from individual meters to a central database and are used for billing purposes. The data were provided directly by the housing association, in an anonymised file under a non-disclosure agreement.

The building dataset contained hot water meter readings in m^3 and space heating meter readings in kilowatt-hours (kWh). Both records, for the target building and control group, cover the period before and after the retrofit. The records are classified as directly measured records, estimated records and manual records. In addition, monthly electricity meter readings were also collected from each participant’s dwelling, before and after retrofit insulation. Interviews were carried out during the different stages of the retrofit process to obtain information about secondary heating (see the implementation overview in Section 4.4).

4.3.3. Structured questionnaires

Interviews with structured questionnaires were carried out at different stages of the retrofit project at the target building. First, at the beginning of the project socio-demographic information was collected (see information detail in Annex E). Secondly, before and after the retrofit information regarding thermal comfort perception and use of secondary heating was collected (Annex E).

4.3.4. Self-completion diaries and follow-up interviews

Self-completion diaries were implemented by guidance on using diaries by Alaszewski (2006) such as guidance on how to complete the diaries, a model example of a completed diary and a checklist of activities can be seen in Annex E. Self-completion diaries were carried out at different stages of the project at the target building, before and after the upgrade, as to ascertain whether occupants change their use of space and heating usage (see the implementation stage details in Section 4.4).

Each participant filled in a self-completion diary (activity and heating diaries) for one week. A follow-up interview at the end of this week was carried out to understand the information in the diaries in detail. Furthermore, follow-up interviews were used to corroborate the information from self-completion diaries. Therefore, notes were made in the diaries by the researcher about the activities performed by the participant when more detail was needed. For example, the self-completion diaries primarily provided information of the main activities during the day (e.g. meal time, getting up, out of home period). Follow-up interviews were used to describe with whom, or what other activities are done during this period.

4.3.5. Semi-structured questionnaire

A final interview was carried out at the end of the study. The first topic was the use of main heating and secondary heating. The interview commenced with what brought them to the use of heating or not. This part was designed to build up a broad picture of how they are heating their flat and it was also partly for triangulation with the self-completion diaries. It moved on to the thermal comfort perception: "how cold or warm do they feel at their flat?". This was used to build up a broad picture of how thermally comfortable they are in their flat and it was also partly for triangulation with the thermal comfort perception questionnaire and mean internal air temperature. These questions were followed by ventilation and infiltration questions, including comparisons before and after the retrofit. These interviews were audio recorded with the permission of the participants.

4.4. Implementation Overview

Implementation of the study was divided into eight stages in order to capture long-term patterns of physical monitoring and occupancy data in the residential building. See the overview of the case study's implementation stages in Figure 4.2, p.100.

Stage 1: recruitment

The recruitment was initiated by the housing association in March 2014, a letter was sent to all tenants introducing the study in the target building. Because a poor response rate from a case study, with a small population would have been very damaging to the research, responses were encouraged through the inclusion of a £50 gift card provided by the Institute for Sustainability at Newcastle University. To reinforce the message, posters were located in the building area (i.e. lifts and at the local café) and postcards were also sent to all the residents (Annex E). The researcher and supervisor also attended to the stakeholder meeting organized by the city council. A drop-in session was also organized at the community café (Annex E).

There was a greater difficulty in recruiting volunteers for a one-year study, in which participants were also required to live at least one year before retrofit (in order to have historical energy heating records). As recruiting participants amongst vulnerable communities is challenging, the study's strategy focused in gaining the trust of residents by using different techniques: letters, posters located at the building, a drop-in session, and the author with a YHN's staff member went twice to knock on doors encouraging residents to participate. The idea that residents were involved in a research study design to understand the impact of the proposed retrofit was well received and aided with participant recruitment. 25 volunteers agreed to participate in the study; 15 residents met the recruitment criteria.

*Stage 2***:** briefing and data monitoring settings

A briefing meeting [36] with each participant was carried out in order to: 1) explain how to fill in the self-completion diaries; 2) where to locate the temperature data loggers; and 3) get the research consent forms signed. A survey brochure was given to each participant with the same information delivered verbally (Annex E). The survey brochure contains the self-completion diaries used to record activities, heating usage periods and information for placing the temperature data loggers. The data loggers were instructed to be placed in the participant's living room on a surface away from direct sunlight and heating[37]. The data loggers were previously set at 30-minute intervals by the author. The participants also signed the research consent form in Annex E, which expresses the willingness to participate in the survey and the authorization to access their electricity and gas meters.

The electricity meter readings started to be collected monthly after the debriefing meeting. In addition, a dataset of monthly gas consumption from each flat in the target building and control group was provided by the housing association. Retrospective gas consumption data were also provided for 2012 and 2013. A

[36] At the café located at Cruddas Park shopping mall.

[37] In the absence of any previous protocol to collect internal temperatures: i.e. how temperature should be monitored; where data loggers should be placed; and how many rooms should be measured.

Gemini data logger, set-up at 30-minute intervals was placed on the roof of the target building to measure external air temperature.

Stage 3: first self-completion diary and follow-up interview

The first self-completion diary was undertaken from 22nd to 28th May 2014. Each participant filled in a self-completion diary (activity and heating diaries) for one week. A follow-up interview at the end of this week was carried out to understand the information in the diaries in detail. This week was chosen because it was the most appropriate proxy to interpret winter time 2014 after retrofit insulation as the average external air temperatures were forecasted to be lower than 15˚C (see Annex F). As the reader would have noted, it was not possible to monitor the internal air temperatures from December 2013 to February 2014, because of all the constraints explained in Section 3.3.3. This stage also collected information regarding thermal comfort perception, socio-demographic information and use of secondary heating (Annex E).

Stage 4: retrieving air temperature data

Air temperature data from the internal and external temperature data loggers were collected and retrieved from May to July 2014.

Stage 5: second self-completion diary and follow-up interview

A second self-completion diary was undertaken from 4th to 10th February 2015. Each participant filled in the diaries for one week and a follow-up interview at the end of this week was conducted to understand the diaries in detail. This week was chosen because was the most appropriate proxy to interpret winter time 2015 after retrofit insulation as the average external air temperatures were forecasted to be lower than 15˚C (see Annex F). However, as the retrofit insulation work was still in process, as some double-glazed windows were not replaced yet in the target building, this self-completion diary was repeated in April 2015.

Stage 6: third self-completion diary and follow-up interview

A third self-completion diary was undertaken from 4th to 10th April 2015. Each participant filled in the diaries for one week and a follow-up interview at the end of this week was also conducted to understand the diaries in detail. This week was chosen because was the most appropriate proxy to interpret winter time 2015 after retrofit insulation, again the average external air temperatures were forecasted to be lower than 15˚C (see Annex F). This stage also included information regarding thermal comfort perception and use of secondary heating (Annex E).

Stage 7: retrieving air temperature data

Air temperature data from the internal and external temperature data loggers were retrieved from February to July 2015 and downloaded into a PC for analysis. 10 participants out 15 had completed the survey pre- and post-retrofit.

Stage 8: final stage

The participants agreed to be interviewed about their insights into the retrofit process (see semi-structured questionnaire in Annex E). The interviews were carried out at the community café or in their flats. In this latter a colleague accompanied the researcher.

As a summary, 10 participants completed the survey. 9 dwellings were accounted as valid responses since relevant changes were not present in the property over the longitudinal survey, such as, for example, family members leaving/coming home.

2014		Detailed monitoring	Meter readings	Self-completion diaries and follow up interviews	Structured questionnaires	Semi structured questionnaires
Mar	Stage1. Recruitment					
May	Stage2. Debriefing and data monitoring settings Stage3. 1st self-completion diary (22nd -28th May) and follow-up interview	☑	☑	☑	☑	
Jul	Stage4. Retrieving temperature data	☑	☑			
Sept			☑			
Dec	Retrofit insulation		☑			
2015 Feb	Stage5. 2nd self-completion diary (4th – 10th Feb) and follow-up interview	☑	☑	☑	☑	
Apr	Stage6. 3rd self-completion diary (4th – 10th April) and follow-up interview	☑	☑	☑	☑	
			☑			
Jul	Stage 7. Retrieving temperature data Stage 8. final interview	☑	☑			☑

Figure 4.2. Overview of case study’s implementation stages.

4.5. Data Analysis and Construction of Metrics

This section describes how the data collected were converted from raw data into meaningful information. The following metrics were constructed to answer the Research Questions.

Metrics:

- Mean standardised internal air temperature and Internal temperature profile (Research Question 1);
- Normalised space heating consumption and secondary heating (electricity consumption for space heating) (Research Question 2);
- Activity profile, actively occupied rooms and use of heating (change in the use of space, Research Question 3);
- Thermal comfort perception (Research Question 3).
- Theme analysis (Research Question 4).

These metrics are explained in the following sections.

4.5.1. Data cleaning and preparation

The first step in the data analysis was to clean the space heating meter reading meters of negative values and estimated records, and convert meter readings into monthly consumption. A total of 1398 meter reading data were collected (456 meter readings from the control building and 942 from the target building) and 1136 records were analysed from a total of 233 flats (see Table 4.2). Potentially erroneous data points from space heating meter reading records, including negative values and estimated records, were removed.

	Space heating consumption meter readings. Total meter readings/ (analysed meter readings (**))		
Year	Control building	Target building	Total
2014 (*)	228 (191)	471 (427)	699 (618)
2015 (*)	228 (194)	471 (324)	699 (518)
Total	456 (385)	942 (751)	1398 (1136)

(*) 3 months (March, April and May).
(**) Analysed meter readings = total meter readings - potentially erroneous data points.

Table 4.2. Meter reading data from the control building and target building.

These months were chosen to allow comparability pre-and post-retrofit, as the target building underwent retrofit from September 2014 until February 2015. The building data show the advantage of the meter readings was not being embedded with the general gas use, so avoiding technique errors from disaggregating it from general gas use. There are two different meter reading records, one for hot water and another for space heating in kWh.

Temperature data were not cleaned as there was insufficient information to decide what points are erroneous, as participants do not follow a pattern or physical rules. As Love (2014) noted in a similar study where temperature data were collected, "*…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*" (ibid., 2014, p.146).

4.5.2. Mean standardised internal air temperature calculation

This metric of mean standardised internal air temperature comparisons was constructed following other studies (Oreszczyn *et al.*, 2006; Love, 2014) to ensure comparability from one year to another in this study and permit comparability with other studies. Standardisation makes internal temperatures independent of external meteorological conditions (Oreszczyn *et al.*, 2006). This work standardises mean internal air temperatures to a fixed external temperature of 5ºC[38] according to the following four steps.

First, days with mean external temperatures above 15ºC were excluded to improve the prediction of mean internal air temperatures in the heating season, because the heating system would normally be switched off because incidental heat gains provided adequate heating (Oreszczyn *et al.*, 2006).

Second, the mean internal temperature was calculated daily. Third, two regressions between mean internal and mean external temperatures were carried out: one pre-retrofit and other post-retrofit. Fourth, a 5ºC single external temperature was selected so as to derive the internal air temperature for the target building pre-retrofit (T1) and post-retrofit (T2) using the calculated regressions.

The metric's change in mean standardised internal air temperature is calculated as:

$$\boldsymbol{\Delta T} = (\boldsymbol{T2}\ (\boldsymbol{Tex} = \mathbf{5}^{\underline{o}}\boldsymbol{C}) - \boldsymbol{T1}(\boldsymbol{Text} = \mathbf{5}^{\underline{o}}\boldsymbol{C})) \qquad \text{Equation 4-1}$$

Where:

ΔT is the difference in mean internal air temperature under standardised conditions;

T1 is the standardized mean internal air temperature (°C) for pre-retrofit;

T2 is the standardized mean internal air temperature (°C) for post-retrofit.

[38] It should be noted that the average heating season temperature in the UK is higher – 6.3ºC (Oreszcyn *et al.*, 2006). Oreszczyn, T., Hong, S.H., Ridley, I. and Wilkinson, P. (2006) 'Determinants of winter indoor temperatures in low income households in England', *Energy and Buildings*, 38(3), pp. 245-252.

4.5.3. Internal temperature profile calculation

The profile temperature was constructed by plotting the daily mean internal air temperatures (°C) so as to observe changes in 24-hour heating periods. The derived plotted graphs show hourly mean internal air temperature values. A trend curve was also plotted on the profile temperature graphs, before and after the upgrade so as to compare them to the BREDEM-12 internal temperature profile (Anderson *et al.*, 2002).

4.5.4. Normalised space heating consumption calculation

The metric change in normalised space heating consumption was constructed following other studies (e.g. Hong *et al.*, 2006) to provide a means of comparing the consumption before and after the upgrade. Space heating consumption was normalised for the variation in indoor–external temperature (heating degrees days[39]) and dwelling size (e.g. Hong *et al.,* 2006). The daily mean internal base temperature was set up to the number of days that the mean outdoor temperature was equal to or below 15°C.

The change in space heating consumption following the retrofit is calculated for the target building (Ea) and control building (Eb) through the difference in space heating consumption under normalised weather and dwelling size conditions:

$$\boldsymbol{\Delta\, Ea \;=\; Ea2\;(HDD = 15) - Ea1(HDD = 15)} \qquad \text{Equation 4-2}$$

$$\boldsymbol{\Delta\, Eb \;=\; Eb2\;(HDD = 15) - Eb1(HDD = 15)} \qquad \text{Equation 4-3}$$

1 = pre-retrofit and 2 = post-retrofit

Where,

$$\boldsymbol{\Delta\, Es \;=\; Ea - Eb} \qquad \text{Equation 4-4}$$

[39] Heating degree days use external temperature data from the weather station at Newcastle Airport.

Δ Es is the difference in space heating consumption under normalized weather and dwelling size conditions for the buildings under study (target (a) and control (b)) ($Wh/K/m^2/day$);

Ea is the weather-normalised space heating consumption for the target building ($Wh/K/m^2/day$);

Eb is the weather-normalised space heating consumption for the control building ($Wh/K/m^2/day$).

4.5.5. Secondary heating: electricity consumption for space heating calculation

As was noted in Section 4.3.2, monthly electricity meter readings were collected from each participant's dwelling at the target building, before and after retrofit insulation. Furthermore, structured interviews were carried out to identify the ownership and use of secondary heating during the retrofit process. Interviews were carried out during the different stages of the retrofit process to obtain information about secondary heating (see implementation overview in Section 4.4). Additionally, self-completion diaries and follow-up interviews were carried out at different stages of the project in the target building, before and after the upgrade, in which each participant filled in self-completion heating diaries for one week. The information provided from the different sources showed that residents did not use other heating sources such as electrical heaters; therefore, this metric and analysis were not developed for this research study.

4.5.6. Activity profile calculation

The aim of the analysis was to explore the change in the use of space that may derive from the effects of retrofit insulation on common patterns of activities. This method groups common daily activities from self-completion diary data from the sample group. 126 diaries were analysed (14 days x 9 dwellings), according to the following method.

The first step is concerned with the codification of the sequence of activities for each day and dwelling in which 126 sequences were obtained. The activities are classified according to Table 4.3.

Activity types	Activity code
Sleeping	A
Personal care	B
Mealtime	C
Creative and fun	D
Physical activities	E
Social activities	F
Work or study related	G
Joint activities	H
Cleaning	I
Out of home	J

Table 4.3. Activity types codified into 10 characters.

Secondly, sequences of activities are transformed on the activity profile by using a method to group the sequences (see more detail in Annex H). Identification of the activity profile is obtained by manipulating sequences of activities. One of the simplest methods of obtaining the activity profile is that of the use of a Position Weight Matrix (PWM) method. The PWM is a matrix M, generated by A×w, where A is a sequence of activities (e.g. A, B, C, An) and w is the length of a window on a sequence (e.g. 19 hours).

A position weight matrix can be obtained by using different methods such as a direct frequency method or Markov chain. Using parsimonious criteria a direct frequency method was chosen, whereby the matrix M for each pattern can be defined as the relative frequency of x at position p, selecting the highest value from each column in which each column represents a probability distribution (Dong and Pei, 2007). The suitability of the PWM method was first tested using data from the pilot survey. More detail is given in Annex H.

Two activity profiles for pre- and post-retrofit are constructed by using this method. The two activity profiles are diagrammed and compared to provide a means of evaluating the change in the use of space before and after the upgrade in Figures 4.3 and 4.4.

Figure 4.3 shows the pre-retrofit activity profile to represent how occupants perform common in-home activities.

	Time period																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Activity frecuency above 20%	56%	28%	21%	25%	34%	43%	29%	34%	35%	27%	34%	34%	31%	33%	35%	45%	33%	58%	82%
	27%	26%	20%	24%	26%	20%		21%	20%	26%	25%						33%		
		22%		21%															
Activity Profile	A	D	D	D	J	J	J	J	J	J	D	D	D	D	D	D	A	A	A
	B	A	C	I	D	D		D	D	D	J						D		
		B		J															

Figure 4.3. Pre-retrofit activity profile including the most frequent activities whose frequency is above 0.2.

Figure 4.4 shows the post-retrofit activity profile to represent how occupants perform different in-home activities.

	Time period																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Activity frecuency above 20%	71%	44%	30%	28%	42%	39%	35%	36%	36%	30%	51%	36%	23%	24%	34%	34%	40%	77%	92%
	12%	19%		26%	28%	30%	33%	27%	21%	23%		25%	21%	23%	28%	22%	37%		
													21%						
Activity Profile	A	B	C	J	J	D	D	J	J	J	J	J	D	D	D	D	D	A	A
	B			I	D	J	J	D	D	D	D	D	C	J	J	J	A		
													J						

Figure 4.4. Post-retrofit activity profile including the most frequent activities whose frequency is above 0.2.

Finally, the activity profiles are:

Pre-retrofit =
[AB][DAB][DC][DIJ][JD][JD][JD][JD][JD][JD]DDDDDD[AD]AA;

Post-retrofit =
[AB][B][C][JI][JD][DJ][DJ][JD][JD][JD][JD][JD][DCJ][DJ][DJ][DJ][DA]AA.

4.5.7. Actively occupied rooms calculation

The aim of the analysis was to explore whether the level of activities change during the time that occupants were at home as a response to the retrofit. The activities that occupants perform within a day were derived from the activity profiles constructed in the previous section 4.5.6. Following this, the activities have been matched to metabolic rates from Table 4.4.

Activity	Metabolic Rate (met unit)
Sleeping	0.7
Reclining	0.8
Seated, quiet	1.0
Standing, relaxed	1.2
Reading, seated	1.0
Writing	1.0
Cooking	1.6–2.0
House cleaning	2.0–3.4
Seated, heavy limb movement	2.2
Dancing, social	2.4–4.4
Calisthenics/exercise	3.0–4.0

Table 4.4. Metabolic Rates for Typical Tasks. Source: '*Table 5.2.1.2 Metabolic rates for Typical tasks*' (ANSI/ASHRAE, 2013)

The number of hours per day that rooms might be actively occupied is a binary status 0 and 1 that represents the condition of occupied rooms when the met is ≥ 1.

The metrics' change in actively occupied rooms is calculated as:

$$\Delta Ao = Ao2 - \mathbf{Ao1} \qquad \text{Equation 4-5}$$

Where:

Δ *Ao* is the difference in the number of hours per day that occupants might occupy their rooms, pre- and post-retrofit;

Ao1 is the number of hours per day that occupants might occupy their rooms pre-retrofit;

Ao2 is the number of hours per day that occupants might occupy their rooms post-retrofit.

4.5.8. Use of heating

This study uses self-completion heating diaries to understand if the energy efficiency upgrade changes the perception of heating patterns. An analysis based on the information of the self-completion heating diaries was planned, but this metric was not further developed because self-completion heating diaries were handed back in blank.

4.5.9. Thermal comfort perception calculation

This study investigates the changes in the perception of thermal comfort following retrofit insulation. Thermal comfort perception data were collected from the structured questionnaires carried out pre- and post-retrofit (see Section 4.3.3 and questionnaire in Annex E). This study compared the change in mean thermal comfort perception. In addition, the mean thermal comfort-related topics perception was also measured such as level of draught, noise level (external noise), external appearance and level of health (related to cold–diseases).

4.5.10. Theme analysis

Two sets of analysis were carried out on the interview data, one for the predetermined themes related to:

- Use of main heating and secondary heating,
- Thermal comfort perception,
- Ventilation,
- Infiltration;

while the other analysis method was used to analyse the emergent themes from the post-retrofit data. Three or more quotes were linked and superimposed to form a theme from this analysis.

4.6. Limitations of the Data Collection Methods

Quasi-experimental methods have proved to be useful in other research studies (Hong *et al.*, 2006; Oreszczyn *et al.*, 2006; Love, 2014). However, they have known theoretical and practical limitations (Sorrell, 2007). In this study there have been major practical limitations. First, exogenous factors, which may modify the demand of the energy service, and confounding variables[40] have not been fully controlled. Second, there was the use of a small and non-randomised sample size, 15 participants for measuring the internal air temperature with a high attrition rate of 40%. Third, there was a reduced spatial and data capture monitoring set-up (one internal air temperature data logger in each participant's living room) and reduced time-resolution data (space heating consumption collected one per month).

The study includes qualitative measures, which enables the study of interactions between occupants and the physical system. However, self-completion diaries have limitations such as the 'risk of honest forgetfulness' and the 'risk of retrospection error' which may lead to 'uncertain compliance' (Bolger *et al.*, 2003, p. 594). Although the qualitative and quantitative information was tested with the concurrent triangulation design, in which self-completion diary data, follow-up interviews, internal air temperature and space heating consumption data were used to check the findings. Furthermore, follow-up interviews were used to corroborate the information from self-completion diaries. Acknowledging these limitations, this study sought to capture only the general routine of the occupants from the diaries. The use of space was evaluated estimating the activity profile, which represents the common patterns of activities, and estimating the actively occupied rooms, which represent the level of activities at home.

[40] Differences in the space-heating outcome in the target building and control building that are not due to the retrofit insulation.

It is important to note that these measurements do not give information to quantify how much heating consumption has changed (or the heating periods) as a result of retrofitting. This is not an exact description of every practice under the use of either space concept or exact number of hours of heating. But rather it is expected to explain qualitatively the change in the use of space following retrofit, understanding the circumstances of individual households and factors which might be lost in an analysis of space heating consumption or internal air temperatures by itself.

In the Discussion Chapter, theoretical and practical limitations are critically explored to suggest how the methodology could be improved in future studies.

4.7. Summary

This chapter has outlined the research methods used for the data collection, analysis and construction of metrics. The research methods for data collection such as detailed monitoring, meter readings, structured questionnaire, self-completion diaries and follow-up interviews, and a semi-structured questionnaire, have been explained and justified. This chapter explains also how the study was implemented in eight stages, in order to capture long-term patterns of physical monitoring and occupancy data in a high-rise social housing building.

This chapter has also described the data analysis steps and the metrics constructed to answer the Research Questions in Chapters 5, 6 and 7. Finally, this chapter has also described the main methodological limitations of this research.

Chapter 5. Results Part 1: Internal Air Temperatures and Space heating Consumption

5.1. Introduction

To understand the effect of retrofit insulation in a high-rise social building, four research questions have to be addressed:

- How do internal temperatures change following an imposed building fabric retrofit insulation?

- How does space heating consumption changes following an imposed building fabric retrofit insulation?

- Which interactions between occupant behavioural factors and physical factors may produce space heating consumption change?

- Why do internal air temperatures change afterwards?

These Research Questions are situated within current research assumptions and the main theoretical approaches (Chapter 2). The first and second Research Questions are based on the premise that temperature take-back after a retrofit exists and can be observed (see research assumptions in Section 2.4). Previous quantitative studies have measured the temperature take-back, which is usually higher in low-income dwellings, as those are often not warm enough for occupancy (Milne and Boardman, 2000; Sorrell *et al.*, 2009) (Section 2.4). However, it was also shown that there is a limited understanding of the relationship between temperature take-back and low-income dwellings as other variables also influence the space heating consumption following retrofit as pre-intervention internal temperatures.

First, the results related to internal air temperatures (Research Question 1) are presented in this chapter, according to the data analysis procedure described in

Section 4.5. Section 5.2.1 shows the change of mean internal air temperature, standardised at 5˚C external temperature, following retrofit and Section 5.2.2 shows the internal temperature profile. This profile is constructed to understand whether the study's internal temperature profile follows the heating regime assumption of the BREDEM-12 internal temperature profile (Anderson *et al.*, 2002).

The results related to the impact of the energy efficiency retrofit interventions on changes in space heating consumption (Research Question 2) are presented in Section 5.3. Section 5.3.1 shows the normalised space heating consumption following retrofit for the target building and the relative difference between the target building and control group building. Section 5.3.2 shows a comparison of the gas consumption of the target building with the national average. The reader is reminded that each table and graph shown in this thesis should be interpreted with caution, because it is unlikely to be representative of a larger sample than the building scale studied.

5.2. Internal Air Temperature

5.2.1. Mean standardised internal air temperature

Figure 5.1 shows internal air mean temperatures at different external temperatures before and after the retrofit. Figure 5.1 also shows that the mean standardised internal air temperature (at 5°C external temperature) ranged from 22.07°C to 22.53°C for the sample (9 dwellings). This is +0.46°C or +2% higher than before the upgrade.

If it is assumed that 21°C, the recommended temperature for healthy environments (DCLG, 2006), is the maximum level of thermal comfort, then Figure 5.1 shows that the internal threshold temperature was achieved even before the retrofit. This may suggest that the fabric efficiency upgrade increased internal air temperatures beyond the recommended internal air temperature for a healthy environment.

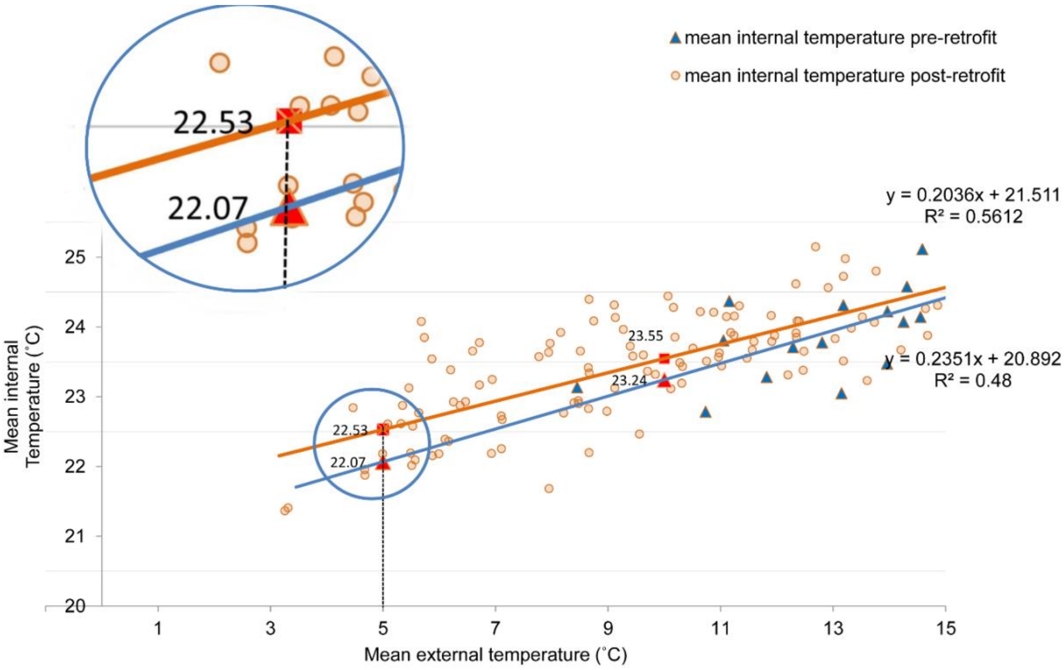


Figure 5.1. Standardised mean internal air temperature of the target building, at 5°C external temperature. Pre- and post-retrofit (n = 9).

5.2.2. Internal temperature profile

Figure 5.2 and Figure 5.3 illustrate the observed internal temperature profile, pre- and post-retrofit respectively. Figure 5.2 and Figure 5.3 are represented by a fourth-order polynomial and show that the mean internal temperature profiles (non-standardised), pre-and post-retrofit, are similar. Furthermore, the figures show that the maximum temperature difference within a day is negligible. For example, pre-retrofit, there is a small difference of less than 1°C between 23.7°C and 24.5°C within a day. Post-retrofit, there is also a small difference from 22.8°C to 24.0°C (1.2°C). These small maximum temperature differences (1°C-1.2°C) suggest that before and after the retrofit dwellings have a quasi-flat internal temperature profile.

This profile is constructed to understand if the study's internal temperature profile follows the heating regime assumption of the BREDEM-12 internal temperature profile. BREDEM assumes a fixed heating demand. For zone 1, the living room, the heating demand temperature (thermostat heating) is 21°C, while the heating period is 9 hours on weekdays (07:00-09:00 hrs, 16:00-23:00 hrs), and 16 hours at weekends (07:00-23:00) (Anderson *et al.*, 2002; Huebner *et al.*, 2013a). Outside these time periods the heating is assumed to be off (Anderson *et al.*, 2002; Huebner *et al.*, 2013a) (see Figure 2.5. p.47).

The flat internal temperature profile of this study does not follow the heating regime assumption of the BREDEM-12 internal temperature profile (Anderson *et al.*, 2002). This may suggest the absence of occupant-controlled heating periods and the heating period length changes as defined by BREDEM-12. See h1 and h2 defined heating period lengths in Figure 2.5. p.47. Consequently, this absence of pre- and post-retrofit heating periods may suggest that the increase in the standardised mean internal air temperature following the upgrade (+0.46°C) is the result of unheated periods. In other words, the increase in the standardised mean internal temperature is the result of building-related physical processes rather than occupant behavioural factors.

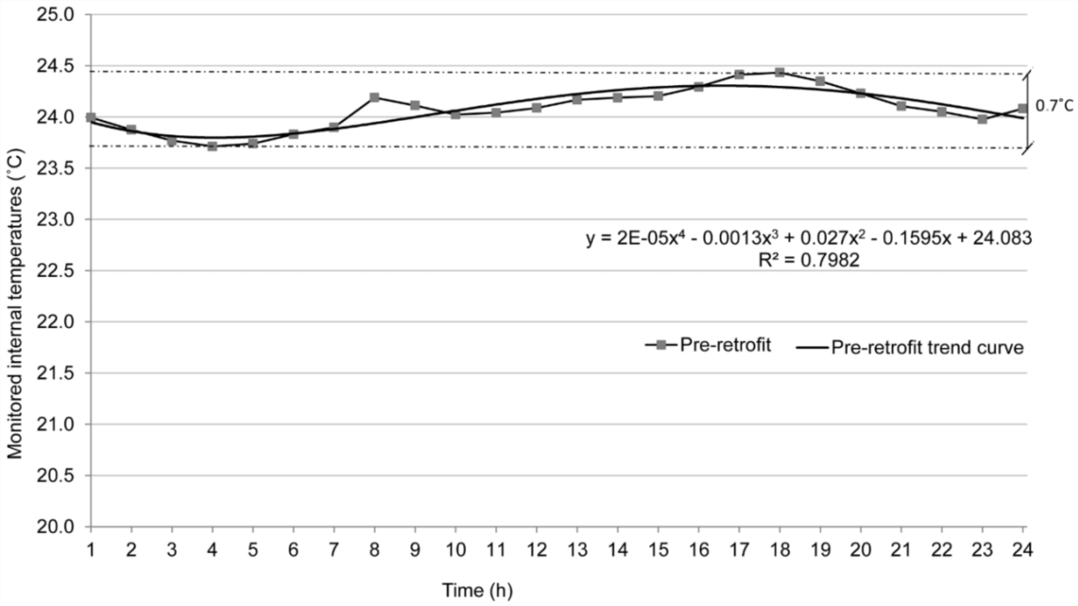


Figure 5.2. Internal temperature profile, pre-retrofit (non-standardised mean internal air temperature) (n = 9).

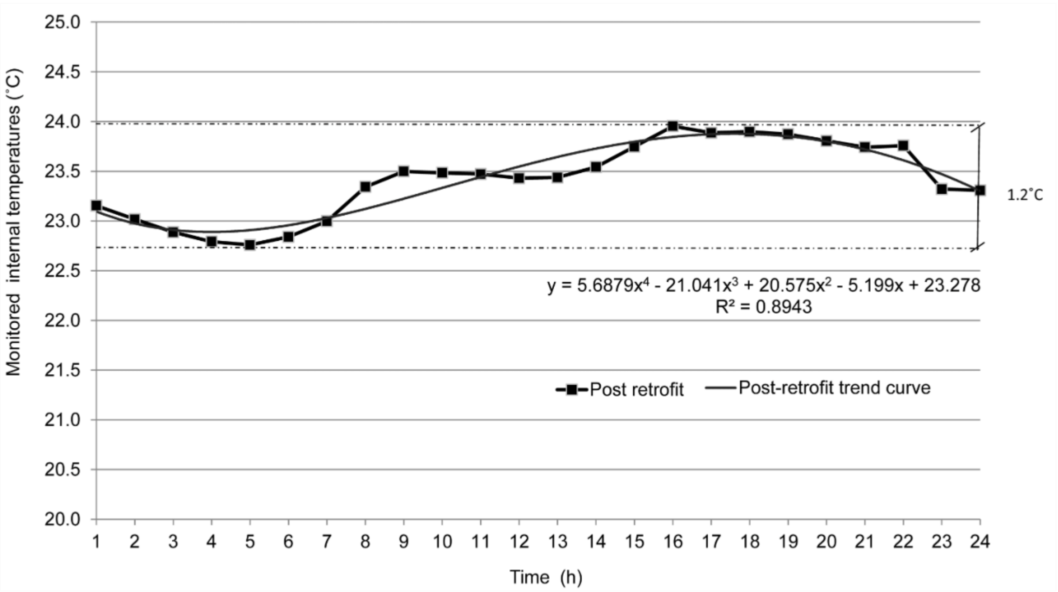


Figure 5.3. Internal temperature profile, post-retrofit (non-standardised mean internal air temperature) (n = 9).

This can also be seen in Table 5.1, in which the single shift in internal air temperatures was 0.3˚C from 08:00 to 09:00 (pre-retrofit) and -0.5˚C from 23:00 to 00:00 (post-retrofit).

Time hr	Time range (hr)	Mean internal air temperature Pre-retrofit (˚C)	Change in mean internal air temperature Pre-retrofit per hour (˚C)	Mean internal air temperature Post-retrofit (˚C)	Change in mean internal air temperature Post-retrofit per hour (˚C)
1	01:00 - 02:00	24.0	-0.1	23.2	-0.1
2	02:00 - 03:00	23.9	-0.1	23.0	-0.2
3	03:00 - 04:00	23.8	-0.1	22.9	-0.1
4	04:00 - 05:00	23.7	-0.1	22.8	-0.1
5	05:00 - 06:00	23.7	0	22.8	0
6	06:00 - 07:00	23.8	0.1	22.8	0
7	07:00 - 08:00	23.9	0.1	23.0	0.2
8	08:00 - 09:00	24.2	0.3	23.3	0.3
9	09:00 - 10:00	24.1	-0.1	23.5	0.2
10	10:00 - 11:00	24.0	-0.1	23.5	0
11	11:00 - 12:00	24.0	0	23.5	0
12	12:00 - 13:00	24.1	0.1	23.4	-0.1
13	13:00 - 14:00	24.2	0.1	23.4	0
14	14:00 - 15:00	24.2	0	23.5	0.1
15	15:00 - 16:00	24.2	0	23.7	0.2
16	16:00 - 17:00	24.3	0.1	24.0	0.3
17	17:00 – 18:00	24.4	0.1	23.9	-0.1
18	18:00 - 19:00	24.4	0	23.9	0
19	19:00 - 20:00	24.3	-0.1	23.9	0
20	20:00 - 21:00	24.2	-0.1	23.8	-0.1
21	21:00 - 22:00	24.1	-0.1	23.7	-0.1
22	22:00 - 23:00	24.1	0	23.8	0.1
23	23:00 - 00:00	24.0	-0.1	23.3	-0.5
24	00:00 - 01:00	24.1	0	23.3	0

Table 5.1. Internal temperature profile (˚C) pre- and post-retrofit (non-standardised, n = 9).

5.3. Space Heating Consumption

5.3.1. Normalised space heating consumption

Table 5.2 shows that the change in normalised space-heating consumption following the retrofit for the space heating target building was -27%. Table 5.2 also shows that the change in mean space heating consumption in the control building during the same period was 7%. As a result, the relative difference between the target and control group is -34%.

	Target building Wh/K/m2/day	Control building Wh/K/m2/day	Difference Target vs Control Building (%)
Pre-retrofit 2014	0.0184	0.0460	
Post-retrofit 2015	0.0134	0.0494	
Δ %	-27%	7%	-34%

Table 5.2. Normalised space heating consumption percentage change in the target building, control building, and relative to each other.

5.3.2. Gas consumption in the target building and national average

Table 5.3 shows the annualised gas consumption for an average property in England and Wales with the following characteristics: floor area (50 m^2 or less); tenure (council housing); income (less than £15,000 per year); number of adults living at the residence (1 adult living at the property); and deprivation level (1st Quintile most deprived) for the years 2012 and 2013. This gas consumption is compared with the target building.

The comparison shows that the target building dwellings consumed considerably less than an average national consumer, in each category and every year analysed. For instance, in 2013 this difference was more than 5000 kWh per year in each category. This comparison should be treated with caution, because UK national gas consumption has been adjusted to external temperature. The normalised space heating consumption following the retrofit for the target building of -27% or -34% relative to the control building is contextualised relative to the national average and should be seen in the context of low gas consumption for the target building (see also SHC including all the meter readings, estimated and directed, in Annex I).

	Annualised mean gas consumption (kWh)					
Year/ Category	Target building (n=88)	50 m^2 or less[1]	By tenure, council housing[2]	Less than £15,000 per year income [3]	By number of adults; 1 adult [4]	1st Quintile (most deprived)[5]
2012	1632	7400	10700	11700	11900	11600
2013	1660	7300	9800	11200	11400	11100

[1]Table 1: Gas consumption by floor area (square metres). England and Wales

[2]Table 9: Gas consumption by tenure. England and Wales `

[3]Table 11: Gas consumption by household income. England and Wales

[4]Table 13: Gas consumption by number of adults. England and Wales

[5] Table 23: Gas consumption by Index of Multiple Deprivation (England)

Table 5.3. Annualised mean gas consumption for England and Wales against the target building consumption between 2012 and 2013. Source: DECC (2013a)

5.3.3. Electricity consumption for the non-heating season

Table 5.4 compares the mean electricity consumption between pre- and post-retrofit between June and September (non-heating season) 2014/2015, in order to understand if occupants may adapt their environment by using cooling appliances (i.e. fan, air conditioning) after the retrofit. The change in electricity consumption following the retrofit for the target building (n = 8) was +2%. Thus, the presence of energy efficiency retrofits appears to have not much of an impact on electricity-consumption increases in the non-heating season. However, it should be noted that these data have not been weather-standardised, because there is not enough information to determine which proportion of the electricity consumption is related to cooling appliances and only a small sample size was analysed.

Electricity consumption (n=8)	Mean electricity consumption (kWh)	Standard error of mean (kWh)
Pre-retrofit	123	16
Post-retrofit	126	20
Δ %	(2%)	

Table 5.4. Mean electricity consumption pre- and post-retrofit and standard error of mean in the target building. Source: monitored energy meter readings (n = 8).

5.4. Conclusion

This chapter set out to answer Research Questions 1 and 2. The first Research Question – How do internal temperatures change following an imposed building fabric retrofit insulation? was answered by comparing the changes of the mean standardised internal air temperature and the internal temperature profile, before and after the retrofit by using monitored data from 9 flats.

The mean internal air temperature increased +0.46˚C, or 2% following the upgrade, from 22.07˚C to 22.53˚C (at standardised condition 5˚C external temperature). If 21˚C is defined as the 'comfort temperature' desired by occupants, the energy efficiency upgrade increased internal temperatures beyond the "comfort temperature". In addition, the analysis of the internal temperature profile suggests that dwellings tended to have a flat temperature profile, which contrasted with the BREDEM-12 (Anderson *et al.*, 2002) heating regime assumption of constant daily heated hours throughout the heating season. Hence, this may imply that the increase in the mean internal temperature is due to physical processes, since the increase of the mean internal air temperature is the result of the unheated periods.

The second Research Question – How does space heating consumption change following an imposed building fabric retrofit insulation? was answered by comparing the changes of normalised space heating consumption pre- and post-retrofit. The normalised space heating consumption change following the retrofit relative to control group was -34%. The results of space heating consumption seems like a very successful undertaking; however, a 34% space heating consumption reduction after the retrofit should be seen in the context of low gas consumption for the target building. In addition, the presence of energy efficiency retrofits appears to have very little impact on electricity consumption in the non–heating season (i.e. cooling).

In attempting to explain the effects on space heating consumption and internal air temperature, this type of analysis of monitored data has been successful. However, it has limitations, since it cannot explain which interaction between behaviour and the physical factor may explain the change in space heating consumption following the retrofit. The next chapter addresses these limitations by the analysis of how occupants adjust the use of space and thermal comfort perception. In addition, Chapter 7 includes the insight gained through the face-to-face interviews to understand why those outcomes occurred.

Chapter 6. Results Part 2: Interactions between Occupant Behavioural and Physical Factors

6.1. Introduction

The previous chapter described how the mean internal temperature and space heating consumption changed following the retrofit. This Result Chapter is devoted to understanding which interaction between behavioural and physical factors may produce a space heating consumption change (Research Question 3).

Research Question 3:

- Which interactions between occupant behavioural factors and physical factors may account for space heating consumption change?

The third Research Question is based on the premise that physical and occupant behavioural factors seem to form a complex system (Lowe *et al*., 2012; Love, 2014), in which temperature take-back is accounted for by the physical factors and the remainder by the occupant’s behavioural change (Hong *et al.*, 2006; Sanders and Phillipson, 2006; Sorrell, 2007) (see research assumptions in Section 2.4). However, to date, the factors determining energy use in buildings are complex and often poorly understood (Oreszczyn and Lowe, 2010). Based on previous research this research proposed to investigate how occupants may adjust the use of space and use of heating.

Trying to catalogue the types of interactions in the use of space that may occur following retrofit insulation, this research proposed to study: 1) changes that may derive from the effects of retrofit insulation on the common patterns of activities (activity profile); and 2) the change in the level of activities during the time that occupants were at home, as a response to retrofit insulation (actively occupied room).

In addition, this study uses qualitative methods to understand whether the energy-efficiency upgrade changes the perception of thermal comfort.

6.2. Activity Profile

Figure 6.1 shows the activity profile or the common daily activities[41] performed pre- and post-retrofit. Figure 6.1 also shows that the common activities performed pre- and post- retrofit, in the same period, were similar. In general, a morning period of activity (i.e. cleaning, cooking and personal care), is followed with a period of inactivity when the occupants may go out or perform an activity at home classified as creative and fun, such as watch TV. Following this period, after 17:00, there is another period of activity until 22:00, when bed-time comes. Perhaps, the major difference between pre- and post-retrofit seems to be that post-retrofit emphasises the likelihood of being out-of-home between 17:00 and 22:00 hrs. Consequently, comments collected from the participants through the follow-up interviews also indicated the occupants do not perceive that retrofit insulation changes common routines at home.

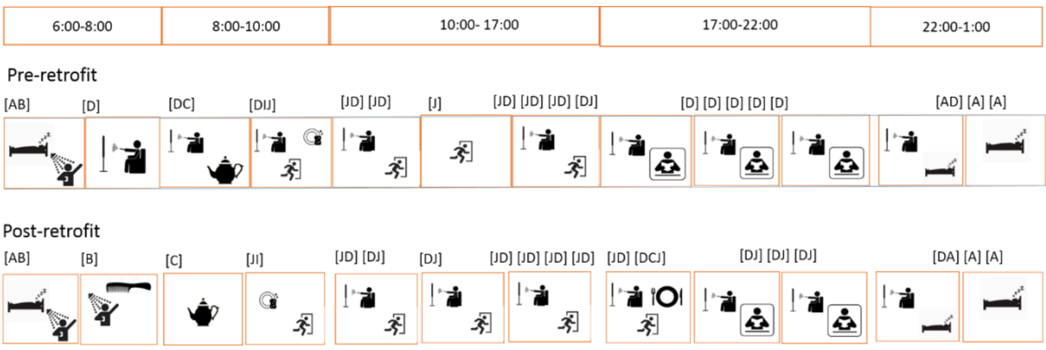


Figure 6.1. Graph showing the activity profiles, pre- and post-retrofit.

41 10 daily activities measured (see Annex H).

6.3. Actively Occupied Rooms

Table 6.1 shows that the level of activities during the time that occupants were at home between 06:00 to 01:00. Table 6.1 also shows that a shift in the level of activities that rooms might be actively occupied (>=1 met), pre- and post-retrofit was similar. It should be noted that this metric is not a measurement of space heating consumption and therefore does not give quantitative information about how much heating consumption has changed (or the heating periods) as a result of retrofitting. It shows, however, that the number of hours that level of activities measured through metabolic rate did not change considerably.

6.4. Use of Heating

It was not possible to categorize the heating periods of the dwellings from the self-completion heating diaries, because most of them did not use the heating at all. Self-completion 'heating diaries' were most of the time returned blank even in the pre-retrofit surveying periods and others had very inconsistent heating schedules, for example, a short length of time after the shower.

	Pre-retrofit			Post-retrofit		
Time period	Activity profile *	Average Met unit **	Actively occupied rooms (hrs)	Activity profile *	Average Met unit **	Actively occupied rooms (hrs)
06:00-07:00	[AB]	1.0	1	[AB]	1.0	1
07:00-08:00	[DAB]	1.0	1	[B]	1.2	1
08:00-09:00	[DC]	1.4	1	[C]	1.8	1
09:00-10:00	[DIJ]	1.9	1	[JI]	2.7	1
10:00-11:00	[JD]	1.0	1	[JD]	1.0	1
11:00-12:00	[JD]	1.0	1	[DJ]	1.0	1
12:00-13:00	[J]	0	0	[DJ]	1.0	1
13:00-14:00	[JD]	1.0	1	[JD]	1.0	1
14:00-15:00	[JD]	1.0	1	[JD]	1.0	1
15:00-16:00	[JD]	1.0	1	[JD]	1.0	1
16:00-17:00	[DJ]	1.0	1	[JD]	1.0	1
17:00-18:00	[D]	1.0	1	[JD]	1.0	1
18:00-19:00	[D]	1.0	1	[DCJ]	1.4	1
19:00-20:00	[D]	1.0	1	[DJ]	1.0	1
20:00-21:00	[D]	1.0	1	[DJ]	1.0	1
21:00-22:00	[D]	1.0	1	[DJ]`	1.0	1
22:00-23:00	[AD]	0.9	1	[DA]	0.9	1
23:00-00:00	[A]	0.7	0	A	0.7	0
00:00-01:00	[A]	0.7	0	A	0.7	0

(*) activities described in Table ‘Activity types’ in Annex H

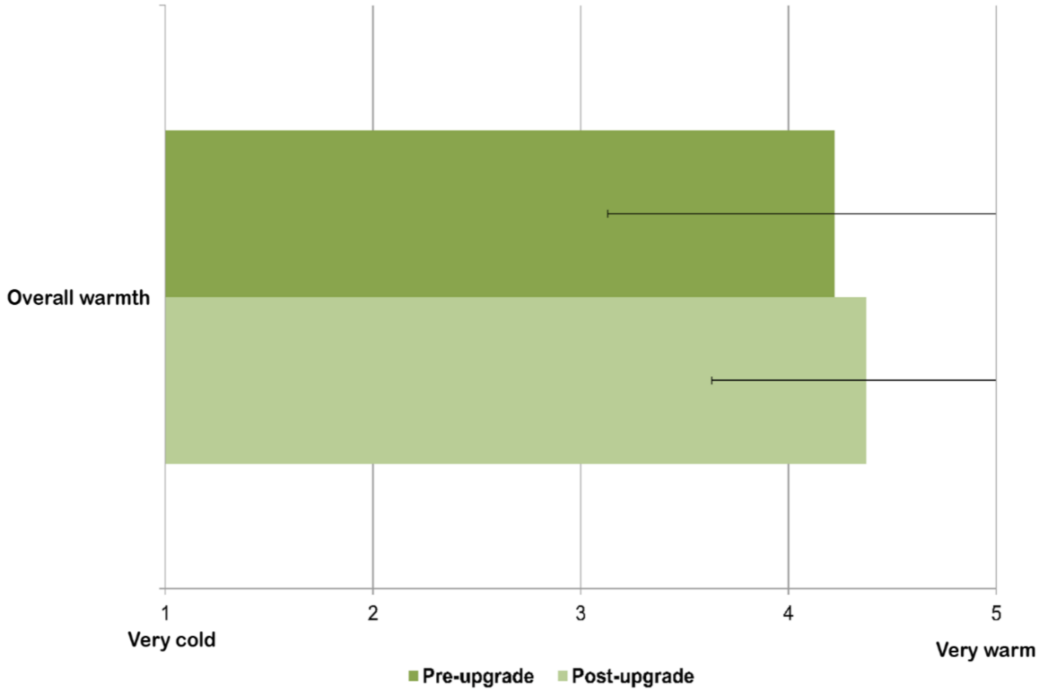
(**) met unit described in Table 5.4.

Table 6.1. Actively occupied rooms pre- and post-retrofit (n = 9).

6.5. Thermal Comfort Perception

Figure 6.2 shows that the energy efficiency upgrade appears to have been associated with an increased thermal comfort perception in which occupants reported transitioning from feeling warm to very warm. This topic is further investigated with qualitative data in Chapter 7.

The thermal comfort-related topics in Table 6.2 show that it appeared that the building had an improvement from bad to good (mean). In addition, both the level of draught and perceived cold-related illness were not perceived as big improvements since they were well evaluated before the upgrade.



Items used a 5-point Likert scale (for example 1= Very cold, 2 = cold, 3 = neutral, 4 = warm, 5 = Very warm)

Figure 6.2. Bar plot of mean thermal preferences (n = 9), the lines in the bars represent the standard deviation votes of thermal perception, pre- and post-retrofit.

	Mean	
Thermal comfort-related topics	Pre-retrofit	Post-retrofit
Appearance	4 - bad	2 - good
Cold-related illness	2 - good	2 - good
Draught	3 - neutral	5 - no draught at all

Table 6.2. Mean preference votes of ‘cold-related illness’, appearance and draught from the longitudinal study (n = 9).

6.6. Conclusion

This chapter set out to answer Research Question 3, namely: which interactions between occupant behavioural factors and physical factors may account for space heating consumption change?. Based on previous research assumptions (Section 2.4), this research proposed to investigate how occupants may adjust the use of space and use of heating.

Trying to catalogue the types of interactions in the use of space that may occur following retrofit insulation, this research proposed to study: 1) changes that may derive from the effects of retrofit insulation on the common patterns of activities (activity profile); and 2) change in the level of activities during the time that occupants were at home, as a response to retrofit insulation (actively occupied room). The results showed that the common activities performed pre- and post-retrofit, in the same period, were similar in terms of metabolic rates and time of the day, pre- and post-retrofit.

In addition, this study uses qualitative methods to understand if the energy efficiency upgrade changes the perception of thermal comfort. The study also found that the presence of the energy efficiency upgrade appears to be associated with an increased thermal comfort perception, transitioning from a perception of feeling warm to very warm. Appearance of the building had a perceived improvement and both the level of draught and perceived cold-related illness were not perceived as big improvements since they were well evaluated before the upgrade. It was not possible to categorize the heating periods of the dwellings from the self-completion heating diaries, because most of them did not use the heating at all.

Chapter 7. Results Part 3: Why Internal Air Temperatures Change Afterwards?

7.1. Introduction

Having described in the previous chapters the detailed findings from the following Research Questions:

- How do internal temperatures change following an imposed building fabric retrofit insulation?

- How does space heating consumption changes following an imposed building fabric retrofit insulation?

- Which interactions between occupant behavioural factors and physical factors may account for that space heating consumption change?

this part of the analysis is devoted to gain qualitative insights to answer the research question:

- Why do internal air temperatures change afterwards?

Sections 7.2 and 7.3 show the perception of heating usage. The perception of the level of warmth is described in Section 7.4. Following this, Sections 7.5 and 7.6 address the perception of infiltration and ventilation. Other perceived positive outcomes of the retrofit such as a reduction in noise and external appearance improvement are described in Section 7.7. Finally, the level of knowledge of the occupant about the imposed retrofit insulation is described in Section 7.8.

7.2. Heating Usage

The level of heating usage mentioned by the occupants, pre- and post- retrofit is low. A male participant mentioned that they have not switched-on the heating for years.

"I've never used ... strange enough they are coming to check the heating now, because I think they looked at the meter and you see it doesn't move for so many years, and so maybe they think is broken ... it doesn't move because I've never turned up"

(Participant 5, post-retrofit interview).

A male occupant described that he had switched-on the heating only on cold days.

"Since March, which was the same with the previous system (referring to the heating periods), I don't have the heating on, other than one or two extreme, extremely cold days, which you will see on the survey ... they got switched-on in the back of April, for I think it was just for 1 hour or 2, 2 or three days, that was all. But generally, the heating's not been on since March"

(Participant 4, post-retrofit interview).

Participant 8 mentioned that he does not use the heating even pre-retrofit, *"I've never used my heating anyway in the whole time that I've been in here"* (Participant 8, post-retrofit interview).

This was also evident when occupants were asked to fill in self-completion 'heating diaries' (Section 6.4). It was not possible to categorize the heating periods of the dwellings using the heating diaries, because most of them did not use the heating at all (self-completion 'heating diaries' were most of the time returned blank even in the pre-retrofit surveying periods) and others had very inconsistent heating schedules, e.g. a short length of time after the shower.

7.3. Secondary Heating

Before the retrofit it was unusual that the occupants felt the need to use secondary heating. Structured interviews were carried out to identify the ownership and use of secondary heating during the retrofit process, and during the different stages of the retrofit process (see Section 5.4) it was showed that residents did not use other heating sources such as electrical heaters. At the time of the pre-retrofit monitoring all of them mentioned that they regularly do not use the primary heating system, and neither had they used a backup heating (secondary system). Although, at the time of the post-retrofit interview, a participant did mention the use of secondary heating, but rarely, this appeared to be because of the noise of the primary heating.

7.4. Thermal Comfort

Consistently with the thermal comfort perception in Section 6.5 and the mean internal temperature (>22º C), the post-retrofit interviews show that they have transitioned from a level of warm to very warm.

"I can't see any difference … It feels about the same to me … really warm" (Participant 1, post-retrofit interview).

Moreover, concern about the summer time increased post-retrofit.

"It feels warm straight away, after the insulation of the wall, like you know … the only thing that I don't know when you got the summer, it is really hot" (Participant 3, post-retrofit interview).

7.5. Ventilation

From the interviews opening windows appears to be the mean way of cooling down the flats. According the occupants' views, opening the windows wide was a common behaviour even before the retrofit.

"*I always have windows open all the time*" (Participant 1, post-retrofit interview);

"I tend to have at least one window open or a couple of windows open for ventilation in and out, but it hasn't changed, I'm still doing the same amount, and I can't see any comparative difference at this stage"

(Participant 4, post-retrofit interview).

One participant noticed an increase in his windows opening behaviour after the retrofit - *"I have to open the windows this year, just for a bit of fresh air"*

(Participant 3, post-retrofit interview).

A conflict between fresh air and warmth was noticed during the night time by the same male participant.

"It is still warm you know (after retrofit), I feel it more at night time in bed. It is like a sauna sometimes, but the thing is you can't leave the windows open at night because the draught […] is very uncomfortable"

(Participant 3, post-retrofit interview).

However, on the positive side, the fact that residents can open the windows and "control" the level of ventilation was well evaluated.

"The ventilation is pretty good, when you open the windows"

(Participant 3, post-retrofit interview);

"If you can open fully way [it] is good, it is alright until you get really hot ... in very hot weather you need the windows wide open, because of the insulation now you don't lose so much heat"

(Participant 8, post-retrofit interview).

7.5.1. The use of fans

The use of fans emerged from the conversations as a mechanism of adaptation for cooling down the flats, which may have implications in the energy consumption in summer or under future uncertain (warmer) climate conditions.

"It is fine, I just open the windows, if it gets hot, you know, I use my fan"

(Participant 1, post-retrofit interview);

"I'm using the fan a bit so it is getting a bit too warm"

(Participant 8, post-retrofit interview).

The analysis of electricity consumption in the non-heating season in Section 5.3.3 showed that there is not a considerable difference between the summer electricity consumption before and after the retrofit. However, the electricity consumption analysis may have a bias since the comparison was not weather-standardised as it was not possible to isolate the cooling appliances' consumption with the other appliances. In addition, it includes September 2014, when the retrofit process started.

7.6. Infiltration

Infiltration is referred to as an involuntary draught or air exchange through unsealed parts of the building fabric such as the wall, windows or doors. Occupants mentioned that they did not experience any draughts with the previous windows. Although another finding emerged from the interviews; some residents commented on draughts through the door.

"The only draught that I get is when it's windy is from the front door … when it is really windy, wind comes up from the staircase, you can't really stop it … like you know"

(Participant 3, post-retrofit interview);

"*... but the door still occasionally bang, I get a draught by my main door"*

(Participant 5, post-retrofit interview).

This leads to another problem, the corridor has been mentioned by the occupants as a common area where the heat is concentrated, although the opinions are diverse about whether or not the installation of new windows improved the air ventilation and indoor temperatures decreased in the corridor:

"I think it's still the same, in fact that they modernised the windows, but it was still the same windows, it is the last window, it is not really big…"

(Participant 3, post-retrofit interview);

"The corridor has a vast improvement, because overheating isn't player anymore, because previously you could not use the windows, because of the extreme windows' draught that come through, so you now can open the windows so the air outside in the corridor can circulate ventilation and temperature is down. So that it is good"

(Participant 4, post-retrofit interview);

"The corridor, it is as hot as it was"

(Participant 8, post-retrofit interview).

7.7. Other Positive Outcomes from the Retrofit Insulation

Occupants also commented about the positive effects of the retrofit such as the reduction in noise and the improvement in external appearance:

"The building looks better on the outside and it is a pity that they have not done inside" (Participant 1, post-retrofit interview);

"As I said, there is no noise I can't hear anything"

(Participant 3, post-retrofit interview);

"It is definitely more quiet [sic], no external noise, so that's a good thing"

(Participant 5, post-retrofit interview).

7.8. Level of Knowledge of the Occupant about the Imposed Retrofit Insulation

Perceived understanding of the energy efficiency upgrade on actual energy savings was not clear for the occupants, mainly because the level of heating usage was low before the retrofit. Therefore, the extent to which dwellers perceived that the upgrade was positive for them was not clear. For example, occupants identified clearly the change with the windows, though they did not clearly perceive the benefit of changing the windows (apart from the aesthetic, which did not please everybody either).

> *"I did not see any difference, because before as well the windows were double-glazed, they were quite new, I mean in the heating as I told you before it is always warm, because of the people, the old people put the heating on"*
>
> (Participant 6, post-retrofit interview).

Note that this participant thinks the building is always very warm (even pre-retrofit) because other tenants (mainly the older ones) tend to turn the heating on all the time.

> Interviewer: *"Did you have any draught before with the previous windows?"*
>
> Participant: *"No, that's why I did not see why they changed it…"*
>
> (Participant 7, post-retrofit interview).

> *"I think it is the glass, and what they said was, they are supposed to keep the flat cool in the summer and warm in the winter, but to me it is just a myth … Why they are so thick?* (she asked to the window installer), *they said they are really good windows"*
>
> (Participant 2, post-retrofit interview).

7.9. Conclusion

This chapter provided a qualitative insight to explain why internal air temperatures change following retrofit insulation. This qualitative evidence may indicate that the studied building reached a limit of comfortable temperature. Participants reported the low heating usage in Section 7.2. In addition, occupants reported transiting from feeling warm to very warm (Section 7.4), the need for fresh air and the trade-off between fresh air and warmth during the night time (Section 7.5). The main adaptive action for cooling down the flat was opening windows. The changes are fairly consistently negative in terms of perception of an increase in temperature and ventilation; occupants perceived some positive effects of the retrofit such as the reduction in noise and the improvement in external appearance.

Chapter 8. Discussion

8.1. Introduction

Four research questions were chosen to address the extent of the retrofit insulation impact on space heating consumption in a high-rise social housing building:

- How do internal temperatures change following an imposed building fabric retrofit insulation?
- How does space heating consumption changes following an imposed building fabric retrofit insulation?
- Which interactions between occupant behavioural factors and physical factors may account for space heating consumption change?
- Why do internal air temperatures change afterwards?

The results discussed in the result chapters provided useful insights into temperature take-back after the building retrofit, but they are subject to theoretical and practical methodological limitations. In this chapter the results are first discussed in Section 8.2 and a critical light is shed on the methodology and ways for improving it are suggested in Section 8.3.

8.2. Results

8.2.1. Energy saving and temperature take-back

At first glance, the results of the upgrade[42] seem to be a very successful undertaking, providing a double-dividend; increased internal temperatures and reduced energy consumption for space heating. The study observed that there is a reduction in normalised space heating consumption of 27% or 34% (relative to the control group) and an estimated increase in mean internal air temperatures was +0.46˚C (from 22.07˚C to 22.53˚C). However, the empirical results do not support assumptions normally made about low-income dwellings 'taking back' energy savings as increased temperatures as the change in space heating consumption is negligible in absolute terms and temperature take-back is relatively small (0.46˚C), when it is compared to other authors, 0.73ºC[43] (Hong, 2011) or from 0.4°C to 0.8°C (Sorrel, 2007).

At the beginning of the research income restriction was proposed to explain the low level of heating usage. Previous studies concerned with fuel poverty have suggested that people tend to turn the heating down and/or limit heating to certain rooms to minimise fuel bill expenditure (Anderson *et al.*, 2010). However, the evaluations of the empirical results suggest that a saturation effect has taken place, which is explained in the next section.

8.2.2. Temperature take-back and saturation effects

The evidence collected from the study in the heating season suggests that the internal temperature of the target building is reaching a limit of a maximum level of thermal comfort (for example, 22.5˚C at 5˚C external temperature). Therefore,

---

[42] Following the combined installation of external solid wall insulation and double glazing

[43] Full insulation

it seems to support Sorrel's (2007) assumption that a saturation effect has taken place.

Living room temperatures in the retrofitted dwellings for the heating season under standardised external conditions of 5˚C temperatures are more than 2.5˚C higher than conditions reported by previous studies for dwellings with energy efficiency upgrades from the Warm Front study (Oreszczyn et al., 2006; Hong, 2011) and are also considerably warmer than the average English dwelling conditions (Shipworth et al., 2010). The evidence collected from the study suggests the flat dwellings following retrofit insulation are reaching an upper level for temperature demanded by occupants, the uncontrolled heat from the heating system and from hot water pipes probably may also contribute to saturation, which is regulated by frequent window opening.

This upper-level temperature may be taken as a saturation (neutral) temperature that corresponds to an indoor air temperature from 22.8˚C to 24.0˚C for living rooms. This result is consistent with saturation temperatures reported by Kavgic *et al.* (2012), the authors reported temperatures from 22.5–24.5˚C in dwellings with district heating, but it is higher than previous assumptions (Sorrell, 2007; Shorrock and Utley, 2008).

This is further supported by four observations from the study. First, high internal air temperatures were prevalent in the sample dwellings, both before and after the retrofit. For example, 63% of the pre-upgrade recorded internal temperature was above 23.5°C (Figure 8.1). This temperature is categorized by SAP-2012 as at 'high risk' of overheating (BRE, 2012) because, during hot weather, it is more likely to be exposed to high internal temperatures (Zero Carbon Hub, 2015). Second, space heating consumption is very low, before and after the retrofit and its change is negligible in absolute terms. Third, the dwellings tended to have a flat internal air temperature, which contrasted with the BREDEM-12 assumption of constant daily heated hours throughout the heating season (Anderson *et al.*, 2002). Fourth, the presence of the energy efficiency upgrade appears to have been associated with an increased thermal comfort perception in which occupants reported transitioning from feeling warm to very warm.

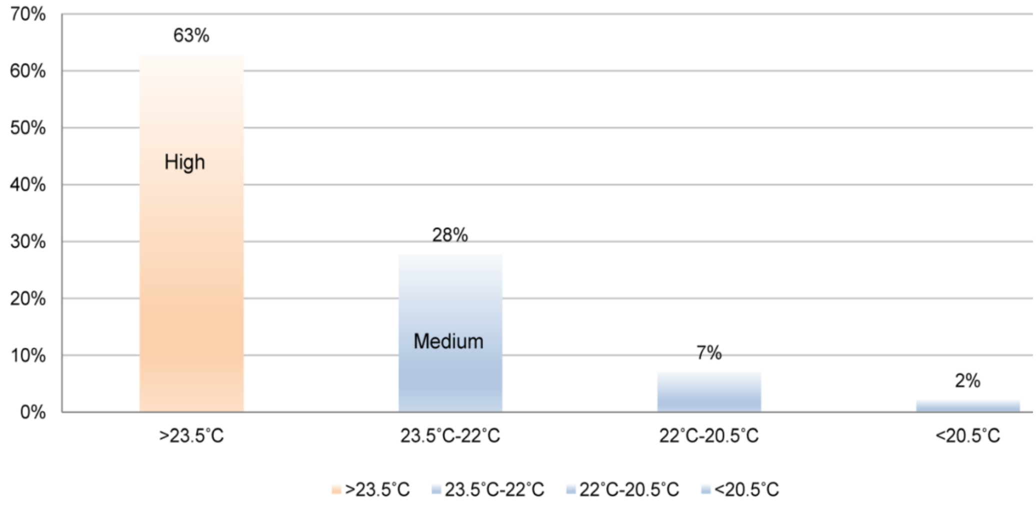


Figure 8.1. Frequency distribution of internal temperature above 23.5°C (%) – pre-retrofit insulation (n = 9).

8.2.3. Temperature take-back, and the relationship between physical factors and occupant behavioural factors

The results based on the analysis of the internal temperature profile suggest that a flat internal temperature profile in the heating season may be interpreted as showing that physical factors (such as the increase in thermal resistance of the building) could be playing a more important role than behavioural factors. The dwellings tended to have a flat internal temperature profile which contrasted with the BREDEM-12 assumption of constant daily heated hours throughout the heating season (Anderson *et al.*, 2002). This link, however, needs to be further investigated as recent studies have theorised that occupant behavioural and (building) physical factors form a complex system whose interactions change and co-evolve over time (Lowe *et al.*, 2012; Love, 2014).

8.2.4. Temperature take-back and occupant behavioural factors

The results suggest that the common daily activities were not adjusted in response to the retrofit insulation (as a response to the internal air temperature increases). This is in terms of metabolic rates and type of activities. Perhaps it is not surprising that the empirical evidence collected in this study does not support the idea of a change in the use of space, based on three main reasons.

First, flats are small (40-80m^2) and therefore there is not enough space for unoccupied areas, in which dwellers tend to use most of the space. Occupants in smaller dwellings are less likely to expand the use of space in comparison with larger dwellings with unheated rooms, as they perceive their dwelling as a 'single space' (DECC, 2013b). Second, it is not possible to limit heating to certain rooms to minimise fuel bill expenditure, as occupants only interact with their heating system through the 'on/off' button and thermostat or zoned controls are not available in the heating control system (Annex D) (at least the main fuel heating and there is no evidence of secondary heating usage). Third, if the dwellers would have decided to turn the heating down in every room to minimise fuel-bill expenditure, as mentioned by previous authors[44], the retrofit works seemed to make very little difference in changing heating usage.

8.2.5. Thermal discomfort

Qualitative evidence from interviews indicates a degree of thermal discomfort following the retrofit, in which occupants perceive a transition from warm to very warm (Sections 6.5 and 7.4). This thermal discomfort was also noticed at night time as a conflict between fresh air and warmth (Section 7.4). For example, a participant exemplifies this discomfort as sleeping in a 'sauna'. Occupants tend to adapt their environment when higher temperatures are experienced over an extended period (Zero Carbon Hub, 2015). For example, in order to maintain an adequate supply of fresh air following the upgrade, the occupants tend to keep the windows opened or increased the window-opening behaviour (Section 7.5). Other studies may offer further support to the idea that occupants tend to open the windows when higher temperatures are experienced. Papantoniou (2015) observed, in a study of similar high-rise social house buildings, that the east façade of the building has always more than 50% of windows opened, no matter the day or the time observed, ranging between 50% and 95%. However, Papantoniou's study has

[44] Although this was not mentioned by the participants.

to be interpreted with caution since the window-opening behaviour was observed over a short time period and does not take account of other behavioural data.

The thermal discomfort experienced by the occupants and the increase in the window-opening behaviour (as occupants can open their windows wide) may suggest the existence of a maximum comfortable temperature in the heating season. However, a risk of overheating in summer needs to be further investigated.

8.2.6. Measuring overheating

This study has not measured the effect of the retrofit on overheating, because it was not the purpose of the research. However, the qualitative results show changes in window-opening behaviour and thermal discomfort. More research is clearly needed to establish whether or not there is a risk of overheating, especially when there is a concern about the unintended overheating effects of a building fabric's retrofit on the occupant's health (Davies and Oreszczyn, 2012).

In order to study overheating, it is recommended to include direct monitoring in future attempts to measure overheating. This includes physical and behavioural data, in longitudinal studies, as is shown in this study. In addition, an overheating threshold needs a consensual agreement in the domestic sector to be reached. This research area (overheating) has several thresholds and approaches in different thermal standards (e.g.ANSI/ASHRAE, 2004; CIBSE, 2006) which generate confusion to classify overheating in a building.

In terms of absolute threshold, for example, CIBSE[45] set a design threshold that specifies discomfort temperature thresholds (CIBSE guide A). For a free-running building CIBSE suggests a discomfort temperature of 28°C for living room areas and 26°C for bedrooms (CIBSE, 2006), whilst overheating criteria are defined as an annual exceedance of the internal temperature over the discomfort threshold of more than 1%, for the period during which the home is occupied (CIBSE, 2006). A Standard Assessment Procedure (SAP) (Appendix P) provides a compliance tool

[45] Chartered Institution of Building Services Engineers

designed to test if a dwelling is at risk of high internal temperatures in summer. The calculation is based on steady state conditions, and takes into consideration heat gains and fabric characteristics of the building to calculate monthly mean summer internal air temperatures (Zero Carbon Hub, 2015). The risk of overheating is defined as over the monthly mean temperature of 23.5ºC. This temperature or higher is considered as "High level of risk associated" (BRE, 2012).

An adaptive model, on the other hand, takes into account the relationship between external conditions and internal temperatures in which occupants do not experience thermal discomfort. For example, CIBSE TM52[46] includes a definition and prediction of overheating in free-running buildings by incorporating the outdoor temperature. The overheating threshold is dynamic and sets out three criteria, with a 'pass' dependent on meeting two out of the three criteria (Zero Carbon Hub, 2015). The British Standard European norms (BS EN) 15521:2007 classify the building into four categories according to the ability of occupants to modify their environment (Zero Carbon Hub, 2015). Another criterion is the maximum temperature recommended for a healthy indoor environment (DCLG, 2006).

Moreover, empirical data need to be collected on a large scale in the domestic sector to predict appropriate thermal comfort and overheating reliably. Empirical data for the thermal models have been collected principally in work environments.

8.3. Critical Reflection on the Research Methodology and Implications for Future Research

This study also provides critical reflections on the research design that may have implications for future work in energy efficient studies in high-rise social housing buildings. For these types of studies, methodology is one of the biggest challenges as it has to balance the availability of data and resources with theoretical design. It is suggested that larger scale longitudinal, ideally randomised, studies with a well-designed counterfactual and comprehensive monitoring set-up of physical building variables (whilst capturing occupants' behaviour) would be needed to explore

[46] Published in 2015

further the effects of a building fabric retrofit. This is, however, a challenging and difficult task which may require a refinement of the quasi-experimental approach as a research design protocol to be applied in future case studies. Critical reflections of the research methodology that may have implications for future work in energy efficient studies are discussed below in Sections 8.3.1, 8.3.2 and 8.3.3.

8.3.1. Counterfactual, exogenous factors and sample size

Longitudinal studies are needed to capture the long-term effects of building fabric retrofit interventions. Comparative studies before and after without a counterfactual are limited as they assume that, in the absence of the intervention, the energy consumption remains unchanged. However, counterfactual evaluations for energy consumption are challenging as they have at least two sources of error: a) for instance, the energy consumption that would have occurred without the energy efficiency improvement; and (b) the energy consumption that would have occurred following the energy efficiency improvement had there been no behavioural change (Sorrell, 2007). Although this study uses a counterfactual for space heating consumption, a more rigorous matching method to determining the eligibility of a control building might have improved the analysis. This remains a limitation for this study, but also for future researchers, since the access to physical and occupants' data of buildings is limited and, thus, the matching physical building characteristics are approximated (e.g. heating system and heating pipes are identical but the internal pipes' routing is not. This might be having an effect as unmetered heat may benefit the target building flats). A regression model based on pre-intervention variables could be used to determine the eligibility of a control building. The dependent variable could have been, for this case, mean monthly consumption per flat per m^2 by building (j) in time (t). The regressors could have included physical and occupants' factors to indicate whether or not the target and control buildings are similar.

Equally, there is a need for controlling various exogenous factors which may modify the demand of the energy service (Frondel and Schmidt, 2005). This study addressed the exogenous factors imposing the "exogeneity" (Frondel and Schmidt,

2005) to control conditions such as the type of retrofit insulation, building physical characteristics, energy tariff, and energy supplier. However, future studies should control further exogenous factors, in particular, those related to occupants' interactions with the building's physical and heating systems such as window opening.

Quasi-experimental studies are subject to selection bias (Shadish *et al.*, 2002). In this case, it was not feasible to perform a randomized sample selection due to, for instance, occupants' resistance to installing a data logger in their flat. In this study, there is also the uncertainty of a small sample size (n=9 internal air temperature, n=157 space heating consumption). Finding the right sample size for the measurement of internal air temperature will probably involve a subjective judgment by the researcher as a full sample size would not be attainable when evaluating a high-rise building (or even 2 or 3 buildings). This judgment could be driven by how representative energy service demand variable(s) (i.e. mean internal air temperature in our case) of the selected sample is. For example, a paired t-test which compares the means of internal air temperature pre-retrofit and post-retrofit might be a way forward. Another option could be to analyse the energy service demand variable(s) of each dwelling with a qualitative research design (see, for example, Love, 2014).

8.3.2. Monitoring set-up

Improving the spatial and data capture monitoring set-up of the energy service demand variable(s) would have been beneficial to the study. For instance, spatially the living room temperature was used in this study as a proxy to construct internal air temperatures in the participants' flats. This is based on the assumption that occupants in small dwellings perceive their place as 'one space' (DECC, 2013b) and the SAP assumption that the living room is the warmest place in a dwelling (Huebner *et al.*, 2013b). However, other studies have shown differences between the living room and other rooms (see, for example, DECC (2009)). Therefore, for future research designs, other rooms such as bedrooms and bathrooms could be included.

Similarly, manipulation of data loggers by occupants is also a source of uncertainty (e.g. exposing a data logger to a source of heat such as a hair drier or secondary heating), which is not controlled by the researcher. In this study, guidelines to occupants were provided to keep data loggers away from sources of direct light and heat. Another source of uncertainty is due to the sensor's characteristics which could be mitigated by following the guides provided by ISO 7726:2001 (British Standards Institution, 2001). The guidelines suggest a sensor response measuring range (10˚C – 40˚C), accuracy (required ± 0.5˚C and desirable ± 0.2˚C), 90% response time and should be located away from any thermal radiation. In addition, data loggers can be calibrated in a thermal chamber under known conditions (for example, set at 20˚C and 50% relative humidity). It is suggested that, for further research, an updated measurement protocol, that enables the comparability between studies, takes these issues into account.

Space heating consumption nested in other gas consumption (e.g. cooking) is open to bias when data are disaggregated through modelling (e.g. space heating consumption and hot water gas in one gas meter record) such as in Hong (2011). In this study, bias was avoided by obtaining space heating meter readings from the energy supplier. Additionally, during the sample control process, space heating consumption by secondary sources was checked. Other uncertainties such as transmission from the meters (at the buildings) to the energy supplier are also present. For future research, ideally a heat meter installed on the meter may be suitable for an accurate measurement. This also enables a high-time-resolution analysis of heating usage (switch on/off).

8.3.3. Occupant behaviour

The study also includes qualitative measures, which enable the study of interactions between occupants and the physical system. However, self-completion diaries have limitations such as the 'risk of honest forgetfulness' and the 'risk of retrospection error', which may lead to 'uncertain compliance' (Bolger *et al.*, 2003, p. 594). To study the changes produced by retrofit insulation in terms of the use of space and adaptive actions such as switching heating on/off, or closing/opening windows, this qualitative measure needs to be complemented with sensors installed on the doors (occupants move room), on the meters (switching heating on/off) and on the windows (opening the windows). In addition, in order to analyse these data comprehensibly, there is a need to upgrade or create thermal comfort models aimed at the domestic sector. However, it is important to note that they need to face challenges that installing sensors pose, especially within home environments. Monitoring occupancy directly might lead to a change in the results; this is because people act differently when they are being monitored (e.g. the Hawthorne effect) and typically requires greater funding.

8.4. Summary

This chapter discussed useful insights regarding energy consumption saving and temperature take-back, temperature take-back and saturation effects, temperature take-back, and the relationship between physical factors and occupant behaviour and thermal discomfort. Since this study and in general studies of temperature take-back following building retrofits are subject to theoretical and practical methodological limitations, a critical light is shed on methodology and ways for improving it were suggested.

Chapter 9. Conclusion

9.1. Introduction

This chapter summarises the background of the research, research questions, research aim/objectives, methodology and limitations in Section 9.2. Section 9.3 describes the key findings of this research. Sections 9.4 and 9.5 describe the contribution to knowledge and necessary further work is proposed if the findings are to be used to inform retrofit policy, respectively. Finally, Section 9.6 suggests recommendations for the housing association for future projects.

9.2. Summary of the Thesis

The European Union Strategy 2020 has influenced the UK's energy efficiency policies in the household sector. Despite the measures installed under the energy efficiency supplier obligations and the Warm-front scheme, concerns have been noted that they have been insufficient to meet the energy saving targets. One of the reasons is the insufficient consideration given to the implications of the temperature take-back and rebound effect on energy efficiency policy (Sorrell, 2007).

In addition, it was identified in the literature review that the energy efficiency of dwellings is often represented using physical metrics such as the U-value or SAP rating. However, the relationship between physical metrics and energy saving is not straightforward, as energy consumption is driven by complex interactions of physical & occupants' behavioural factors, which are often poorly understood using current paradigms. This can be also seen in normative models used to account the energy heating saving from energy efficiency upgrades.

There is a growing awareness of the difference between the actual savings achieved from the energy efficiency measures and the estimates from the theoretical models. This has been termed by Sorrell *et al.* (2009) as shortfall. The known reasons for the shortfall are the occupant factors with the remainder due to other factors, such as equations (e.g. mathematical models of heat transfer), input parameters of the physical-based models (e.g. baseline U-values) and technical failures (i.e. installation, performance of equipment) (Sanders and Phillipson, 2006; Sorrell *et al.*, 2009). Particularly, in terms of household heating, the term temperature take-back has been coined to explain the predicted energy consumption savings converted into increased internal temperatures. Occupants may take part in the energy saving after the retrofit as increased internal temperatures, particularly in dwellings occupied by low-income householders (Milne and Boardman, 2000; Sorrell, 2007). The temperature take-back ranges from 0.4°C to 0.8°C and this may imply that a 1°C increase of the internal temperature leads to approximately 10% of space heating consumption (Sorrel, 2007).

However, it was not clear how occupant behaviour might respond to a retrofit in terms of changing their heating behaviour. Particularly, it was unclear how people respond to a retrofit insulation in a high-rise social housing building, for example, whether or not they adapt their heating behaviour or change their use of space or increase their thermal comfort. The factors determining energy use in buildings are complex and often poorly understood (Oreszczyn and Lowe, 2010). Recent studies have suggested that this complexity is underpinned by the fact that physical and occupant behavioural factors form a complex system (Lowe *et al.*, 2012; Love, 2014).

With this problem in mind the following research questions were developed. These four research questions were situated within current research assumptions and methodologies to address the extent to which retrofit insulation impact on space heating consumption in a high-rise social housing building:

- How do internal air temperatures change following an imposed building fabric retrofit insulation?

- How does space heating consumption changes following an imposed building fabric retrofit insulation?

- Which interactions between occupant behavioural factors and physical factors may account for space heating consumption change?

- Why do internal air temperatures change afterwards?

The aim of this study was to investigate the effects of retrofit insulation on space heating consumption to deepen the understanding of the temperature take-back, in which occupants take part of the energy saving after energy efficiency upgrades as increased indoor temperatures, through an empirical study. The objectives of this study were as follows:

1. To examine the effect of an energy efficiency upgrade on energy consumption for space heating by using a method of analysis that quantifies the change of the energy service – internal air temperature;

2. To examine the effect of an energy efficiency upgrade on energy consumption for space heating by using a method of analysis that quantifies the change of the energy input – space heating consumption;

3. To identify occupant responses that can explain the effect of the energy efficiency upgrade on energy consumption for space heating.

This research follows an intervention design approach (Creswell, 2015) which combines a ‘quasi-experimental’ (Sorrell, 2007; Sorrell *et al.*, 2009) and qualitative approach. The evidence was collected over a two-year-long study including physical monitoring and qualitative data before and after the retrofit, carried out on a high-rise social housing building in the Riverside Dean area in Newcastle upon Tyne, UK.

This study area was limited to a case study, the retrofit project at the Cruddas Park House, as it was the only project managed by the social housing association ‘Your

Homes Newcastle'[47] which had secured retrofit funding[48] at the time of the survey (February 2014). Therefore, the study results obtained need to be considered under this scope. The results of this study are indicative of the effect of building fabric investments (regarding one type of retrofit insulation, external solid wall and double-glazing windows) on space heating consumption in a high-rise social housing, other dwellings or retrofits might lead to different responses. However, it is noted that generally every building is different either in design, construction, or operational characteristics. Ultimately, this research shines a more critical light on how future research design could be improved and lead to what can be translated into hypotheses for future studies with larger sample sizes, which can inform energy policies.

9.3. Key Findings

The main findings of this case study in a high-rise social housing building are summarised as follows.

- A change in normalised space heating consumption of -27% or -34% relative to a control group, following the combined installation of external solid wall insulation and double glazing was observed. This 34% of space heating consumption reduction after the retrofit should be seen in the context of low gas consumption for the target building. This is also supported by the qualitative evidence that also suggests a low usage of heating (before and after the retrofit).

- The mean internal air temperature change, with weather standardised at 5˚C external temperature, was +0.46˚C. Temperature take-back is relatively small (i.e. 0.46°C at 5°C external temperature) compared to other studies. Thus, the empirical results do not support assumptions normally made about low-income dwellings 'taking back' energy savings as increased temperatures. More

[47] Your Homes Newcastle is the housing association responsible for managing council homes on behalf of Newcastle City Council.

[48] ECO funding to develop other retrofit projects were cancelled and support (interviewers) from YHN to undertake the survey was revoked.

generally, the study also indicates a potential upper-limit to an indoor air temperature of 22.8˚C to 24.0˚C for living rooms.

- The effect known as saturation (Maxwell *et al.*, 2011) might be taking place due to internal air temperatures reaching a limit of the maximum level of thermal comfort (e.g. 22.5°C). This supports Sorrel's (2007) assumptions that temperature take-back decreases owing to saturation effects when pre-intervention internal air temperatures saturate (approaching 21ºC).

- When temperature take-back reaches the saturation level, the increase of internal air temperature might be more dependent on the physical factor and less dependent on occupant behaviour in the heating season. Thus, the increase of the standardised mean internal air temperature following the upgrade (+0.46°C) is the result of unheated periods.

- The findings also suggest that the change in the 'use of space' was relatively small in the heating season, and there is no evidence that occupants are using their homes more intensively or previously unused rooms become occupied.

- The saturation of temperatures led to occupant thermal dissatisfaction, in response to which occupants were cooling their dwellings by frequent window opening. It might be a risk of overheating in summer time which needs to be observed, as this study has not measured the effect of retrofit insulation on overheating.

9.4. Contribution to the Knowledge

The empirical study undertaken in the case study indicated that following retrofit insulation the achieved internal air temperatures were high in the living room (> 22˚C), reaching saturation in the heating season[49] with a potential upper limit to the

[49] The uncontrolled heat from the heating system and from hot water pipes, probably, may also contribute to higher temperatures.

internal air temperature of 22.8˚C to 24.0˚C for living rooms. The saturation of temperatures has led to a very low space heating consumption. These findings perhaps suggest that assumptions normally made about low-income dwellings 'taking back' energy savings as increased temperatures do not accurately reflect the reality of the energy efficiency upgrades in low-income dwellings, particularly, an energy efficiency retrofit that achieves saturation. These results also suggest that low-income households are not necessarily willing to pay for higher levels of heating.

In recent years the academic discussions and policymakers have expressed concern about temperature take-back of energy saving policies, which significantly reduce the impacts of energy efficiency programmes, especially in low-income households in the UK. However, this study provides evidence that energy efficiency measures, targeting low-income dwellings, designed to achieve saturation might prevent temperature take-back, achieving both thermal comfort and low energy use.

In light of this evidence, and if this results were found to be broadly true in the UK, the energy policies need to revise some of their assumptions on take-back of energy saving space. For example, the efficiency savings from the household measures in the UK for the ECO and Green Deal assume a comfort factor of 15% (DECC, 2014a) and Ireland's national energy efficiency action plan assumes for the Better Energy Warmer Homes Scheme (WHS) a comfort uptake of 70% in low-income households (DCENR, 2014). This study perhaps suggests that temperature take-back needs to be accounted for as a response of the temperature saturation achieved by the different energy efficiency improvements.

Saturation of temperatures has also led to occupant thermal dissatisfaction, in response to which occupants were cooling their dwellings by frequently opening windows. Therefore, retrofit projects that tend to achieve saturation effect (e.g. deep retrofit insulation) need to be delivered in such a way so as to achieve the main motivations for energy efficiency upgrades, reducing space heating (hereby CO_2) and fuel poverty, and also to prevent thermal dissatisfaction and risk of overheating. Overheating might increase the energy demand for cooling (hereby increasing CO_2) and create health hazards for occupants. This study might have important implications for predicting the effectiveness of energy efficiency upgrades on future works for residential buildings; however, the wider applicability of this case study research’s results is restricted. Other types of buildings, socio-economic dweller characteristics or energy efficiency interventions may lead to different responses. This thesis therefore suggests recommendations from this work that can be translated into hypotheses for future studies in the following section.

9.5. Recommendations for Future Studies

This study suggests that it is necessary to investigate further the saturation effect in different dwellings, following the critical reflection on the research methodology in Section 8.3. For example, studies with larger sample sizes and (ideally) randomised samples, other types of buildings, socio-economic dweller characteristics or energy efficiency interventions.

The following hypotheses related to the saturation effect can be formed by using the findings in this study:

– When temperature take-back reaches saturation effect, the space heating consumption decreases and internal air temperatures increase following the retrofit;

– When temperature take-back reaches saturation effect, the empirical results do not support assumptions normally made about low-income dwellings ‘taking back’ energy savings as increased temperatures;

– When temperature take-back reaches saturation effect, behavioural factors play a minor role compared to physical factors in the heating season to increase the internal air temperature.

Furthermore, since the current discussion of implementing deep retrofit insulation may create a scenario of saturation effect, it might be interesting to test these hypotheses in a deep retrofit project, and examine the risk of overheating.

In addition, the likely performance of retrofit projects needs to be assessed by taking into account a methodology that includes occupants, building fabric and heating-system factors. Similarly, energy models, that neglect the importance of these interactions, need to include more empirical data to improve their predictions.

9.6. Recommendations for the Housing Association for Future Projects

This research provides recommendations for the housing association for future projects, since this study stemmed from a query of a social provider (YHN) to understand the effects of building fabric retrofit better.

<u>Evaluation of heating and cooling needs</u>

Particularly, for the target building there is a need to establish clearly whether or not there is a risk of overheating, especially when other authors have suggested the unintended overheating effects of a building fabric retrofit on occupant health (Davies and Oreszczyn, 2012). If so, improving ventilation or a heating system upgrade might be considered as part of the solution for the target building.

In general, for future buildings that are planned to be retrofitted, pre-retrofit monitoring evaluation might help to understand the current needs of heating and cooling. For example, a retrofit protocol might be created, including a comprehensive analysis of the building’s physical factors (e.g. insulation, draught proofing, glazing, heating system, thermostatic controls, etc.) and occupant factors interacting with physical factors (e.g. internal air temperature and space heating).

Funding is needed for the pre-monitoring evaluation as part of the retrofit scheme. This quote from STBA (2015) exemplifies a more comprehensive approach that is needed to evaluate a retrofit project:

> Achieving responsible retrofit often requires compromises between different values. It also requires a Whole Building Approach whereby there is integration of the fabric measures (such as insulation, new windows, draught proofing), and services (particularly ventilation, heating, controls and renewables) along with proper consideration of how people live and use the building. All of these must be adapted to the

> context of the building (its exposure, status, condition, form, etc.). When these are integrated well, a building is in balance.
>
> *(STBA, 2015, p. 6).*

<u>Collaborative process between the stakeholders</u>

A feedback loop between the dwellers and other stakeholders (council, builders, etc.) might be beneficial for improving the process of retrofitting. For example, it would be beneficial to include occupant thermal comfort perception as an input, thus occupants are consulted, improving the accuracy of the results.

Other authors also support the importance of understanding the effects of energy upgrades on energy saving (Caird *et al.*, 2012). Although the importance of understanding often refers to new technology in which occupants have to learn how to use it (for example, heating systems), community involvement might help to avoid problems with the building fabric (e.g. ventilation) and, in turn, for its occupants (e.g. health issues) following retrofit measures. It is important to note that dwellers were informed at different stages of the retrofit process. For example, at the start of the study, occupants were invited to a stakeholder meeting, in which information was given about the project. However, there are social and technical language barriers that may prevent social tenants from being involved in the project.

References

ACE (2013) 'Fact-file: The Cold Man of Europe'. London: Association for the Conservation of Energy.

ACE (2015) 'The Cold Man of Europe – 2015 update'. London: Association for the Conservation of Energy.

Alaszewski, A.M. (2006) *Using Diaries for Social Research*. SAGE Publications [Online]. Available at: http://ncl.eblib.com/patron/FullRecord.aspx?p=334610 (Accessed: 14 February 2017).

Anderson, B.R., Chapman, P.F., Cutland, N.G., Dickson, C.M., Doran, S.M., Henderson, G., Henderson, J.H., Iles, P.J., Kosmina, L. and Shorrock, L.D. (2002) *BREDEM-12 Model description: 2001 update*. Garston, Watford, UK.

Anderson, W., White, V. and Finney, A. (2010) *"You just have to get by". Coping with low incomes and cold homes*. Bristol.

Andrew, S. and Halcomb, E.J. (2009) *Mixed Methods Research for Nursing and the Health Sciences*. Oxford, UK: Wiley-Blackwell.

ANSI/ASHRAE (2004) *ASHRAE Standard 55-2004. Thermal Environmental Conditions for Human Occupancy*. Atlanta, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ANSI/ASHRAE (2013) 'ASHRAE Standard 55-2013. Thermal Environmental Conditions for Human Occupancy'. Atlanta, USA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Armstrong group (2012) 'Powering up for UK district heating project', *World Pumps*, 2012(8), pp. 22-23.

BBC News (2013) 'T.Dan Smith',edn), 24th February, 2003. [Online] Available at: http://www.bbc.co.uk/insideout/northeast/series2/tdansmith_newcastlepolitics.shtml (Accessed: 14 February 2017).

Beaumont, A. (2007) 'Hard to Treat Homes in England', *ENHR conference*. Rotterdam, 25-28 June 2007.

BEIS (2017) *Household Energy Efficiency National Statistics. Detailed Report 2016*. London: Department for Business, Energy & Industrial Strategy.

Boardman, B., Darby, S., Killip, G., Hinnels, M., Jardine, C. and Palmer, J. (2005) *40% House*. Oxford, UK.

Bolger, N., Davis, A. and Rafaeli, E. (2003) 'Diary Methods: Capturing Life as it is Lived', *Annual Review of Psychology*, 54(1), pp. 579-616.

BRE (2008) *A study of hard-to-treat homes using the English house condition survey, Part 1 – dwelling and household characteristics of hard-to-treat homes*. London: Building Research Establishment Limited.

BRE (2012) *The Government's Standard Assessment Procedure for Energy Rating of Dwellings. SAP 2012 version 9.92*. Watford, UK: Building Research Establishment Limited.

BRE (2014) *SAP 2012: the government's standard assessment procedure for energy rating of dwellings, version 9.92 (OCT 2013)*. Watford, UK: Building Research Establishment Limited.

British Standards Institution (1996) *BS EN ISO 7345:1996. Thermal insulation — Physical quantities and definitions*. European Committee for Standardization (CEN).

British Standards Institution (2001) *BS EN 7726:2001. Ergonomics of the thermal environment - Instrument for measuring physical quantities* London: BSI publications.

British Standards Institution (2005) 'BS EN ISO 7730. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria'. ISO. Available at: https://books.google.co.uk/books?id=0cclPwAACAAJ.

British Standards Institution (2007) 'BS EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings-addressing indoor air quality, thermal environment, lighting and acoustics'. Brussels: European Committee for Standardization (CEN).

British Standards Institution (2017) *BS EN ISO 6946:2017. Building components and building elements - Thermal resistance and thermal transmittance - Calculation methods*. London: BSI Standards Limited 2017.

Bryman, A. (2012) *Social research methods*. Oxford: Oxford University Press.

Buildings Performance Institute Europe (2011) 'Europe's buildings under the microscope – A country-by-country review of the energy performance of buildings'. Belgium: BPIE.

Caird, S., Roy, R. and Potter, S. (2012) 'Domestic heat pumps in the UK: user behaviour, satisfaction and performance', *Energy Efficiency*, 5(3), pp. 283-301.

Chatterton, T. (2011) *An introduction to Thinking about 'Energy Behaviour': a Multi Model Approach, a paper for the Department of Energy and Climate Change*. London: Department of Energy & Climate Change.

CIBSE (2006) *CIBSE Guide A, Environmental design*. London, UK: Chartered Institution of Building Services Engineers.

Creswell, J. (2009) *Research design: Qualitative, quantitative, and mixed methods approaches*. 3rd edn. Thousand Oaks, California: SAGE Publications, Inc.

Creswell, J. (2015) *A concise introduction to mixed methods research*. 3rd edn. Thousand Oaks, California: SAGE Publications, Inc.

Davies, M. and Oreszczyn, T. (2012) 'The unintended consequences of decarbonising the built environment: A UK case study', *Energy and Buildings*, 46, pp. 80-85.

Davis, L.W. (2008) 'Durable goods and residential demand for energy and water: evidence from a field trial', *The RAND Journal of Economics*, 39(2), pp. 530-546.

DCENR (2014) *National energy efficiency action plan 2014*.Department of Communications, Energy and Natural Resources.

DCLG (2006) *Housing health and safety rating system- guidance for landlords and property related professionals*. London: Department for Communities and Local Government.

DCLG (2013) *English Housing Survey: HOMES Annual report on England's housing stock, 2011*. London: Department for Communities and Local Government.

DCLG (2016a) *English Housing Survey Headline Report 2014-15*. London: Department for Communities and Local Government.

DCLG (2016b) *English Housing Survey Headline Report 2014-15 Section 2: Tables, Figures and Annex Tables*. London:Department for Communities and Local Government.

DCLG (2017a) *2015-16 English Housing Survey Headline Report Section 2. Annex Table 2.7: Energy efficiency rating bands, by tenure, 2005 and 2015*. London: Department for Communities and Local Government.

DCLG (2017b) *English Housing Survey Headline Report 2015-16* London: Department for Communities and Local Government.

DECC (2009) *Final report: In situ: monitoring of efficiencies of condensing boilers and use of secondary heating.* London: Department of Energy & Climate Change.

DECC (2011) *Research report. Evaluation synthesis of energy supplier obligation policies*. London: Department of Energy & Climate Change.

DECC (2012) *Final Stage Impact Assessment for the Green Deal and Energy Company Obligation*. London: Department of Energy & Climate Change.

DECC (2013a) *Consumption headlines tables 2013*. London: National Energy Efficiency Data Framework (NEED). [Online]. Available at: https://www.gov.uk/government/statistics/national-energy-efficiency-data-framework-need-report-summary-of-analysis-2015 (Accessed: 14 February 2017).

DECC (2013b) *What people want from their heating controls: a qualitative study. Tech. Rep. October*. London: Department of Energy & Climate Change.

DECC (2014a) *Estimated impacts of energy and climate change policies on energy prices and bills*. London: Department of Energy & Climate Change.

DECC (2014b) *Evaluation of the Carbon Emissions Reduction Target and Community Energy Saving Programme: Executive Summary. Research undertaken for DECC by Ipsos MORI, CAG Consultants, UCL and Energy Saving Trust.* London: Department of Energy & Climate Change.

DECC (2014c) *UK National Energy Efficiency Action Plan*. London: Department of Energy & Climate Change.

DECC (2015) *Annual Fuel Poverty Statistics Report 2015*. London: HM Government.

DECC (2016a) *Annual Fuel Poverty Statistics Report, 2016*. London: Department of Energy & Climate Change.

DECC (2016b) *ECO: Help to Heat. Consultation document*. London: Department of Energy & Climate Change.

Denscombe, M. (2014) *The Good Research Guide: For Small-scale Social Research Projects*. McGraw-Hill Education. Available at: http://ncl.eblib.com/patron/FullRecord.aspx?p=1910221> (Accessed: 14 February 2017).

Deurinck, M., Saelens, D. and Roels, S. (2012) 'Assessment of the physical part of the temperature takeback for residential retrofits', *Energy and Buildings*, 52, pp. 112-121.

Doherty, S. and Miller, E. (2000) 'A computerized household activity scheduling survey', *Transportation*, 27(1), pp. 75-97.

Dong, G. and Pei, J. (2007) *Sequence Data Mining*. New York: Springer.

Ellegård, K. and Palm, J. (2011) 'Visualizing energy consumption activities as a tool for making everyday life more sustainable', *Applied Energy*, 88(5), pp. 1920-1926.

Energy and Climate Change Committee (2016) *Home energy efficiency and demand reduction. Fourth Report of Session 2015–16*. London: House of Commons.

EST (2002) 'Good practice guide 138. Internal wall insulation in existing housing, a guide for specifiers and contractors'. Energy Saving Trust. Available at: http://regulations.completepicture.co.uk/pdf/Energy%20Conservation/Insulation/Internal%20wall%20insulation%20in%20existing%20housing%20-%20a%20guide%20for%20specifiers%20and%20contra.pdf (Accessed: 15 October 2017).

EST (2010) *Sustainable refurbishment Towards an 80% reduction in CO2 emissions, water efficiency, waste reduction, and climate change adaptation*. London.

European Parliament and Council (2012) *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.Official Journal of the European Union*. [Online]. Available at: http://www.buildup.eu/en/practices/publications/directive-201227eu-european-parliament-and-council-25-october-2012-energy (Accessed: 14 February 2017).

Fanger, P.O. (1970) *Thermal comfort. Analysis and applications in environmental engineering*. Copenhagen: Danish Technical Press

Frondel, M. and Schmidt, C.M. (2005) 'Evaluating environmental programs: the perspective of modern evaluation research', *Ecological Economics*, 55, pp. 515-526.

Gale, E.A.M. (2004) 'The Hawthorne studies—a fable for our times?', *QJM*, 97(7), pp. 439-449.

Galvin, R. (2015) *The Rebound Effect in Home Heating: A guide for policymakers and practitioners*. Abingdon,Oxon; New York, NY: Routledge.

Galvin, R. and Sunikka-Blank, M. (2013) *A Critical Appraisal of Germany's Thermal Retrofit Policy: Turning Down the Heat*. London; New York: Springer-Verlag.

Galvin, R. and Sunikka-Blank, M. (2014) 'Disaggregating the causes of falling consumption of domestic heating energy in Germany', *Energy Efficiency*, 7(5), pp. 851-864.

Gilbertson, J., Stevens, M., Stiell, B. and Thorogood, N. (2006) 'Home is where the hearth is: grant recipients' views of England's home energy efficiency scheme (Warm Front)', *Soc Sci Med*, 63(4), pp. 946-56.

Glendinning, M. and Muthesius, S. (1994) *Tower Block: Modern Public Housing in England, Scotland, Wales, and Northern Ireland*. New Haven: Paul Mellon Centre for Studies in British Art by Yale University Press.

Green, G. and Gilbertson, J. (2008) *Warm Front Better Health, Health Impact Evaluation of the Warm Front Scheme.*

Hitchings, R. (2012) 'People can talk about their practices', *Area*, 44(1), pp. 61-67.

HM Government (2015) *The building regulation 2010. Approved document L1B: conservation of fuel and power in existing dwellings. 2015 edition*. London: NBS.

Hong (2011) *Changes in space heating energy consumption following energy efficient refurbishment in low-income dwellings in England*. Ph.D. thesis. UCL.

Hong, Oreszczyn, T. and Ridley, I. (2006) 'The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings', *Energy and Buildings*, 38(10), pp. 1171-1181.

Hong, S.H., Gilbertson, J., Oreszczyn, T., Green, G. and Ridley, I. (2009) 'A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment', *Building and Environment*, 44(6), pp. 1228-1236.

Hough, D. and Page, R. (2015) *ECO, the Energy Company Obligation* (Number CBP 06814). [Online]. Available at: http://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN06814 (Accessed: 14 February 2017).

Huebner, G.M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M. and Summerfield, A. (2013a) 'Heating patterns in English homes: Comparing results from a national survey against common model assumptions', *Building and Environment*, 70, pp. 298-305.

Huebner, G.M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M. and Summerfield, A. (2013b) 'The reality of English living rooms – A comparison of internal temperatures against common model assumptions', *Energy and Buildings*, 66, pp. 688-696.

Humphreys, M.A., Nicol, J.F. and Raja, I.A. (2007) 'Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach', *Advances in Building Energy Research*, 1(1), pp. 55-88.

INCA (2015) 'Best Practice Guide External Wall Insulation INCA Insulated Render and Cladding Association'. London: Insulated Render and Cladding Association Ltd.

Institute of Health Equity (2014) *Local action on health inequalities: Fuel poverty and cold-home related health problems*. London: UCL Institute of Health Equity

Jenkins, D.P. (2010) 'The value of retrofitting carbon-saving measures into fuel poor social housing', *Energy Policy*, 38(2), pp. 832-839.

Johnson, M.B. (1971) *Household behaviour: consumption, income and wealth*. Harmondsworth: Penguin Education.

Johnson, R.B. and Onwuegbuzie, A.J. (2004) 'Mixed Methods Research: A Research Paradigm Whose Time Has Come', *Educational Researcher*, 33(7), pp. 14-26.

Jones, A. (2013) 'Re-Generate Newcastle DECC Heat Networks Roadshow' *Presentation to DECC Heat Networks Roadshow* 18th July 2013. Newcastle.

Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z. and Djurovic-Petrovic, M. (2010) 'A review of bottom-up building stock models for energy consumption in the residential sector', *Building and Environment*, 45(7), pp. 1683-1697.

Kavgic, M., Summerfield, A., Mumovic, D., Stevanovic, Z.M., Turanjanin, V. and Stevanovic, Z.Z. (2012) 'Characteristics of indoor temperatures over winter for Belgrade urban dwellings: indications of thermal comfort and space heating energy demand', *Energy and Buildings*, 47, pp. 506-514.

Langevin, J., Wen, J. and Gurian, P.L. (2013) *IAQ 2013*. Vancouver, Canada, Oct 15–18. ASHRAE.

Law, G.R., Green, R. and Ellison, G.T.H. (2012) 'Confounding and Causal Path Diagrams', in Tu, Y.-K. and Greenwood, C.D. (eds.) *Modern Methods for Epidemiology*. Dordrecht: Springer Netherlands, pp. 1-13.

Lomas, K.J. (2010) 'Carbon reduction in existing buildings: a transdisciplinary approach', *Building Research & Information*, 38(1), pp. 1-11.

Love, J. (2014) *Understanding the interactions between occupants, heating systems and building fabricin the context of energy efficient building fabric retrofit in social housing*. Ph.D. thesis. UCL.

Lowe, R., Chiu, L.F., Raslan, R. and Altamirano, H. (2012) *Retrofit insights: perspectives for an emerging industry*. London.

Maxwell, D., Owen, P., McAndrew, L., Muehmel, K. and Neubauer, A. (2011) *Addressing the Rebound Effect, a report for the European Commission DG Environment*. [Online]. Available at: http://ec.europa.eu/environment/eussd/pdf/rebound_effect_report.pdf (Accessed: 14 February 2017).

Milne, G. and Boardman, B. (2000) 'Making cold homes warmer: the effect of energy efficiency improvements in low-income homes A report to the Energy Action Grants Agency Charitable Trust', *Energy Policy*, 28(6), pp. 411-424.

Milsom (2014) *Solid wall heat losses and the potential for energy saving, Literature review* Watford, UK: Building Research Establishment Ltd.

Natarajan, S. and Levermore, G.J. (2007) 'Domestic futures—Which way to a low-carbon housing stock?', *Energy Policy*, 35(11), pp. 5728-5736.

Nicholson, W. (2005) *Microeconomic Theory: Basic Principles and Extensions*. 9th edn. Mason, Ohio: Thomson/South-Western.

Nicol, F., Humphreys, M. and Roaf, S. (2012) *Adaptive Thermal Comfort: Principles and Practice*. Abingdon, Oxfordshire, UK: Taylor & Francis.

O'Doherty, B. (2000) *Riverside Dene Regeneration*. Newcastle: Newcastle city council.

Ofgem (2013a) *Community Energy Saving Programme Update*. London: The Office of Gas and Electricity Markets (Ofgem e-serve).

Ofgem (2013b) *The final report of the Carbon Emissions Reduction Target (CERT) 2008-2012*. London: The Office of Gas and Electricity Markets (Ofgem).

Ofgem (2013c) *The final report of the Community Energy Saving Programme (CESP) 2009-2012* London: The Office of Gas and Electricity Markets (Ofgem).

Ofgem (2015) *Energy Companies Obligation. Final report January-13 - March 15*. London: The Office of Gas and Electricity Markets (Ofgem).

Oreszczyn, T., Hong, S.H., Ridley, I. and Wilkinson, P. (2006) 'Determinants of winter indoor temperatures in low income households in England', *Energy and Buildings*, 38(3), pp. 245-252.

Oreszczyn, T. and Lowe, R. (2010) 'Challenges for energy and buildings research: objectives, methods and funding mechanisms', *Building Research & Information*, 38(1), pp. 107-122.

Palmer, J. and Cooper, I. (2012) *United Kingdom housing energy fact file 2012*. [Online]. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/201167/uk_housing_fact_file_2012.pdf (Accessed: 15/10/2017).

Palmer, J. and Cooper, I. (2013) *United Kingdom housing energy fact file 2013*. [Online]. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/345141/uk_housing_fact_file_2013.pdf (Accessed: 15/10/2017).

Papantoniou (2015) *Impact of Natural Ventilation on high-rise social housing buildings, in Newcastle Upon Tyne, UK*. MSc. thesis. Newcastle University.

Parsons, H.M. (1974) 'What Happened at Hawthorne?', *New evidence suggests the Hawthorne effect resulted from operant reinforcement contingencies*, 183(4128), pp. 922-932.

Peeters, L., Dear, R.d., Hensen, J. and D'haeseleer, W. (2009) 'Thermal comfort in residential buildings: Comfort values and scales for building energy simulation', *Applied Energy*, 86(5), pp. 772-780.

Rosenberg, J.P. and Yates, P.M. (2007) 'Schematic representation of case study research designs', *Journal of Advanced Nursing*, 60(4), pp. 447-452.

Rosenow, J. and Eyre, N. (2014) 'Residential energy efficiency programmes in the UK: a roadmap for recovery', *10th BIEE Academic Conference: Balancing Competing Energy Policy Goals* St John's College, Oxford, 17/18 September 2014.

Sanders, C. and Phillipson, M. (2006) *An Analysis of the Difference between Measured and Predicted Energy Savings when Houses are Insulated* Centre for Research on Indoor Climate and Health, Glasgow Caledonian University; 2006.

Schwartz, D., Fischhoff, B., Krishnamurti, T. and Sowell, F. (2013) 'The Hawthorne effect and energy awareness', *Proceedings of the National Academy of Sciences*, 110(38), pp. 15242-15246.

Shadish, W.R., Cook, T.D. and Campbell, D.T. (2002) *Experimental and Quasi-experimental Designs for Generalized causal inference*. Wadsworth Cengage Learning.

Sharpe and Shearer (2012) *Proceedings of Retrofit 2012 conference, University of Salford, Manchester.*

Shipworth, M. (2011) 'Thermostat settings in English houses: No evidence of change between 1984 and 2007', *Building and Environment*, 46(3), pp. 635-642.

Shipworth, M., Firth, S.K., Gentry, M.I., Wright, A.J., Shipworth, D.T. and Lomas, K.J. (2010) 'Central heating thermostat settings and timing: building demographics', *Building Research & Information*, 38(1), pp. 50-69.

Shorrock and Utley (2008) *Domestic energy fact file 2008*. Watford: Building Research Establishment.

Shorrock, L.D. and Dunster, J.E. (1997) 'The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock', *Energy Policy*, 25(12), pp. 1027-1037.

Shorrock, L.D., Henderson, J. and Utley, J.I. (2005) *Reducing carbon emissions from the UK housing stock*. Watford: Building Research Establishment.

Shove, E. (2003) 'Converging Conventions of Comfort, Cleanliness and Convenience', *Journal of Consumer Policy*, 26(4), pp. 395-418.

Shove, E. and Walker, G. (2014) 'What Is Energy For? Social Practice and Energy Demand', *Theory, Culture & Society*, 31(5), pp. 41-58.

Sorrell, S. (2007) *The Rebound Effect: An Assessment of the Evidence for Economy-wide Energy Savings from Improved Energy Efficiency*. [Online]. Available at: http://www.ukerc.ac.uk/programmes/technology-and-policy-assessment/the-rebound-effect-report.html (Accessed: 14 February 2017).

Sorrell, S. (2015) 'Reducing energy demand: A review of issues, challenges and approaches', *Renewable and Sustainable Energy Reviews*, 47, pp. 74-82.

Sorrell, S. and Dimitropoulos, J. (2008) 'The rebound effect: Microeconomic definitions, limitations and extensions', *Ecological Economics*, 65(3), pp. 636-649.

Sorrell, S., Dimitropoulos, J. and Sommerville, M. (2009) 'Empirical estimates of the direct rebound effect: A review', *Energy Policy*, 37(4), pp. 1356-1371.

STBA (2015) *Planning responsible retrofit of traditional buildings*. [Online]. Available at: http://www.sdfoundation.org.uk/downloads/Guide-1-Planning-Responsible-Retrofit-2015-08.pdf (Accessed: 14 February 2017).

Sunikka-Blank, M. and Galvin, R. (2012) 'Introducing the prebound effect: the gap between performance and actual energy consumption', *Building Research & Information*, 40(3), pp. 260-273.

Sweatman, P. and Managan, K. (2010) *Financing Energy Efficiency Building Retrofits*. Madrid.

Thorpe, D. (2013) *Energy Management in Buildings: The Earthscan Expert Guide*. London, New York: Taylor & Francis.

Tinytag (2016) *Data Loggers*. Available at: geminidataloggers.com. (Accessed: 30 September, 2016).

URBED (2016) *Retrofit factfile. A short summary of facts and publications relevant to domestic retrofit.* [Online]. Available at: http://carbon.coop/sites/default/files/attachments/2016-09-12/2016%20URBED%20Tyndall%20The%20Retrofit%20factfile%20-%20facts%20and%20publications.pdf (Accessed: 14 February 2017).

UWE (2009) *Evolution of Building Elements*. Available at: https://fet.uwe.ac.uk/conweb/house_ages/elements/print.htm (Accessed: 29 June 2017).

Watson, C. and Bolton, P. (2013) *Carbon Emissions Reduction Target (CERT)* (SN/SC/06196). [Online]. Available at: http://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN06196 (Accessed: 14 February 2017).

Wickström, G. and Bendix, T. (2000) 'The "Hawthorne effect" - what did the original Hawthorne studies actually show?', *Scandinavian Journal of Work, Environment & Health*, (4), pp. 363-367.

Wilkinson, P., Landon, M., Armstrong, B., Stevenson, S., McKee, M. and Fletcher, T. (2001) *Cold comfort: the social and environmental determinants of excess winter death in England, 1986-1996*. Bristol, UK.

YHN (2015) *Unpublished document - Socio-demographic characteristics of Riverside Dene buildings*.

Yin, R.K. (2009) *Case Study Research: Design and Methods*. Los Angeles, California: SAGE Publications.

Yin, R.K. (2014) *Case Study Research: Design and Methods*. Los Angeles, California: SAGE Publications.

Yu, Y. (2016) *High Domestic Tower Energy Demand Reduction via Retrofitting: a simulation based study*. MSc. thesis. Newcastle University.

Zero Carbon Hub (2015) *Defining overheating. Evidence Review*. London. [Online]. Available at: http://www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH-OverheatingEvidenceReview-Definitions.pdf (Accessed: 14 February 2017).

Annex A

Equations of direct rebound effect as an efficiency elasticity (direct measure):

$$\boldsymbol{\eta\varepsilon(\mathrm{E}) = \eta\varepsilon(S) - 1}$$
(0-1)[50]

$\eta\varepsilon(E)$ is the elasticity of the demand for energy (E) with respect to energy efficiency (ε);

$\eta\varepsilon(S)$ is the elasticity of the demand for energy services (S) with respect to energy efficiency.

Equations of direct rebound effect as price elasticity (indirect measure):

$$\boldsymbol{\eta\varepsilon(E) = -\eta p_s(S) - 1}$$
(0-2)[51]

$$\boldsymbol{\eta\varepsilon(E) = -\eta PE(E) - 1}$$
(0-3)[52]

$\eta\varepsilon(E)$ is the elasticity of the demand for energy (E) with respect to energy efficiency (ε);

$\eta p_s(S)$ is the elasticity of the demand for energy services (S) with respect to energy cost of energy services (p_s).

$\eta p_E(E)$ is the elasticity of the demand for energy with respect to energy price.

---

50 Sorrel *et al.*, 2009

51 Sorrel *et al.*, 2009

52 Sorrel *et al.*, 2009

Annex B

Riverside Dene Area history

As part of a programme of slum clearance and redevelopment, houses in the Riverside Dene area were pulled down and new high-rise buildings were built in the 60s (Glendinning and Muthesius, 1994). This project was pursued by Newcastle's major, Mr. T. Dan Smith, nicknamed as 'Mr Newcastle', who envisioned Newcastle upon Tyne as 'the Brasilia of the North' (BBC News, 2013). He mentioned that "*I wanted to see the creation of a 20th century equivalent of [John] Dobson's masterpiece*" (Smith autobiography as cited in BBC News, 2013). As a result 11 blocks were built: 8 15-storey blocks, 2 12-storey blocks and Cruddas Park House (CPH). CPH is a 23-storey tower block built in 1969, 1- and 2-bedroom-flats and originally electrically heated.

Insufficient finance investment for long-term maintenance and high levels of anti-social behaviour and crime led to a downturn in popularity in the area (annual turnover of tenancies were as high as 20.4%) (O'Doherty, 2000). In 2000, the government responded with a range of area-based initiatives: 5 towers were demolished and the remaining tower blocks were refurbished (Jones, 2013). The regeneration used a mixed-tenure strategy, providing 5 tower blocks for social tenants (full occupancy) and 1 tower block for home-owners (with assisted mortgages from Newcastle City Council), the site was renamed as Riverside Dene to overcome the stigma from people's associations with the place.

Figure Annex B1.‘Last days of The Poplars’. Demolition of the Poplars building and the Hawthorns building (control building), recently refurbished, is to the right. Source: geograph.org.uk

Figure Annex B. ‘Riverside Dene area December 2016’. Source: own source.

Annex C

Cruddas Park House Heating Installation (information provided by YHN)

Network-pipes' routing:

Mild steel LTHW heating pipework in vertical risers (in ducts) in the main corridors serves horizontal runs on the 6th 7th, 13th and 14th floors. These runs pass through the ceiling voids in the corridors then through a flat to drop vertically within the bedroom cupboard passing to the flats below. Branches tee off within the cupboard for each individual flat. The heating to each flat connects via a two-port valve and heat meter to a pipe coil within a forced-fan warm air unit with a ducted air stub duct system serving the rooms. The two-port valve is controlled directly by a electro-mechanical thermostat in the lounge. The other rooms with heating (bedrooms and passage) have no controls. There is no heating to the kitchen, bathroom and WC within the flats.

Considerable free (unmetered) heat is given off in the horizontal runs to the bedrooms and the runs vertically within in the cupboard, which in turn are serving the flats above and below. Some of the main corridors also suffer from overheating; most likely the ones with the horizontal pipework and the corridors immediately above.

These mains have a constant flow with a constant temperature operating 24/7 in many cases with the insulation removed in the bedroom cupboard to make better use of the free heat. In addition, the tower block has centralised hot-water storage with the same distribution system for the hot-water flow and return pipework. The flats have kitchens and bathrooms at opposite ends so require more than one riser. This again adds to the free incidental heat within the block. The hot water is metered at the bathroom and kitchen using by a volumetric meter. Again these systems run 24/7.

The Hawthorns Heating Installation

Network-pipes' routing:

Steel pre-insulated primary mains from the boiler house serve a heat station on the ground floor. Plastic vertical risers carry LTHW from the plate heat exchangers up through the building. Horizontal runs pass through each flat to the local bespoke heat-exchange unit in a cupboard. This unit provides heating via a plate heat exchanger and hot water indirectly via a coil running through a stored mass of hot water. This reduces the on-demand hot-water load. The incoming mains to the exchanger and thermal store are metered within the unit.

All the pipes are well insulated as is the hot-water store to current standards. The heating is controlled by a programmable room thermostat acting on a 2-port valve within the unit. Heating in the flats is a 2-pipe wet system using panel radiators.

The room thermostat is in an internal passage and is probably easily satisfied by the ambient conditions in there. We have had to move one or two into the lounge. The thermal hot water store is continuously topped up regardless of the heating demand but the tanks are well insulated. Water leaving the coil within the store is automatically blended down to 43°C. A further 2-port valve closes when both heating and hot water are satisfied (it was originally a 3-port valve but the recirculated heat caused unmetered overheating). Not all 3-port valves were replaced but doing this caused a considerable reduction in free heat.

Annex D

Heating controls in the target building

Figure Annex D. Heating controls in the target building

Annex E

1. Cover letter

Dear Resident

CAN YOU HELP US UNDERSTAND ENERGY USE BETTER?

Newcastle University have contacted us as they want to carry out a research project into energy use – the Energy Activity Study. They are interested in Cruddas Park as it is due major work so that residents will find it easier to heat their homes more comfortably and potentially at lower cost.

The study will look at about 30 households and their energy use. It will start in April 2014, and last for one year. Those households involved will have two face to face interviews, and need to keep an activity diary for 1 week, 4 times in the year.

Why should I be involved?

The information can be used to understand how people use energy within their home before and after the investment work (insulation and new windows) and whether any advice and information needs to be given to enable residents to live in more comfortable homes at lower cost. To this extent, everyone in the block can benefit.

Individual households which take part in the study with interviews and diaries will receive a £50 Eldon Square voucher from Newcastle University as a thank you for their commitment if they are able to participate from start to finish.

What about my confidentiality?

The Energy Activity Survey promises to protect your privacy. The information will be used solely for academic purposes and it will be treated as strictly confidential and at no time will you or your household be identified.

What happens next?

If you would like to be considered to take part in the study, or you have further questions, please contact;

Macarena Rodriquez, Research Student
School of Architecture Planning and Landscape
Newcastle University
Newcastle upon Tyne
NE1 7RU

[Telephone no]

energyresearch@newcastle.ac.uk

For more information and meet the project team - Drop-in session

Venue;	Oasis Café, Cruddas Park Shopping Centre
Date;	Monday 7th April
Time;	4.00pm until 6.00pm

Please call in at whatever time suits you and we can answer any questions you may have. Tea and coffee will be available.

Please note that we intend to finalise our list of households by **Monday 14 April**. Households will be chosen to give a representative balance of the block, rather than on a first come basis.

Yours faithfully

Tom Jarman
Environmental Sustainability Co-ordinator

Macarena Rodriquez
Newcastle University

2. Postcard and Poster used to recruit participants.


YOUR ACTIVITIES = YOUR kW
Energy Activity
1ST STEP:
Help us to understand how energy is consumed in your daily activities.
Filling a week activity diary, 4 times in the year
Get involved in a face to face interview and tell us more about your activities.
2ND STEP:
CONTACT US TODAY!
EMAIL US AT : energyresearch@newcastle.ac.uk
OR GIVE US A CALL: 0191 278 8625
ONCE FINISHED YOU WILL GET:
£50
Eldon Square voucher
intu
Eldon Square
If you would like to be considered to take part in the study, or you have further questions, please contact us at :
Email: energyresearch@newcastle.ac.uk
Phone: 0191 278 8625
Tell us about your Activities
HELP US TO UNDERSTAND HOW YOUR BUILDING WORKS
Take our SURVEY
Newcastle University

3. Drop-in Session Leaflet

Energy Activity Survey

The Energy Activity Survey is a household survey run by Newcastle University and sponsored by the Newcastle Institute for Research on Sustainability to understand How Energy is Consumed in Daily Activities.

Why should I participate?

We will be better able to understand how you use energy, and how this changes after the work (new windows and external insulation). We can use this information to help you save money on your energy bills and heat your home more comfortably.

If you complete the activities for the research (see below) you are eligible to receive a £50 Eldon Square voucher from Newcastle University upon successful completion of the survey.

What do I need to do?

- Fill in an activity diary
- Complete two 30 minute face to face interviews

When?

April 2014	1 week activity diary and 1 interview
August 2014 (*)	1 week activity diary
February 2015 (*)	1 week activity diary
May 2015 (*)	1 week activity-diary and 1 interview

(*) dates are approximate and subject to change

The information collected will be used solely for academic purposes. We will not share your data with third parties for purposes of marketing. The survey is voluntary and confidential. This survey is limited to one person per household. THE SURVEY IS INDEPENDENT WITH NO AFFILIATION WITH YHN. Participants are free to withdraw from this study at any time.

Interested?

If you are thinking about participating or you have any question, please contact us at energyresearch@ncl.ac.uk or 01912788625.

Newcastle University

4. Consent form

RESEARCH CONSENT FORM

Newcastle University

Please read and complete this form carefully. If you are willing to participate in this study, please tick the appropriate responses and sign and date the declaration at the end. If you do not understand anything and would like more information, please ask.

I, the undersigned, confirm that (please tick box as appropriate):

1.	I have read and understood the information about the project, as provided in the energy activity brochure	☐
2.	I have been given the opportunity to ask questions about the project and my participation.	☐
3.	I voluntarily agree to participate in the project.	☐
4.	I understand I can withdraw at any time without giving reasons and that I will not be penalised for withdrawing nor will I be questioned on why I have withdrawn.	☐
5.	The procedures regarding confidentiality have been clearly explained (e.g. Data records will be identified only though the ID number; anonymisation of data) to me.	☐
6.	I understand that the research will involve to fill activity diaries for 1 week four times and a face to face 20 min interview.	☐
7.	I understand that to carry out this research I have to provide my energy consumption information by means of meter readings, energy bills or signing the form authority (*). (*) the form authority allows that Your Home Newcastle may ask for your energy consumption to your current energy supplier.	☐
8.	The use of the data in research, publications, sharing and archiving has been explained to me.	☐
9.	I understand that other researchers will have access to this data only if they agree to preserve the confidentiality of the data and if they agree to the terms I have specified in this form.	☐
10.	I, along with the Researcher, agree to sign and date this informed consent form.	☐

Participant	**Signature**	**Date**		
Name of Participant				
Researcher/Supervisor	**Signature**	**Date**	**Position**	**contact**
Macarena Rodriguez			**PhD Student** Newcastle University	**m.rodriguez@ncl.ac.uk**
Carlos Calderon			Senior lecturer School of Architecture Planning and Landscape Newcastle University	**carlos.calderon@ncl.ac.uk** **+44(0)1912086025**

5. Tenant participation form

Tenant Participation Form

Resident Contact Details:

Title:	First Name:	Surname:
Email Address:		
Mobile Number:	Telephone Number:	
Flat Number:		
How would you like to be contacted: ○ Phone ○ Mobile ○ Email	Any comments?	

Where did you find information about the Survey?

Poster ☐	*Cafe Oasis* ☐	*YHN Letter* ☐
Postcard ☐	*Cruddas Park reception* ☐	*Other* ☐

Survey Brochure: Self-completion diary

Energy *Activity*

This brochure will provide you with information about the survey, **how to participate** and how to contact us for information.

About the survey >>>

The Energy Activity Survey is carry out by Newcastle University to understand how energy is consumed by households.

We will ask you to complete an activity diary for 1 week, 4 times in the year and be involved in 2 face to face interviews to tell us more about your activities.

It will start in April 2014 and last for 1 year.

The survey is voluntary and confidential. The information collected will be used solely for academic purposes. We will not share your data with third parties for purposes of marketing.

Participants are free to withdraw from this study at any time.

Respondents taking part in the study are eligible to receive a £50 Eldon Square voucher from Newcastle University upon successful completion of the survey.

This survey is limited to one person per household.

The survey is independent with no affiliation with YHN.

FOR MORE INFORMATION

contact us at

energyresearch@newcastle.ac.uk

Energy Activity

1

Debriefing >>>

The results will be used for a student's doctorate and will be available at the end of 2015.

The information can be used to understand how people use energy within their home before and after the investment work (insulation and new windows).

Participants and YHN will be informed at the end of the project by mail about the energy model and the main results. This result will be disseminated also in academic journals and in conferences.

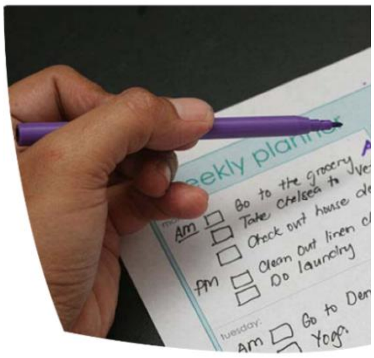
The information you provide will be treated as strictly confidential at no time will you or your household be identified. We will not pass any personal information to YHN.

If you want to receive information about the results please let us know during the survey.

energyresearch@ncl.ac.uk.

Energy Activity

How to participate >>>



Please fill in the activity diary and locate the data logger following the instructions below.

How to fill in the diary

1. Mark with an “X” on the timetable to record your **in-home** daily activities. (Please don’t record activities out of home)

2. Record your and your family member’s activities for one week.

3. If you make a mistake, please just cross it out.

4. Tell us more about your activities in a 15 min interview, when the questionnaire will be collected.

How to locate the data logger

1. Please place the data logger in the living room.

2. It <u>should not be located</u> close to walls or in the path of direct sunlight and frequent air movements or heat.

Energy
Activit

Diary example >>>

Activities	6:00 7:00	7:00 8:00	8:00 9:00	9:00 10:0	10:00 11:00	11:00 12:00	12:00 13:00	13:00 14:00	14:00 15:00	15:00 16:00	16:00 17:00	17:00 18:00	18:00 19:00	19:00 20:00	20:00 21:00	21:00 22:00	22:00 23:00	23:00 24:00	24:00 01:00
Personal Care			X																
Mealtime				X										X					
Creative and fun				X											X				
Physical activities																			
Social activities																			
Work or study related																			
Joint activities																			
Sleeping	X	X																	
Out of home					X	X	X	X	X	X	X	X							
Cleaning																			

4

Activity definition >>>

Personal care:
Activities related to personal hygiene such as taking a shower, bath, brushing your teeth. Activities related to personal care such as drying or ironing your hair.

Mealtime:
Cooking or/and reheating food for breakfast, lunch or dinner.

Creative and fun:
Playing games, listening music, watching TV, reading, surfing on internet, chatting, talking by telephone.

Physical activities:
Doing exercise at home, e.g. running on running belt.

Social activities:
Invite relatives or/and friends to your house

Work or study related:
reading, working on your laptop.

Joint activities:
Household member shared activities in home.
For example having family dinner.

Cleaning:
It means daily cleaning e.g. clear out and wipe down the sink, dishes..etc.
.

Activities	6:00 7:00	7:00 8:00	8:00 9:00	9:00 10:00	10:00 11:00	11:00 12:00	12:00 13:00	13:00 14:00	14:00 15:00	15:00 16:00	16:00 17:00	17:00 18:00	18:00 19:00	19:00 20:00	20:00 21:00	21:00 22:00	22:00 23:00	23:00 24:00	24:00 01:00
Personal Care																			
Mealtime																			
Creative and fun																			
Physical activities																			
Social activities																			
Work or study re-																			
Joint activities																			
Sleeping																			
Cleaning																			
Out of home																			

6

Cleaning

Tasks	DAILY	WEEKLY	MONTHLY	N/A
Dishes				
Laundry (wash bed sheets, towels)				
Laundry (OTHER)				
Dust				
Clean bathroom(s)				
Vacuum				
Mop floors				
Clean kitchen appliances				
Take out garbage				
Check refrigerator for spoiled food				
Water plants				
Clean walls and light fixtures				
Clean windows				
Defrost freezer				
Deep clean appliances				

	Appliance	Personal care	Mealtime	Creative and fun	Physical act.	Social act	work or study related	other
1	Broadband router							
2	Desktop computer							
3	Laptop							
4	Games console							
5	Electric drill							
6	Freeze							
7	Fridge							
8	Fridge-freezer							
9	Grill/hob							
10	Heating blanket							
11	LCD TV							
12	Plasma TV							
13	Other TV							
14	electric Toothbrush							
15	Smart phone (charge)							
16	Tablet -ipad (charge)							
17	TV box							
18	Video, DVD or CD							
19	charging phone							
20	Deep fryer							
21	Dishwasher							
22	Electric Shower							
23	Extractor fan							
24	Hair straightener							
25	hairdryer							
26	hoover							
27	Iron							
28	kettle							
29	microwave							
30	oven							
31	radio							
32	shaver							
33	toaster							
34	Washing mashine							

contact us at

energyresearch@newcastle.ac.uk

Macarena Rodri-guez	**PhD Student** Newcastle University	m.rodriguez@ncl.ac.uk
Carlos Calderon	**Senior lecturer** School of Architecture Planning and Landscape Newcastle University	carlos.calderon@ncl.ac.uk +44(0)1912086025

Energy Activity

Newcastle University

Heating diaries

Heating from 22nd May to 28th May 2014

Activities	6:00 7:00	7:00 8:00	8:00 9:00	9:00 10:00	10:00 11:00	11:00 12:00	12:00 13:00	13:00 14:00	14:00 15:00	15:00 16:00	16:00 17:00	17:00 18:00	18:00 19:00	19:00 20:00	20:00 21:00	21:00 22:00	22:00 23:00	23:00 24:00	24:00 01:00
Monday																			
Tuesday																			
Wednesday																			
Thursday																			
Friday																			
Saturday																			
Sunday																			

1

Winter diary

Winter diary

Activities	6:00 7:00	7:00 8:00	8:00 9:00	9:00 10:00	10:00 11:00	11:00 12:00	12:00 13:00	13:00 14:00	14:00 15:00	15:00 16:00	16:00 17:00	17:00 18:00	18:00 19:00	19:00 20:00	20:00 21:00	21:00 22:00	22:00 23:00	23:00 24:00	24:00 01:00
Personal Care																			
Mealtime																			
Creative and fun																			
Physical activities																			
Social activities																			
Work or study re-																			
Joint activities																			
Sleeping																			
Cleaning																			
Out of																			

Follow-up interview Guide

ID participant:

Interviewer's Notes:

Before we start, I'd like to explain what we'll be doing during the interview, which will take no longer than 20 minutes. Basically, I'll ask you questions about your responses to the diary. This interview will be kept strictly confidential and your identity will remain anonymous when I write-up the results of the study. Any questions before we begin?

Questions: (15 minutes)

1. When you responded the diary, you indicated that you were doing X [answer based on the diary response]. Can you explain a bit more about x (with whom, where, why) you were doing X?

2. Do you think doing x is part of your normal routine? What did you do after doing X? From the activities responded in the diary, do you think there is something that is not part of your normal routine? When you responded the diary, you indicated that you were going out at X. Do you normally go out at this time?

3. If there are more people involved: When you responded the diary, you indicated that you were doing x with x. How often have you doing x with x to find out about situations similar to X in your normal routine?

Go to Closing: (5 min)

4. Probe: What do you think of this diary, do you think helps to understand what do you do at home?

5. Is there anything you would like to add about what we've been discussing?

Closing:

Thank you very much for your time.

Survey brochure: Socio-demographic information (Structured questionnaire)

Your profile

Gender	1: Female 2: Male
Age	1: 6 or less 2: 7-15 3:16-20 4:21-30 5: 31-40 6: 41-50 7: 51-60 8:61-70 9: 71-80 10: 80 or more
What is your relationship to the head of the household	1: head 2: Wife/Husband/Partner 3: Son/daughter 4: Sibling 5: Parent 6: Other relative 7: Unrelated.
What best describes your education level	1: Without formal education 2: CSE/ O-level/ GCSE/ 3: A-Levels/FE College 4: University degree or Equivalent/ 5: Postgraduate studies 6: Don't know /Refused 7: Other (specify)_____________________
What best describes your employment status	1: Student 2: Employed full time 3: Housewife 4: Employed part time 5: Unemployed 6: Retired 7: Unable to work 8: Don't know/R Refused 9: Other (specify) _____________________

1

Thermal comfort perception questionnaire

I RESPONDENT CHARACTERISTICS

Ia. How long have you and your family stayed at the current residence? ___

Ib. How many people currently live in your home year-round? ___

Ic. Which one of the following best describes your household? [Read categories] [select one]

1: Live alone
2: Couple
3: Couple and Children (up to 15 years old)
4: Extended Family
5: Share other Adults
6: One Adult and Children (up to 15 years old)
7: Don't know
8: Refuse

II OTHER HEATER AND FUEL

Id. Do you often use any other types of equipment to heat your home?

a. [Yes: 1/ No:2]

ii. [If Yes] What fuel does the (type of equipment) of heating equipment use?
[[Read categories] [Select one]
1: Electricity
2: Natural gas
3: Bottled gas (LPG or Propane)
4: Fuel oil
5: Solar
6: Don't know
7: Refused
Other (Specify) _____________

III HEATING BEHAVIOUR

How do you evaluate the following questions?

1	How would you describe the overall level of warmth in your home at the moment?	*Very cold 1*	*2*	*3*	*4*	*Very warm 5*
2	How would you describe the overall level of draught in your home?	*Very draught 1*	*2*	*3*	*4*	*Not draught at all 5*
3	How would you describe the overall level of noise in your home? (external noise)	*Very noisy 1*	*2*	*3*	*4*	*Not at all 5*
4	Do you feel comfortable at home?	*Very comfortable 1*	*2*	*3*	*4*	*Not at all 5*
5	How would you describe external appearance of your home/building?	*Very Good 1*	*2*	*3*	*4*	*Very bad 5*
6	How would you describe your level of health? (ONLY RELATED TO COLD–DISEASES)	*Very good 1*	*2*	*3*	*4*	*Very bad 5*

Member 1:

Ie. Gender: 1 Female/ 2 Male

If. Age: ___

Ig. Relation to head of household:

1: head
2: Wife/Husband/Partner
3: Son/daughter
4: Sibling
5: Parent
6: other relative
7: unrelated.

Ih. Education level [Read categories] [select one]

1: Without formal education
2: CSE/ O-level/ GCSE/
3: A-Levels/FE College
4: University degree or Equivalent/
5: Postgraduate studies
6: Don't know
7: Other (specify)_____________________

Ii. Employment status? [Read categories] [Select one]

1: Student
2: Employed full time
3: Housewife
4: Employed part time
5: Unemployed
6: Retired
7: Unable to work
8: Don't know/R Refused
9: Other (specify) ____

Ij. How long does (he/she) typically spend in the house in weekdays and weekends?
Weekdays____ (hours) and weekends ____ (hours)

Semi-structured questionnaire

1. <u>Relevant changes</u>

Can you think of any changes in your home since the first survey (May 2014) that might affect the amount of energy that you pay for?

For example. Having more people living with you, getting a new job, sick.

2. <u>Final interview:</u>

Let's talk about the building

What do you think about the retrofit insulation in terms of:

- Heating usage (Use of main heating and secondary heating;
- Thermal comfort perception (how warm or cold do you feel);
- Ventilation;
- Infiltration?

Annex F

Weather Forecast

1. May 2014

Newcastle Airport

5:24 PM GMT on February 07, 2017 (GMT +0000)

Today Forecast

Weather History for EGNT - May, 2014

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
				1 Actual: 8° | 6° 0.00 mm Average: 12° | 4° 0.15 mm	2 Actual: 9° | 1° 0.00 mm Average: 13° | 4° 0.15 mm	3 Actual: 12° | -1° 0.00 mm Average: 12° | 5° 0.18 mm
4 Actual: 16° | 9° 0.00 mm Average: 12° | 5° 0.18 mm	5 Actual: 16° | 8° 0.00 mm Average: 13° | 4° 0.18 mm	6 Actual: 16° | 10° 0.00 mm Average: 13° | 4° 0.18 mm	7 Actual: 13° | 6° 0.00 mm Average: 13° | 4° 0.15 mm	8 Actual: 14° | 9° 0.00 mm Average: 13° | 4° 0.15 mm	9 Actual: 14° | 8° 0.00 mm Average: 13° | 4° 0.15 mm	10 Actual: 15° | 8° 0.00 mm Average: 13° | 5° 0.18 mm
11 Actual: 13° | 7° 0.00 mm Average: 13° | 5° 0.18 mm	12 Actual: 12° | 6° 0.00 mm Average: 13° | 6° 0.18 mm	13 Actual: 13° | 3° 0.00 mm Average: 13° | 6° 0.18 mm	14 Actual: 16° | 4° 0.00 mm Average: 14° | 6° 0.18 mm	15 Actual: 17° | 10° 0.00 mm Average: 14° | 6° 0.18 mm	16 Actual: 20° | 8° 0.00 mm Average: 14° | 6° 0.18 mm	17 Actual: 20° | 10° 0.00 mm Average: 14° | 6° 0.18 mm
18 Actual: 22° | 11° 0.00 mm Average: 14° | 6° 0.18 mm	19 Actual: 19° | 7° 0.00 mm Average: 14° | 6° 0.15 mm	20 Actual: 14° | 9° 0.00 mm Average: 14° | 6° 0.15 mm	21 Actual: 18° | 9° 0.00 mm Average: 14° | 6° 0.15 mm	22 Actual: 11° | 7° 0.00 mm Average: 14° | 6° 0.15 mm	23 Actual: 9° | 8° 0.00 mm Average: 14° | 6° 0.15 mm	24 Actual: 12° | 9° 0.00 mm Average: 14° | 7° 0.18 mm
25 Actual: 15° | 9° 0.00 mm Average: 14° | 7° 0.18 mm	26 Actual: 18° | 9° 0.00 mm Average: 14° | 7° 0.18 mm	27 Actual: 16° | 9° 0.00 mm Average: 14° | 7° 0.18 mm	28 Actual: 12° | 10° 0.00 mm Average: 14° | 7° 0.18 mm	29 Actual: 14° | 10° 0.00 mm Average: 14° | 7° 0.20 mm	30 Actual: 14° | 9° 0.00 mm Average: 15° | 7° 0.20 mm	31 Actual: 17° | 6° 0.00 mm Average: 15° | 7° 0.20 mm

Calendar Legend

Sunny Clear · Mostly Cloudy · Partly Cloudy · Cloudy · Rain · Snow

Hail Flurries · Thunderstorms · Hazy Fog · Sleet · '?' denotes 'chance of' · Unknown

2. Feb 2015

Newcastle Airport

5:33 PM GMT on February 07, 2017 (GMT +0000)

Today Forecast

Weather History for EGNT - February, 2015

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1 Actual: 3° | -4° 0.00 cm Average: 7° | 2° 0.20 mm	2 Actual: 3° | -4° 0.00 mm Average: 7° | 2° 0.20 mm	3 Actual: 4° | -5° 0.00 mm Average: 7° | 2° 0.20 mm	4 Actual: 4° | 0° 0.00 mm Average: 7° | 2° 0.20 mm	5 Actual: 6° | 1° 0.00 mm Average: 7° | 1° 0.18 mm	6 Actual: 6° | 0° 0.00 mm Average: 7° | 1° 0.18 mm	7 Actual: 6° | -2° 0.00 mm Average: 7° | 2° 0.20 mm
8 Actual: 6° | -1° 0.00 mm Average: 7° | 2° 0.18 mm	9 Actual: 8° | 3° 0.00 mm Average: 7° | 2° 0.18 mm	10 Actual: 6° | 0° 0.00 mm Average: 7° | 2° 0.18 mm	11 Actual: 6° | 0° 0.00 mm Average: 7° | 2° 0.15 mm	12 Actual: 7° | 2° 0.00 mm Average: 7° | 2° 0.15 mm	13 Actual: 6° | 2° 0.00 mm Average: 7° | 1° 0.13 mm	14 Actual: 8° | 3° 0.00 mm Average: 7° | 1° 0.13 mm
15 Actual: 7° | 4° 0.00 mm Average: 7° | 1° 0.13 mm	16 Actual: 7° | 0° 0.00 mm Average: 7° | 1° 0.13 mm	17 Actual: 8° | 0° 0.00 mm Average: 7° | 1° 0.13 mm	18 Actual: 12° | 6° 0.00 mm Average: 7° | 1° 0.13 mm	19 Actual: 9° | 2° 0.00 mm Average: 7° | 1° 0.15 mm	20 Actual: 7° | 1° 0.00 mm Average: 7° | 1° 0.15 mm	21 Actual: 6° | 0° 0.00 mm Average: 7° | 1° 0.15 mm
22 Actual: 7° | -1° 0.00 mm Average: 6° | 1° 0.18 mm	23 Actual: 6° | 1° 0.00 cm Average: 6° | 1° 0.18 mm	24 Actual: 5° | 2° 0.00 mm Average: 6° | 0° 0.18 mm	25 Actual: 9° | 1° 0.00 mm Average: 6° | 0° 0.20 mm	26 Actual: 11° | 2° 0.00 mm Average: 6° | -1° 0.20 mm	27 Actual: 7° | 2° 0.00 mm Average: 6° | -1° 0.23 mm	28 Actual: 11° | 6° 0.00 mm Average: 6° | -1° 0.20 mm

Calendar Legend

Sunny Clear · Mostly Cloudy · Partly Cloudy · Cloudy · Rain · Snow

Hail Flurries · Thunderstorms · Hazy Fog · Sleet · '?' denotes 'chance of' · Unknown

3. April_2015

Newcastle Airport

5:36 PM GMT on February 07, 2017 (GMT +0000)

Today Forecast

Weather History for EGNT - April, 2015

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
			1 Actual: 8° | 2° 0.00 mm Average: 11° | 3° 0.23 mm	2 Actual: 10° | -1° 0.00 mm Average: 10° | 3° 0.20 mm	3 Actual: 8° | 4° 0.00 mm Average: 10° | 3° 0.20 mm	4 Actual: 11° | 5° 0.00 mm Average: 10° | 3° 0.20 mm
5 Actual: 18° | 3° 0.00 mm Average: 10° | 3° 0.20 mm	6 Actual: 18° | 4° 0.00 mm Average: 10° | 3° 0.20 mm	7 Actual: 14° | 5° 0.00 mm Average: 10° | 3° 0.20 mm	8 Actual: 15° | 2° 0.00 mm Average: 10° | 2° 0.18 mm	9 Actual: 18° | 3° 0.00 mm Average: 10° | 2° 0.18 mm	10 Actual: 18° | 3° 0.00 mm Average: 10° | 2° 0.18 mm	11 Actual: 10° | 4° 0.00 mm Average: 10° | 2° 0.18 mm
12 Actual: 9° | 3° 0.00 mm Average: 10° | 2° 0.18 mm	13 Actual: 13° | 2° 0.00 mm Average: 10° | 2° 0.18 mm	14 Actual: 15° | 10° 0.00 mm Average: 10° | 2° 0.20 mm	15 Actual: 13° | 3° 0.00 mm Average: 10° | 2° 0.20 mm	16 Actual: 13° | 1° 0.00 mm Average: 10° | 2° 0.20 mm	17 Actual: 11° | 3° 0.00 mm Average: 10° | 3° 0.20 mm	18 Actual: 10° | -1° 0.00 mm Average: 11° | 3° 0.23 mm
19 Actual: 10° | 1° 0.00 mm Average: 11° | 3° 0.20 mm	20 Actual: 15° | 2° 0.00 mm Average: 11° | 4° 0.20 mm	21 Actual: 16° | 2° 0.00 mm Average: 11° | 4° 0.20 mm	22 Actual: 16° | 2° 0.00 mm Average: 12° | 4° 0.20 mm	23 Actual: 21° | 3° 0.00 mm Average: 12° | 4° 0.20 mm	24 Actual: 18° | 6° 0.00 mm Average: 12° | 4° 0.20 mm	25 Actual: 12° | 4° 0.00 mm Average: 12° | 4° 0.18 mm
26 Actual: 10° | 0° 0.00 mm Average: 12° | 4° 0.18 mm	27 Actual: 11° | -2° 0.00 mm Average: 12° | 4° 0.18 mm	28 Actual: 10° | 2° 0.00 mm Average: 12° | 4° 0.18 mm	29 Actual: 11° | 4° 0.00 mm Average: 12° | 4° 0.15 mm	30 Actual: 10° | 3° 0.00 mm Average: 12° | 4° 0.15 mm		

Calendar Legend

Sunny Clear · Mostly Cloudy · Partly Cloudy · Cloudy · Rain · Snow

Hail Flurries · Thunderstorms · Hazy Fog · Sleet · '?' denotes 'chance of' · Unknown

Annex G

Pilot Survey

A time-based diary with 'fixed-time schedules' was used (Bolger *et al.*, 2003) to capture hourly activities that are centred around the daily life and household during one week, before and after the upgrade. The chosen activities are described as follows:

A. Sleep;

B. Personal care: activities related to personal hygiene such as taking a shower, bath, brushing teeth and activities related to personal care such as drying or ironing hair or getting dressed;

C. Mealtime episodes: cooking or reheating food for breakfast, lunch or dinner;

D. Home duty: cleaning the house;

E. Creative and fun: playing games, listening to music, watching TV, reading, surfing on the internet, chatting, talking by telephone;

F. Intellectual episodes: reading, surfing on the internet for study purposes;

G. Physical episodes: doing exercise at home, e.g. running on a running belt;

H. Social episodes: activities with relatives or/and friends in your house;

I. Spontaneous episodes: different activities every day;

J. Work-related: activities related to work at home;

K. Joint episodes: household member shared activities in-home such as having family dinner (shared activities must be synchronized with other activities, for example, "having family dinner" includes mealtime and joint activity);

L. Out-of-home activities.

The activity diaries were completed without problems, although the following gaps were found, which are outlined in Table ‘Activity diary gaps’ below. In addition, in order to collect heating period information, a heating schedule diary was added. Given the evidence in Table ‘Activity diary gaps’, amendments to the structure of the activity survey sheet were made to the self-completion diary, the final self-completion diary is shown in Annex E.

Activities	Comments	Amendments
Sleep	No comment on this question.	
Personal care	No comment on this question	
Mealtime episodes	Although respondents made little or no comment on this question, the meaning of the word ‘episodes’ was not clear	The word “episodes” was eliminated.
Home duty	Principally home duties such as hoovering, laundry or ironing are tasks that people usually do not do every day (e.g. once per week or twice per month), and then it cannot be allocated in an average day.	This section required further attention and it was added to a week-task sheet. This item was replaced by ‘cleaning’.
Creative and fun	No comment on this question	

Intellectual episodes	Respondents found this item not clear since they were confused with work episodes.	Intellectual episodes and work episodes were replaced by work and study activities.
Physical episodes	Although respondents made little or no comment on this question, the meaning of the word 'episodes' was not clear	The word "episodes" was replaced by activities.
Social episodes	Although respondents made little or no comment on this question, the meaning of the word 'episodes' was not clear.	The word "episodes" was replaced by activities.
Spontaneous episodes	Although respondents made no comment on this question, the activities related to 'spontaneous episodes' cannot be measured in terms of energy consumption, therefore, information obtained is pointless.	The item was eliminated.
Work-related	Respondents found this item was not clear since they were confused with intellectual episodes.	Intellectual episodes and work episodes were replaced by work and study activities.
Joint episodes	No comment on this question.	The word "episodes" was replaced by activities.
Out of home	No comment on this question.	

Table Annex G. 'Activity diary gaps'.

Annex H

Method to group the sequence of activities

The steps to construct an activity profile are:

1. Sequence of activities: based on the information collected on the self-completion diaries, the information was organised in a sequence of activities for each day and dwelling, according to the Figure '*Diagram of steps to obtain the activity profile'*;

2. Activity profile: the sequence of activities is transformed in the activity profile sequence by using the method position weight matrix. An overview of different steps is shown in the Figure *'Diagram of steps to obtain the activity profile'*.

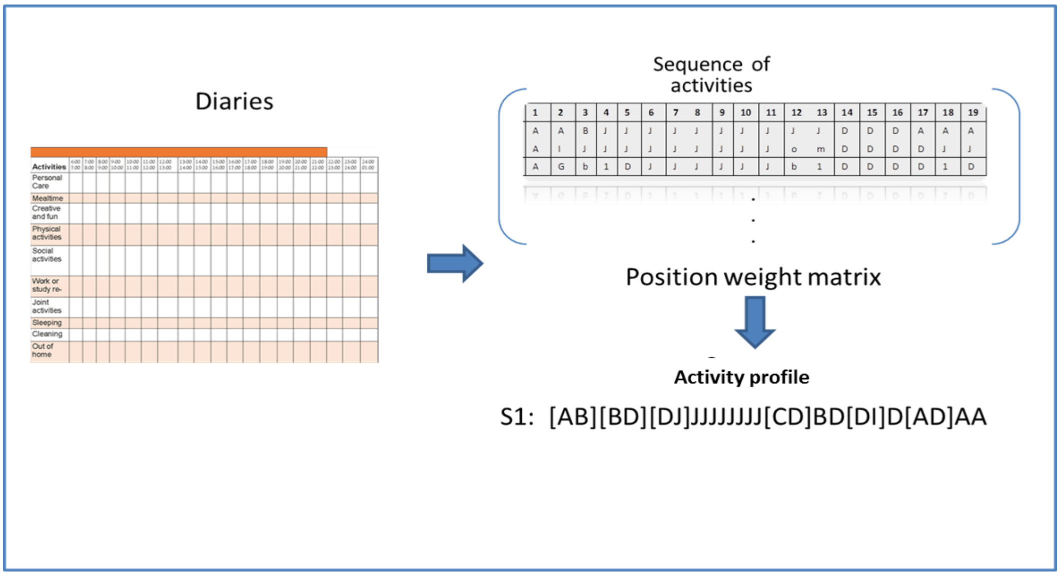


Figure 'Diagram of steps to obtain the activity profile'.

Sequence of activities

The symbols (alphabet) used to represent the activity types in the sequence of activities identify common daily activities that the occupants might perform at home. The activities might be repeated in the sequence, in different time periods, for example, cleaning at breakfast or dinner time. The activities were codified into 10 characters according to the Table 'Activity types'.

Activity types	Letter_act_program
Sleeping	A
Personal care	B
Mealtime	C
Creative and fun	D
Physical activities	E
Social activities	F
Work or study related	G
Joint activities	H
Cleaning	I
Out of home	J

Table ‘Activity types’. Activity types codified into 10 characters.

The length of a window on a sequence has been uniformly sampled in 19 periods of 1 hour (represented in Table by ID times), from 06:00 to 01:00 (19 hours) (see the *Table* ‘Time schedule’).

ID times	Time Description	Begin	End
1	Time1	06:00:00	07:00:00
2	Time2	07:00:00	08:00:00
3	Time3	08:00:00	09:00:00
4	Time4	09:00:00	10:00:00
5	Time5	10:00:00	11:00:00
6	Time6	11:00:00	12:00:00
7	Time7	12:00:00	13:00:00
8	Time8	13:00:00	14:00:00
9	Time9	14:00:00	15:00:00
10	Time10	15:00:00	16:00:00
11	Time11	16:00:00	17:00:00
12	Time12	17:00:00	18:00:00
13	Time13	18:00:00	19:00:00
14	Time14	19:00:00	20:00:00
15	Time15	20:00:00	21:00:00

ID times	Time Description	Begin	End
16	Time16	21:00:00	22:00:00
17	Time17	22:00:00	23:00:00
18	Time18	23:00:00	00:00:00
19	Time19	00:00:00	01:00:00

Table 'Time schedule'

A basic exemplification of how self-completion diary data were codified into the sequence of activities is shown in the Figure '*Diary example'*

<table>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td></tr>
<tr><td colspan="2">Sleep -> A</td><td>Personal care->B</td><td colspan="10">Out of home->J</td></tr>
<tr><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td></tr>
<tr><td colspan="3">Creative and fun->D</td><td colspan="3">Sleep->A</td></tr>
</table>

Figure 'Diary example'. Example of how diaries (in-home schedules) were codified into sequence of activities.

Activity profile

Identification of the activity profile is obtained by manipulating sequences of activities. One of the simplest methods of obtaining the activity profile is that of the use of a Position Weight Matrix (PWM) method. The PWM is a matrix M, generated by A×w, where A is a sequence of symbols (A1, A2, A3, An) and w is the length of a window on a sequence.

A position weight matrix can be obtained using different methods such as the direct frequency method or the Markov chain. Using parsimonious criteria a direct frequency method was chosen, whereby the matrix M for each pattern can be defined as the relative frequency of x at position p by selecting the highest value from each column in which each column represents a probability distribution (Dong and Pei, 2007). Therefore, M(x,p) can be represented as follows:

$$M(x,p) = \frac{n\ (x,p)}{N}$$

The suitability of the Position Weight Matrix (PWM) method was tested by using data from the pilot survey (see Table 'Position Weight Matrix'). Based on the test, a "consensus sequence" or activity profile was obtained by including the most frequent symbol whose frequency is above 0.4 for each position.

The consensus sequence for the pilot study was:

S' = A[AB][BC]LLLLLLLLLLCCDEAA

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
A	**0.8**	**0.4**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.4**	**0.8**
B	0.2	**0.4**	**0.4**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0.2	**0.4**	0.2	0	0	0	0	0.2	0	0	0	0.2	**0.4**	**0.4**	0	0	0	0
D	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	**0.4**	0	0	0
E	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0.2	0.2	**0.6**	0.2	0
F	0	0	0	0	0	0	0	0	0	0	0.2	0	0.2	0.2	0.2	0	0	0	0.2
G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0.2	0.2	0.2	0
I	0	0	0	0	0	0	0	0.2	0	0	0	0.2	0	0	0	0.2	0	0.2	0
J	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	0	0.2	**0.8**	**0.8**	**1**	**1**	**0.8**	**0.8**	**0.8**	**0.8**	**0.6**	**0.6**	0.2	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0
O	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0

Table 'Position Weight Matrix'. Position Weight Matrix obtained from the pilot survey.

An activity profile for the study survey was obtained by including the most frequent activities whose frequency is above 0.2 (20% of frequency of the activity).

Annex I

Further calculation on the space heating consumption of the target building.

Methodology

A database of monthly space heating meter-point data for the years 2012–2013 was also used to examine the consumption of previous years in the target building (n=157). The annualised space heating data are derived from the difference between two meter readings (January and December), taking into account all the records, estimated and direct record (only negatives were not considered). See the Table ‘Annualised mean space heating consumption for the target building below.

Year	Annualised mean space heating consumption: Target building (kWh) *
2012	1357
2013	1396

(*) n=157

Table ‘Annualised mean space heating consumption’ for the target building in kWh.