CHANGES IN SPACE HEATING ENERGY CONSUMPTION FOLLOWING ENERGY EFFICIENT REFURBISHMENT IN LOW-INCOME DWELLINGS IN ENGLAND

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Student Declaration:

I, Sung-Hyon HONG, confirm that the work presented in this thesis is his own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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ABSTRACT

This study examines the change in the space heating energy consumption and its associated cost and carbon emissions following retrofit energy efficiency upgrade. 3 to 4 week fuel consumption and temperature data were collected from some 1500 dwellings over two successive winters in 2001/2002 and 2002/2003. The case study dwellings were occupied by elderly householders or families with young children and were either awaiting or had received a combination of draught proofing, insulation and central heating measures under England's *Warm Front Scheme*.

The findings show that the *Warm Front Scheme* resulted in a mean increase of 1.6 °C in indoor temperature and a mean increase of 12 % in fuel consumption. Nevertheless, the switch from electricity to gas for space heating following the introduction of gas boilers resulted in a mean reduction in heating cost by 7 %. The scheme was found to have negligible impact on carbon emissions.

Characteristic differences were observed with individual energy efficiency measures. Central heating resulted in the greatest temperature rise by 2.3 °C followed by insulation by 0.7 °C with a negligible impact from draught proofing. Clear evidence was found in householders increasing the demand temperature following the introduction of a central heating system while no evidence of this was found following the introduction of insulation.

In terms of energy use, insulation resulted in a mean saving of 9 % but fell short by 74 % to 84 % from the theoretical prediction while central heating resulted in a mean increase of 29 % in the energy consumption. Draught proofing was found to have little impact on the energy use.

When examined in terms of energy cost, insulation and central heating all resulted in

mean cost savings of 13 % and 9 % respectively but falling short by 55 % to 72 % and 57 % to 82 % compared to their respective theoretically predicted mean cost savings. Insulation also resulted in mean carbon emissions saving of 13 % but fell short by 56 % to 73 % from the theoretical prediction while central heating resulted in insignificant carbon emissions saving. Combining insulation with central heating was found to be beneficial in terms of mitigating the energy consumption rise associated with central heating from 29 % down to 16 % while maximizing the temperature gain by as much as 3.1 °C.

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CHAPTER 1 INTRODUCTION

1.1. Research Aim

The aim of this research is to explore the saving in space heating energy consumption, energy cost and carbon emissions following retrofit installation of energy saving measures of draught proofing, insulation and central heating in low-income dwellings in England. Specifically, the research work develops the findings of the author's previous study which found an increase in the energy consumption following England's *Warm Front Scheme* energy efficiency upgrade (Appendix 1) [1] despite householders reporting reduced difficulty in paying fuel bills [2]. The objectives of this study are as follows:

1. To examine the impact of energy efficiency upgrade on the energy consumption using a method of analysis different from the author's previous study to reconfirm the findings on the increased energy consumption,
2. To examine the impact of energy efficiency upgrade on the energy cost and carbon emissions, relationships not explored by the author in the previous study.
3. To examine the impact of internal temperature change on the energy consumption and its associated cost and carbon emissions, relationships not explored by the author in the previous study.
4. To identify factors other than the temperature that can explain the increase in the energy consumption.
5. To examine whether the key energy efficiency upgrade measures – draught proofing, insulation and central heating – have characteristically different impact on the energy consumption and its associated cost and carbon emissions.

1.2. Research Context

Improvement in dwelling energy efficiency frequently results in householder taking the cost benefit of energy saving as increased indoor temperature, a process known as the *take-back* or the *comfort taking*. This results in less energy saving than what is theoretically expected. There are also other factors that contribute to the reduced energy saving such as energy efficiency measures failing to deliver the theoretically expected performance [3, 4, 5] and occupant behaviour. For reasons such as these, policies aimed at reducing the carbon emissions by improving the energy efficiency of housing may not deliver the intended effect.

Energy efficiency is a key strategy adopted by the government in England to tackle fuel poverty which is linked to around 40,000 excess deaths during winter months [29]. The *Warm Front Scheme* is the government's main tool for tackling fuel poverty in England by providing grants to improve home energy efficiency to fuel poor households in the private rented and owner-occupied sectors [2]. The scheme targets households who are at most risk to cold temperature, i.e. the young, the aged and those with long term illness, by reducing energy cost and improving indoor temperature *to ensure that the most vulnerable households need no longer risk ill-health due to a cold home*.

The database used in this study was collected as a part of a large national study titled the *Health Impact Evaluation of Warm Front* [2] aimed to evaluate the impact of the *Warm Front Scheme* on the health and quality of life of the grant recipients. The case study dwellings were either in receipt of or were awaiting the installation of energy efficiency measures, mainly draught proofing, insulation and energy efficient heating system. The data consists of property condition, household condition, monitored temperature, relative humidity and fuel consumption data collected from some 3000 dwellings representing five main urban clusters in England making the it one of the largest data sets of its kind ever collected in a single study in the UK.

1.3. Research Significance

The significance of this thesis is that it examines a complex topic by explaining why actual energy saving following domestic energy efficiency upgrade falls short of the theoretically predicted saving. Although a handful of studies in the past have investigated this topic in the UK, the magnitude and the cause behind the *shortfall* are still debatable and *… very uncertain until further detailed monitoring and analysis is carried out"* [14]. The further evidence provided from this study is expected to make a significant contribution in this subject area where more research is currently needed. The following qualities are what make this study unique:

One, despite the *Warm Front* data set including one of the most comprehensive before and after intervention monitored temperature and fuel consumption data, these were not originally collected to assess the building energy performance. This required the complicated pathways of data processing described in Chapter 4 to derive the data suitable for the analyses in this study. Consequently, the findings based on a sample size collected from some 3000 dwellings give robustness to this study.

Two, the investigations are carried out for the individual energy efficiency measures of draught proofing, insulation and central heating whose effects in practice are rarely observed in isolation since they tend to be found in combination with other measures.

Three, the impact of energy efficiency measures are assessed by three different parameters, i.e. delivered energy, energy cost and carbon emissions. The findings from this thesis show that significantly different magnitudes of change result depending on the choice of the parameter.

Four, extensive use was made of the data collected on the in situ performance of the energy efficiency measures. This information was then fed into the modelled predictions in order to examine the sensitivity of the theoretically predicted energy saving in response to the quality of the input data.

Five, the BRE Domestic Energy Model 8 (BREDEM) is used in this study to determine the theoretical energy saving. The choice is determined by the fact that BREDEM is one of the most widely used domestic energy modelling tool in the UK – along with its variants – and also the tool used in most UK based studies which investigated the impact of energy efficiency measures on the energy saving thereby providing a common platform with which to compare the findings of this study.

1.4. Research Outline

This section summarizes the content of each chapter:

Chapter 2, *Background and Review of Literature*. The comprehensive analyses undertaken in this thesis is what makes this study unique when compared to the other UK based studies in the past.

Chapter 3, *Warm Front Study and Warm Front Data*. The *Health Impact Evaluation of the Warm Front Scheme* was commissioned by the government in England in order to understand the impact of the *Warm Front Scheme*. The *Warm Front* database was collected as a part of this national study and is used as the database of this thesis.

Chapter 4, *Methodology*. The key variables used in this thesis were derived following complex data processing and references to evidence produced from third party studies. The method used in determining the relationship between the temperature change and the fuel consumption, one of the key investigations of this thesis, is described.

Chapter 5, *Characteristics of Case Study Dwellings*. The disproportionately large representation of the younger households in the case study group means that it is neither an accurate representation of the national fuel poor nor the national *Warm Front* households. On the other hand, the proportion of the elderly households in the sample is found to be similar to that of the national fuel poor

Chapter 6, *Factors Contributing to the Shortfall*. The in situ performance of the three main *Warm Front* energy efficiency measures of draught proofing, insulation and central heating are found to differ or fall short of their theoretically predicted levels of performance.

Chapter 7, *Saving*. The introduction of energy efficiency measures did not necessarily result in energy saving. Characteristically different levels of saving were found in relation to different intervention measures and in relation to different parameters used in measuring the change.

Chapter 8, *Temperature*. The introduction of energy efficiency measures resulted in increased indoor temperature with the greatest increase observed with the combination of insulation and central heating followed by central heating followed by insulation. The *comfort taking* was found to be associated with central heating only.

Chapter 9, *Comfort Taking*. The effect of energy efficiency measures is examined in relation to the energy consumption and the indoor temperature.

Chapter 10, *Loss*. The *loss* was observed with all energy efficiency measures indicating that the measures are not delivering the theoretically expected level of saving despite taking into account the *comfort taking*.

Chapter 11, *Shortfall*. Two methods are used to determine the shortfall. One, by combining the *comfort taking* and the *loss* and two, by determining the difference between the model predicted and the monitored savings.

Chapter 12, *Shortfall Factor*. The *comfort taking*, the *loss* and the *shortfall* are expressed as percentages of the theoretically predicted saving.

Chapter 13, *Discussion*. A multitude of factors are found to determine the *comfort taking*, the *loss* and the *shortfall*. These include the type of energy efficiency measure, the parameter used to measure the change in energy use, the dwelling temperature and the method used in determining the theoretically predicted saving.

Chapter 14, *Conclusion*. Although the *Warm Front Scheme* did not result in energy and carbon emissions saving, the scheme was effective in achieving its aims by reducing the space heating related fuel cost and improving the indoor temperature.

CHAPTER 2 BACKGROUND AND REVIEW OF LITERATURE

The aim of this chapter is to present why the topic of the shortfall in energy saving is important within the context of UK's interest in tackling carbon emissions and fuel poverty and what answers the existing literature are not providing which this thesis has set out to address.

2.1. Climate Change

The earth experienced a mean rise in its atmospheric temperature by 0.6 ± 0.2 °C in the last century while the 1990's witnessed the warmest decade in this millennium. This change in the atmospheric behaviour is now commonly referred to as 'climate change' or 'global warming' and is being attributed to the increased atmospheric concentration of green house gases observed in the atmosphere. Although green house gases (water vapour, methane, carbon dioxide) are found naturally in the atmosphere, a pronounced rise in the level of carbon dioxide has been observed over the last century from a pre-industrial era level of 280 ppm to 368 ppm which is increasingly thought to be the result of human activity associated with the burning of fossil fuel.

Without a substantial climate policy by the international community, the global temperatures are likely to increase by 1.4 °C to 5.8 °C between the period 1990 and 2100. Although the effect from climate change will vary according to regions, the likely adverse impacts include rise in the sea level, frequent droughts and floods and extreme weather patterns [6].

2.2. International Response to Climate Change

In recognition of the global impact of climate change, several international milestone achievements have taken place over the last two decades to tackle the climate change. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was founded to assess and to disseminate information on climate change. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was agreed at the Earth Summit in Rio de Janeiro by the majority of world nations recognizing the need to stabilize greenhouse gas emissions with developed countries taking the lead aiming to reduce greenhouse gas emissions to 1990 levels by 2000 [7]. In 1997 the Kyoto Protocol was ratified as an amendment to the UNFCCC and came into force as a legally binding agreement in 2005 for developed countries agreeing to reduce the overall emissions of a basket of greenhouse gases by 5.2 % below 1990 levels over the five-year period of 2008-2012 [8].

The European Union (EU) have been taking a lead in tackling the climate change with the then 15 EU Member States agreeing under the Kyoto Protocol to reduce the basket of greenhouse gases by 8 % below 1990 levels. In 2000, the European Climate Change Programme (ECCP) was established to develop European-level policies and strategies to meet the Kyoto Protocol target by implementing EU emissions trading scheme, the use of renewable energy sources and increased building energy performance. The EU member states have also moved policies beyond the Kyoto target by aiming to reduce the green house gas emissions by 15-30 % below the 1990 level by 2020 and 60-80 % by 2050 [9].

2.3. Climate Change Programme in the UK

Under the Kyoto agreement, the UK is committed to reduce six major greenhouse gas (carbon dioxide, methane, nitrous oxide and three fluorinated gases) emissions by 12.5 % below the 1990 level by 2008-2012 [11]. Domestically, a more stringent target beyond the Kyoto agreement was set to reduce the carbon dioxide emissions by 60 %

below the 2000 level by the year 2050 [10, 11] which will limit its concentration to no more than 550 parts per million if adopted by other industrial nations limiting the rise in the global temperature to no more than 2 °C, a level beyond which the consequences of the natural disaster is predicted to be severe.

UK's commitment to achieve its post-Kyoto emissions target is underlined by its introduction of the draft Climate Change Bill in 2007 designed as a legally binding framework to move the UK into a low-carbon economy through a comprehensive program of legislation and accountability administered by an independent committee. The issue of personal carbon trading in the UK as a means to curb carbon emissions is also included for the first time in this bill [12]. UK aims to deliver its post-Kyoto Protocol carbon target mainly by focusing on improved energy efficiency, increased use of renewable energy sources and EU emissions trading scheme.

2.4. Energy Efficiency Commitment in the UK

Achieving UK's post-Kyoto Protocol carbon emissions target is identified as one of UK's long-term energy policies in the Energy White Paper together with the aims of national energy security, sustainable economic growth and the elimination of fuel poverty. While the main driver behind UK's reduction in carbon dioxide from 1990 to 2004 came from the restructuring of the energy supply industry reducing the carbon content of electricity generation by about 30% [13], energy efficiency which is defined as *'the cheapest, cleanest and safest way of addressing our energy policy objectives*', lies at the heart of the success in UK's energy policy and is expected to deliver about half of the projected carbon dioxide reduction by 2020 [11].

UK's energy policy places great emphasis in attaining energy efficiency in the building sector which currently accounts for more than half of UK's total carbon emissions from their operation, heating and cooling. More than half of this is generated from the housing sector.

2.5. Carbon Emissions from UK Dwellings

Between 1970 to 2001 carbon emissions from the UK housing sector decreased by 23 % (11.9 MtC) [15]. The main reasons are attributed to the restructuring in the power supply industry from coal to gas generation since the mid 1990s and increased shift in the domestic primary fuel mix from solid to gas (1970, solid: 39 %, gas: 24 %; 2001, solid: 4 %, gas: 67 %) [15]. Housing currently accounts for just over 30 % of all carbon dioxide emissions in the UK and by 2010 the emissions from housing are expected to rise 18.5 % above the 1990 level with continued increase beyond 2010 [14]. Under the UK Energy Efficiency Action Plan, the government aims to reduce the domestic carbon emissions by 31 % by 2020 below the 1990 level [14].

2.6. Energy Consumption in UK Dwellings

Nevertheless, during the same period between 1970 to 2001, the domestic energy consumption increased by 32 % [15]. The increase is attributed to the combination of increased number of households by 36 %, increased mean internal temperature from 12.6 °C to 18.9 °C, increased household income by 30 % since 1990 and increased ownership of electrical appliances by 157 % (lighting rose by 63 %) [15]. On the other hand, improvements in dwelling and appliance energy efficiency since 1970's combined with increased mean external temperature from 5.8 °C in 1970 to 7.2 °C in 2000 is thought to have contributed to a 46 % saving in fuel use compared to what would have been without these improvements [15, 16].

2.7. Energy Efficiency in UK Dwellings

Space and water heating accounts for the majority of UK domestic energy use and are thought to contribute 84 % of the total delivered energy with the remainder 16 % used for cooking, appliances and lighting [13]. The proportion taken up by space heating is also thought to increase in dwellings with poorer energy efficiency which is likely to be the case in older dwellings where space heating can take up as much as 63 % in a pre-1910 dwelling, 44 % in a circa 1975 dwelling and 33 % in a post-1995 dwelling [17].

In 2007, there were a total of 22.2 million dwellings in the UK 59 % of which were built prior to1964 - before the introduction of energy performance guideline in the Building Regulations in 1965 [18]. As such improving the energy efficiency of the current UK dwelling stock presents a great saving opportunity in the heating related energy consumption and carbon emissions.

Over the years, energy efficiency in the UK dwellings has improved through increased ownership of draught stripping, insulation and energy efficient heating systems. Taking England as an example, the proportion of dwellings owning loft insulation of at least 150mm increased from 25 % in 2003 to 36 % in 2007 [18]; in 2007, the ownership of cavity wall insulation was 47 % among cavity walled dwellings accounting for 70 % of the English housing stock compared to 22 % in 1996 [18]. The ownership of combination boilers has also seen a remarkable growth from 14 % to 29 % of English dwellings over the same period [18]. On the other hand, the ownership of condensing boilers has been slow with only 10 % owning one in 2007 [18]. The ownership of full double glazing also increased from 26 % in 1996 to 67 % in 2007 [18].

Traditionally, the uptake of energy efficiency measures by the UK housing sector has been slow mainly due to a historically low energy price where an average UK family spent about 2.9 % of its total income on energy in 2004 [19]. There is further discouragement for investment in energy efficiency measures as a result of high initial capital cost and the long pay-back periods of 3 to 4 years in the case of insulation and 5 to 6 years in the case of double glazing [17] combined with hassle factors associated with their installation.

Improved domestic energy efficiency is currently being implemented by introducing more stringent energy performance standards such as floor insulation and condensing boilers as the minimum requirement through Part L of the Building Regulations. All dwellings are also required to be energy rated at the point of sale through the EU Directive on Energy Performance of Buildings [9]. There are also various government sponsored residential energy conservation schemes involving local authorities such as Home Energy Conservation Act 1995 (HECA) and the Decent Homes Standard while energy suppliers are required by government’s Energy Efficiency Commitment to meet certain domestic energy efficiency targets [14]. However, newly built and refurbished housing add to less than 1 % of the total UK housing stock each year while 63 % of dwellings in the private sector [18] in the UK makes investment into energy efficient measures difficult thereby posing a challenge in improving the energy performance of existing dwellings.

With continued rise in the fuel cost, on the other hand, the benefits to be gained from improved energy performance is becoming more tangible and particularly among the low income households who tend live in poorly insulated and heated dwellings and who tend to spend a greater proportion of their income on fuel bill. However, for a large number of these households, the initial investment required for energy efficiency upgrade is prohibitive.

2.8. Fuel Poverty in the UK

By definition, a household is classified as being fuel poor if the annual fuel expenditure (space heating, water heating, lights and appliances) required to maintain a satisfactory temperature at home (living room: 21 °C, bedroom: 18 °C) in winter is in excess of 10 % of the annual household income [21, 22]. In 2007, about 4 million households in the UK (2.8 million in England) were estimated to be in fuel poverty [24]. During the period of 1996 and 2004, the number of fuel poor households fell by 4.5 million in the UK (4 million in England) from a combination of reduced energy price, increased income and government initiated energy efficiency programs. However, the rise in energy price is estimated to have increased the fuel poor by 2 million households since 2004 [24] and this trend is likely to continue with increasing energy cost into the future [64].

Of the 4.5 million UK fuel poor households in 2008, about 3.75 million (3.3 million in England) were identified as belonging in the vulnerable group, i.e. households with young children or aged or disabled or those suffering from long-term illness [24]. Of the vulnerable, around half is estimated to belong in the elderly group, 43 % suffering from disability or long-term illness, 65 % in receipt of some type of income benefit and 74 % living alone all of which reflect the limited earning potential of these groups [23].

Another major contributing factor to fuel poverty is also dwelling energy inefficiency. Over a quarter of dwellings occupied by fuel poor households have a SAP rating [68] (a measure of domestic space and water heating energy efficiency ranging from a score of 0 to 100 where higher values represent greater energy efficiency) below 35 [69] compared to the English average of 52 in 2008 [18].

The poor energy efficiency can mainly be explained by the large proportion of the fuel poor dwellings being represented by the older stock with 84 % pre-dating 1965 compared to only 57 % in England [24]. This also explains why 48 % of the fuel poor dwellings have solid walls compared to only 20 % in England and, among cavity walled dwellings, why 73 % of those occupied by fuel poor households are missing in insulation. Although 60 % of the fuel poor own gas central heating, those without central heating are four and a half times more likely to be in fuel poverty [25]. About 80 % of the fuel poor are in private sector housing mainly due to a large proportion of the older households owning their own homes [24, 25, 26].

One of the main social concerns involving fuel poverty is the mental and physical strains that can be caused by living in cold homes leading to increased morbidity and mortality especially among the vulnerable group contributing to UK's strain on the health care service and its excess winter mortality (23,500 in 2004 with over 90 % over 65 years of age) [27, 28, 29, 30]. The degree of exposure to cold is especially pronounced in the aged group due to the need to spend long hours indoors thereby increasing the strain on the fuel cost. Compared to the mean hall temperature of 17.9 °C [25] – spot measurements taken at the time of occupancy – experienced in average English dwellings, the temperature in a fuel poor dwelling is estimated to be around 17.0 °C [25, 29] which is well below the World Health Organization recommended minimum level of 18 °C to minimize health risks among the young and the elderly.

The UK government has set out to eliminate fuel poverty '*as far as reasonably practicable'* among the vulnerable group (children and elderly) by the year 2010 and for the rest of the population by the year 2016 in England. This commitment was first set out in UK's Fuel Poverty Strategy in 2001 [24] and reaffirmed in the government's Energy White Paper in 2003 [11]. Improving the housing energy efficiency is one of the main government strategies designed to reduce fuel poverty.

2.9. The *Warm Front Scheme*

In 2000 the *Warm Front Energy Efficiency Scheme* (the *Warm Front Scheme*) was launched to tackle fuel poverty in England among the vulnerable households living in the private sector by providing grants for retrofit energy efficiency measures [2]. By 2009 over 2 million households in England have benefited from the scheme [24].

Until 2005, two types of *Warm Front Schemes* were available (the energy efficiency packages upon which this study is based): the *Warm Front* with a maximum grant limit of £1,500 for families with children under the age of 16 and the *Warm Front Plus* with a maximum grant limit of £2,500 for households with a member aged 60 or over. The grants offer a combination of draught proofing, loft insulation, cavity wall insulation, heating repair, boiler replacement, storage heater and hot water jacket depending on the dwelling condition. The two schemes mainly differ in that a gas central heating system with up to 5 radiators or up to 3 storage heaters (where gas network is unavailable) are provided for the elderly group and gas wall heaters for the younger households. In 2005, the scheme was upgraded to include a gas central heating system for all the grant recipients.

Identifying the fuel poor however remains a major challenge for the scheme which relies on a selection of benefits as proxy indicators of fuel poverty. Only 30 % of the dwellings that were targeted based on this method were identified as being fuel poor while a third or more of the fuel poor households that do not claim any benefits are automatically disqualified [31]. If the government's fuel poverty target is to be met, the scheme needs to target the fuel poor more effectively by expanding the eligibility criteria to include more low-income households, pensioners and those living in low energy-efficient homes [32] and by extending the grant scheme to include more measures to tackle those in severe fuel poverty [65].

2.10. The *Warm Front Study*

The *Health Impact Evaluation of Warm Front Energy Efficiency Scheme* (the *Warm Front Study*) was commissioned in 2001 by the Energy Saving Trust on behalf of the Department for Environment, Food and Rural Affairs (Defra), the Welsh Assembly Government and the Department of Health in order to evaluate the impact of the *Warm Front Scheme* on the residents' health and quality of life [2]. A vast amount of property, household and environment related data was collected as a part of the research carried out by a consortium of social scientists of epidemiologists, building scientist and health, housing and community researchers (the *Warm Front Study Group*) drawn from Sheffield Hallam University, London School of Hygiene & Tropical Medicine and University College London. The data set collected from the *Warm Front Study* (the *Warm Front Data*) is extensively used in this thesis. Details about the *Warm Front Study* and the *Warm Front Data* are described in depth in Chapter 3.

2.11. Energy Efficiency Measures and Mean Internal Temperature

Draught proofing, insulation and central heating are designed to achieve energy saving, but the mechanism in which this is achieved differs between draught proofing/insulation and central heating.

The energy saving principle behind draught proofing and insulation is shown in an idealized diagram in Figure 2.1 which shows 21 °C as the demand temperature, 10 °C as the base temperature and space heating between the hours of 8 am to 10 am and 5 pm to 10 pm [33]. Draught proofing and insulation increase the building heatloss performance resulting in reduced 'warm-up' and 'cool-down' periods leading to increased mean indoor and background temperatures. Energy saving is thus achieved from reduced demand in space heating requirement in delivering the demand temperature. Insulation also has the added benefit of increasing the mean radiant temperature by increasing the surface temperatures of walls and ceilings. This increases the thermal comfort perception and further reduces the space heating need [34]

The energy saving principle behind a new central heating system is shown in an idealized diagram in Figure 2.1 which also shows 21 °C as the demand temperature, 10 °C as the base temperature and space heating between the hours of 8 am to 10 am and 5 pm to 10 pm. A higher demand temperature of 21 °C is shown for the central heating system to reflect an increase in the space heating capacity. A central heating system lengthens the time during which the demand temperature is actually achieved over the heating period by reducing the ‘warm-up’ period from increased appliance efficiency resulting in increased mean indoor temperature. Energy saving is thus achieved from reduced space heating need and increased efficiency in converting delivered energy into useful heat.

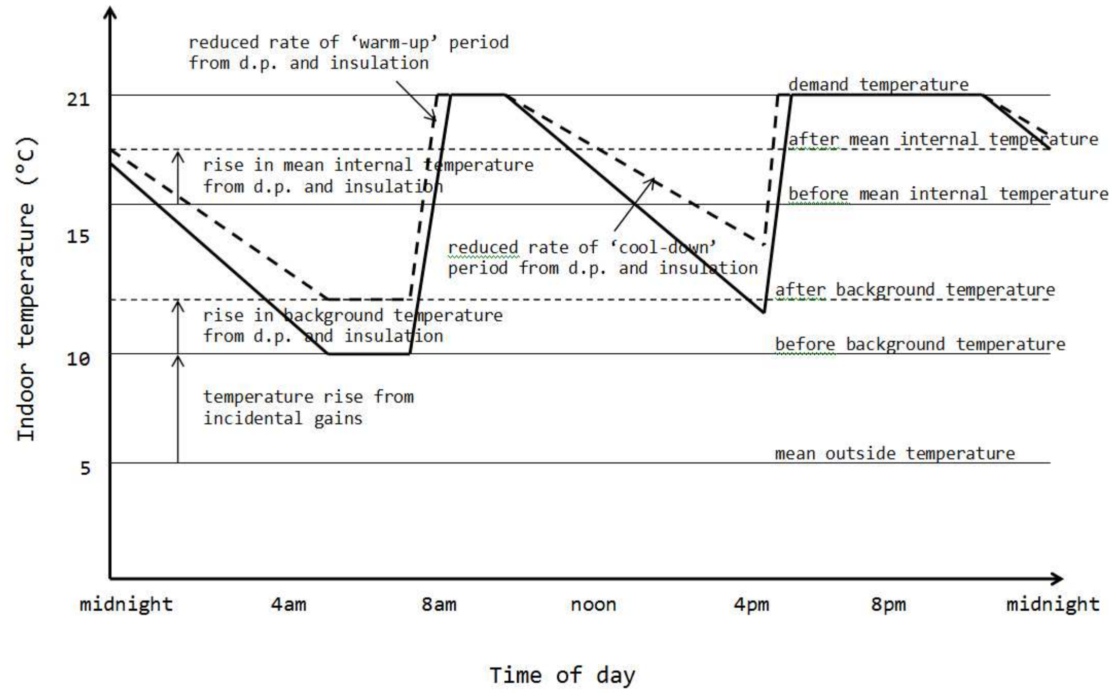
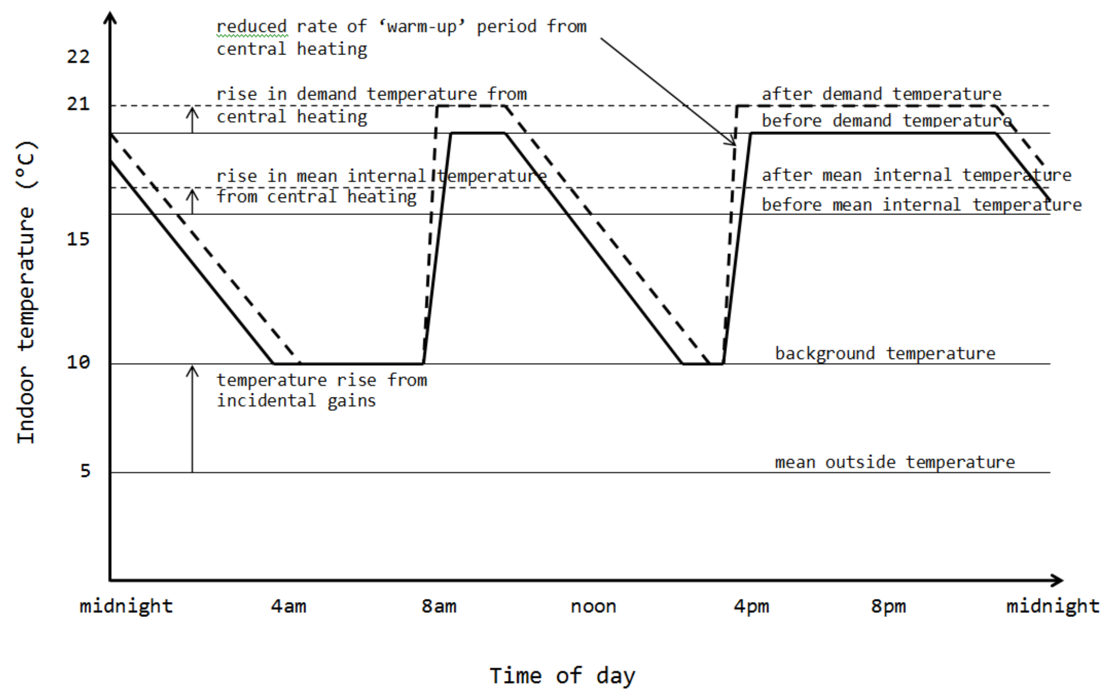


Figure 2.1: Effect of central heating on the mean indoor temperature.



2.12. Factors Determining Reduced Energy Saving

Domestic energy efficiency measures such as draught proofing, insulation and efficient boilers are designed to reduce energy use and carbon emissions associated with space heating. However, studies in the past have shown that the actual saving achieved from these measures often do not deliver the full potential saving estimated from theoretical models, a difference often termed the *shortfall*, the *take back* or the *rebound effect* [35, 36, 37].

Most empirical evidences on the *shortfall* are from studies on residential heating and cooling and automotive transport in developed countries. To avoid ambiguity, the term *shortfall* is used in this study to describe the *shortfall* in the actual energy saving and the analysis is limited to residential space heating only.

2.12.1. Occupancy Factors

One of the main contributors to the *shortfall* in residential space heating is the occupants' behavior where reduced marginal cost in space heating following energy efficiency upgrade results in a greater demand in indoor temperature. This particular relationship is described in this study the *comfort taking*. Although the *comfort taking* undermines energy saving, energy efficiency schemes such as *Warm Front* partly rely on this mechanism to deliver affordable warmth.

Lack of knowledge on how a modern heating system operates is also known to contribute to reduced energy saving. A study by Bell & Lowe of 32 UK dwellings that underwent energy efficiency upgrade found that about 80 % of households were still using local gas fire in some combination with central heating explaining a part of the reason why only 60 % of the potential saving was observed in one post-retrofit case study house [20].

Evidence was also found in householders tending to wear less clothing with increased ownership of energy efficiency measures. This behavior could be explained as the desire to achieve physical comfort from improved thermal comfort condition. This inevitably results in greater energy consumption compared to the level when no change in the clothing level has taken place [38].

Other occupancy behavior which would result in reduced energy saving is increased ventilation. Although no evidence is currently available on the effect of energy efficiency measures on ventilation, i.e. through the use of windows instead of mechanical system, the increased airtightness can lead to poor indoor air quality from increased concentration of odor and moisture and increased indoor temperature encouraging occupants to open windows more frequently.

2.12.2. Non-occupancy Factors

Previous analysis of the effect of the *Warm Front Scheme* on the dwelling air tightness (Appendix 3) [3] has shown little reduction in the air leakage rate as the result of draught proofing having little impact in reducing unwanted draught due to an unexpected increase in the air leakage rate from lifting of the floorboards required as a part of the process in installing the central heating system (Section 6.1).

A study carried out by BRE investigating the in situ insulation condition revealed many defects which resulted in an increase in the estimated U-values [5]. Thermographic images taken from 85 post-*Warm* Front case study dwellings that have received retrofit insulation also revealed many areas with missing insulation which in theory should have been insulated leading to increased U-values, a subject which will be discussed in detail in Section 6.2).

Field trials of condensing boilers undertaken by The Carbon Trust have also shown that domestic boilers in the UK may only achieve performance about 5 % below the laboratory tested SUDBUK efficiencies due to a combination of poor design, commissioning and setting of controls [4].

2.13. Magnitude of Reduced Energy Saving

The *shortfall* is normally measured as a percentage of the unrealized saving in the useful work in relation to the potential theoretical saving. The magnitude of the *shortfall* is often debatable and this is reflected in a statement by defra that "*The* '*Comfort taking factor' … is very uncertain until further detailed monitoring and analysis is carried out"*. Variations in the magnitude of the *shortfall* can result for several reasons [14].

One of the main factors behind the uncertainty is that the *shortfall* is influenced by the initial dwelling temperature prior to the refurbishment with a greater level of the comfort taking found to be associated with a lower initial temperature [39]. On the other hand, the relationship between the initial dwelling temperature and the *comfort taking* is not always apparent [41] and could also be confounded by social factors such as household income [40].

The lack of consensus in the research community over the definition of the terminologies used in describing the unrealized saving is also thought to contribute to the difference in the magnitude of the *shortfalls*. Typically the *comfort taking*, the *take back* or the *rebound effect* represent the *shortfall* in real energy saving arising from increased energy use associated with increased internal temperature. However comfort taking alone often cannot explain the difference between the actual and the theoretical energy saving because there are still other factors contributing to the *shortfall*. If this distinction is not made it may lead to overestimation in the comfort taking [39].

Although the delivered energy is mainly used to quantify the *shortfall* in most studies, changes in indoor temperature, energy cost, number of rooms heated or number of hours heated can also be used as measurable parameters in the case of residential heating. This study shows that by using different parameters, i.e. delivered energy, energy cost and carbon emissions, the *shortfall* figures will vary considerably highlighting the significance of their choice.

Finally, because the *shortfall* is measured in relation the theoretically predicted saving, the choice of the model used in estimating the predicted saving will also be a significant determinant in the magnitude of the *shortfall*. Different models will not only show different sensitivities to the same input parameters but the same model will also provide different results depending on the quality of the input data. The sensitivity of the *shortfall* on the theoretical model is also explored in this study.

2.14. Comparison of Reduced Energy Saving

Table 2.1 compares the magnitudes of the *shortfall*s associated with residential heating and insulation improvement based on three reports all of which provide extensive reviews and summaries of evidence collected from numerous independent studies that investigated the *shortfall*. One such study is by Greening & Greene whose work is the earliest of this type published in 1998 reviewing the findings on the *shortfall* from US based studies 26 of which examined residential heating [37]. The second such report is by Sorrel published in 2007 which is another comprehensive report that reviewed the *shortfall* drawing cases extensively from the UK and US experiences 24 of which examined residential heating [36]. The third such report is the study by Sanders and Philipson [35] published in 2006 which provides a comprehensive review of 13 UK based studies that have investigated the *shortfall* in energy saving following the installation of insulation. The results of the findings from the four reports are summarized and compared in Table 2.1. In addition to the *shortfall*, the *comfort taking* figure is also included if these are known.

Both the Greening & Greene and the Sorrel studies estimate the magnitude of the *comfort taking* in the range of 10 % to 30 %. The close agreement found between these two studies is thought to be the result of many of the same reports having been included in both studies. In comparison, the *comfort taking* estimated in the Sanders & Phillipson report is between 14 % to 17 %.

Table 2.1: Comparison of the *comfort taking* and the *shortfall* in residential heating energy consumption.

study	case studies	intervention	method	no. of studies	*comfort taking* (%)	*shortfall* (%)
Greening & Greene (1998) [3]	USA	insulation/ heating	evaluation study econometric study	14 12	10%~30%	-
Sorrel (2007) [2]	USA UK Canada Germany	insulation/ heating	evaluation study econometric study	15 9	10%~30%	>=50%
Sanders & Phillipson (2006) [1]	UK	insulation	evaluation study	13	14%~17%	50%

2.15. Characteristics of UK Based Studies

The UK studies that investigated the *shortfall* in the actual energy saving are well documented in the Sanders & Phillipson report [35]. Most of these have based their analyses on some combination of monitored temperature and fuel use data before and after energy efficiency upgrade categorizing them as *evaluation* type studies in contrast to *econometric* studies which rely on statistical method based on secondary data sources originally collected for other purposes [36].

Several studies had available both the monitored temperature and the fuel use data. The study carried out by Hong et. al (Appendix 1) [1] is one of the largest studies based on three to four week monitored data collected from some 1300 dwellings eligible under the *Warm Front Scheme*. The study by Martin & Watson [41] is also based on a group of *Warm Front* dwellings with a minimum of 11 weeks of data collected from 88 dwellings. Although the sample size is unknown, Milne and Boardman's [39] study also accessed temperature and fuel use data originally monitored from different projects across the UK. The availability of both data types enabled the determination of the *shortfall* and the *comfort taking* in the latter two studies whereas in the first study the *comfort taking* was not determined because the analysis was based on fuel use data normalized to temperature. A study by Shorrock [42] shows how the *comfort taking* can be determined without the monitored fuel use data by comparing the relationship of the monitored temperature to the heat loss parameter to the equivalent relationship predicted by BREDEM.

Most of the UK based studies used some version of the Building Research Establishment Domestic Energy Model (BREDEM) (Section 2.16) to calculate the potential energy saving [1, 39, 41, 43]. The reason behind the choice of BREDEM is that it is UK's most widely used domestic energy modelling tool. Typically the potential energy saving is determined by modelling the change in the energy use under standard temperature conditions. If the monitored temperature data is available, the *comfort taking* can also be determined by adjusting the demand temperature or the heating schedule until the predicted temperature is matched to the monitored temperature with the change in temperature or energy consumption representing the *comfort taking* [42, 43]. In a study by Martin & Watson, the monitored temperature was substituted into BREDEM and the resulting *shortfall* in the energy saving when compared to BREDEM prediction under standard heating regime quantified as the comfort taking [41].

Most UK based studies have examined the *shortfall* in energy saving from insulation. The estimated figures are between 14 % to 17 % for the *comfort taking* [35, 41, 42, 43] and between 40 % to 67 % for the *shortfall* [1, 35, 41, 43]. The *comfort taking* figures indicate that insulation is having an impact on the household behavior to increase the demand for thermal comfort despite heating controls having remained the same. When examining the change in temperature and energy use associated with insulation, however, it is important to distinguish the temperature rise from the physical process (Figure 2.1) and the rise from the *comfort taking* (Figure 2.2).

Ideally, the effect of insulation is best examined by focusing on dwellings that have undergone changes to insulation only while keeping the other changes to a minimum [41]. On the other hand, in many studies energy efficiency measures are found in different combinations [39] which necessitate controlling for other variables such as by using a statistical method [1].

In comparison to insulation focused studies, there is a lower number of UK based studies that have examined the effect of a modern central heating system on domestic energy consumption. In spite of the limited in number, these studies have found some evidence of retrofit central heating measures resulting in increased energy usage.

The preliminary findings from the *Warm Front Study* (Appendix 1) [1] indicated no energy saving from new central heating despite adjusting for increased internal temperature indicating that no improvement in the energy performance was observed despite a more efficient space heating appliance. This resulted in an increase in the energy use due to increased demand temperature. Although the study by Milne & Boardman [39] did not examine the effect of central heating by itself, two case study groups which included central heating as a part of the energy efficiency package showed an increased in the energy use.

2.16. BREDEM 8

BRE Domestic Energy Model 8 (BREDEM) is one of the most widely used monthly domestic modelling tools for dwellings in the UK. In addition to monthly space heating energy use, BREDEM also estimates energy use for water heating, lighting, electrical appliances and cooking [33].

BREDEM is selected in this study to estimate the theoretical saving expected from energy efficiency upgrade because one, the monthly version makes it convenient to substitute the 3 to 4 week *Warm Front* monitored temperature into the model and two, most of the UK based studies that have investigated the impact of energy saving measures have also used BREDEM or variations of it providing a common theoretical basis for comparison.

BREDEM is a two zone – zone 1: living area and zone 2: rest of dwelling – model with separate demand temperature and heating schedule for each zone. The input parameters required can be classified as those describing the site (degree day region, wind speed, overshading), physical characteristic (dimension, construction, U-value), back ground ventilation rate, heating system (fuel efficiency, fuel type, heating controls), hot water heating and occupancy (occupant number, heating duration, demand temperature). The space heating requirement is calculated based on the principle of energy balance that takes into account the transmission and ventilation heat losses, demand temperature, heating pattern, external climatic condition, passive heat gains and appliance efficiency.

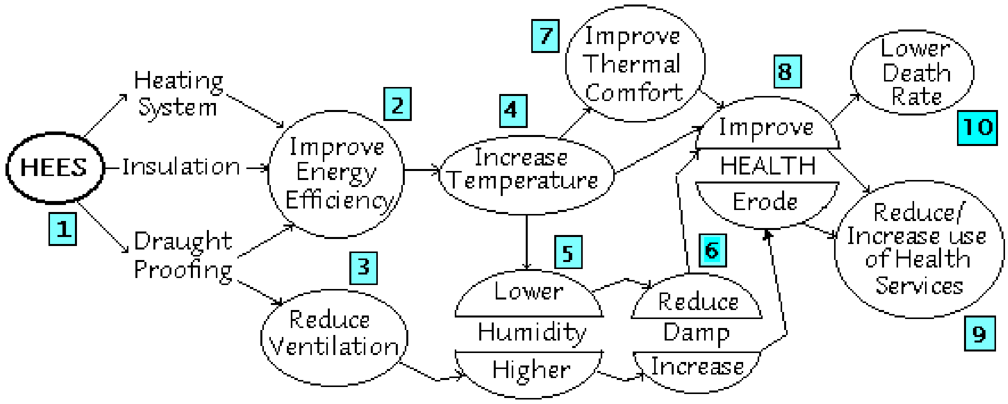
CHAPTER 3 WARM FRONT STUDY AND WARM FRONT DATA

The *Warm Front Study* [2] was commissioned in 2001 with the support of the Department for Environment, Food and Rural Affairs (Defra) and the Welsh Assembly Government under the contract with Energy Saving Trust (EST) to evaluate the impact of England's *Warm Front Scheme* on the residents' health and quality of life. A major part of this study entailed the collection of the *Warm Front Data* consisting of property, household, fuel consumption and environmental data from some 3000 dwellings. This chapter introduces the *Warm Front Study* and the *Warm Front Data*.

3.1. The *Warm Front Study* Design

The *Warm Front Study* was designed to combine empirical survey with statistical and epidemiological analysis to model the potential impact of improved energy efficiency on householder's mental and physical health, quality of life and the use of health care services. Core to the investigation was documenting and quantifying changes in parameters such as energy efficiency, ventilation, indoor temperature, relative humidity and thermal comfort in a representative sample of case study dwellings so that the potential impact of these on health could be studied. The hypothesized pathways from these changes to health are shown in Figure 3.1.

Figure 3.1: Hypothesized pathways from *Warm Front* intervention to improvements in health



3.2. The *Warm Front Study* Group

The *Warm Front Study* was carried out by the *Warm Front Study Group* which is a consortium of epidemiologists, building scientist and health, housing and community researchers drawn from Centre for Regional Economic and Social Research (CRESR) at Sheffield Hallam University), London School of Hygiene & Tropical Medicine and the Bartlett School of Graduate Studies (University College London). Managed Services and Consultancy Ltd. (MSC) oversaw the property physical condition surveys and the National Centre for Social Research (Natcen) was responsible for the household condition surveys.

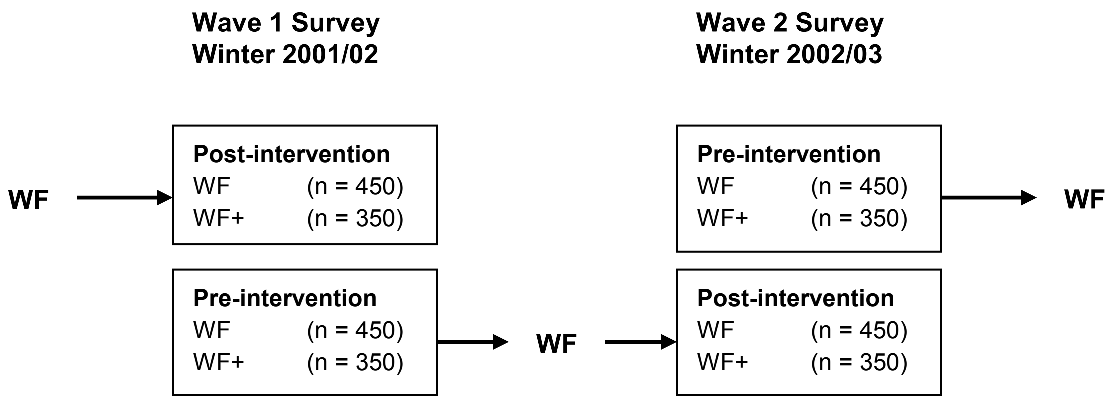
As a part of the *Warm Front Study Group*, the author was the principle investigator at the Bartlett School of Graduate Studies leading the energy efficiency survey by being directly responsible in collecting data from all 236 dwellings that underwent energy efficiency survey (Section 3.4.6). He was also the principle investigator in the building science element of the *Warm Front Study* and the principle author in four (Appendix 1 [1], Appendix 2 [44], Appendix 3 [3], Appendix 4 [38]) of the six papers [45, 46] that focused on the building science topic.

3.3. The *Warm Front* Case Study Dwellings

The *Warm Front Study* originally aimed to collect data from a total of 3200 dwellings over two successive winters of 2001/02 (winter 1) and 2002/03 (winter 2) from five urban clusters surrounding Birmingham, Liverpool, Manchester, Newcastle and Southampton to provide a good representation of different physical environments, housing types and climatic conditions of England.

The case study dwellings were initially recruited to the study by CRESR from electronic lists of grant applicants provided by Eaga Partnership Ltd. who is the principle agent of the *Warm Front Scheme*. The dwellings on the list were either awaiting (*pre-WF*) or have already undergone energy efficiency upgrade (*post-WF*). The *Warm Front* case study dwellings were then short-listed from the list to target a balanced number of dwellings, as shown in Figure 3.2, qualified under the basic *Warm Front* grant scheme (WF) – for recipients aged below 60 – and the *Warm Front Plus* grant scheme (WF+) – for recipients aged 60 or above – which are largely distinguished by the inclusion of a gas central heating system in the latter group. The survey sequence was also designed to target 800 *pre*- and 800 *post-WF* dwellings in each winter forming the cross-sectional comparison group in each winter with the 800 *pre-WF* dwellings in winter 1 forming the longitudinal comparison group as *post-WF* in winter 2. Although not shown in the figure, the dwellings were also targeted to achieve a balanced representation of the different urban clusters.

Figure 3.2: The *Warm Front Study* design showing the total number of originally targeted case study dwellings.



3.4. The *Warm Front Data*

The *Warm Front Data* represents a comprehensive set of information describing the property condition, household characteristic, energy consumption, ventilation, indoor environment and thermal comfort was obtained from the case study sample dwellings by a combination of surveying, interviewing and monitoring as a part of the *Warm Front Study*. All 3200 dwellings originally targeted under the *Warm Front Study* initially underwent the property condition survey (Section 3.4.1) followed by the household condition survey (Section 3.4.2) a week or two later. About 50 % of the sub-sample was further targeted for the environmental survey (temperature and relative humidity) (Section 3.4.3), about 80 % for the thermal comfort survey (Section 3.4.5) and a very small group of 8 % for the energy efficiency survey (Section 3.4.6). The *Warm Front Data* describing the property characteristic, energy efficiency, ventilation, indoor temperature and energy consumption are extensively referred to and analyzed in this study. The following sections describe the methods used in their collection.

3.4.1. The Warm Front Property Condition Survey

The property condition survey was managed and carried out by the professional surveyors of MSC. The property condition data was collected during an hour long on-site visit by recording measurements on a standardized 10 page stock condition survey sheet a sample of which is included in Appendix 5.

The main purpose of the property condition survey was to collect information describing the physical characteristic of the building: dwellings age, structure, dimension, number of rooms, window type, presence of damp or mould, insulation thickness, space heating appliances, water heating appliance and fuel type. Information on the ownership of household appliances was not collected during the survey. The information collected from the property condition survey was sufficient enough, i.e. following extensive data processing, to model the energy performance of each dwelling in BREDEM. All the property condition data was stored in Microsoft Access format.

3.4.2. The Warm Front Household Condition Survey

The household condition survey was managed and carried out by the professional surveyors of Natcen who carried out one on-site interview per household and recorded household responses into a laptop computer. The average duration of an interview lasted 50 minutes and was conducted during the two to three week period that the indoor temperature and relative humidity of the property was being monitored.

The main purpose of the household condition data was to collect information on vital statistics, heating and environmental comfort, hot water and appliance use, security and social capital, self-assessed health, utilization of health and social services, the *Warm Front* process and socio-economic status. All the household condition data was stored in SPSS format. A draft version of the preliminary household questionnaire is included in Appendix 6.

3.4.3. The Warm Front Environment Survey

The living room and bedroom temperature and relative humidity were continuously monitored at half-hourly intervals using Gemini TinyTag data loggers for periods of two to three weeks between December and early May in about half of the case study dwellings yielding around two thousand measurements for each monitored room. The external temperature and relative humidity were also recorded at half-hourly intervals at central locations of each of the surveyed urban clusters from December to April for the two surveyed winters. The purpose of the environmental survey was to record the changes in the indoor temperature and relative humidity associated with the *Warm Front Scheme*. All the environmental data was stored in Microsoft Access format.

3.4.4. The Warm Front Fuel Consumption Survey

The total fuel consumption, i.e. gas and electricity, level was collected as a part of the property condition survey by taking the initial meter readings when the data loggers were left and by reading the final meter readings two to three weeks later when the loggers were removed. The purpose of the fuel consumption survey was to record the changes in the gas and electricity use before and after the *Warm Front* upgrade. No end use specific gas and electricity consumption measurements were monitored and also no information was collected on the use of non-metered fuel such as solid, paraffin and oil. All the fuel consumption data was stored in Microsoft Excel format.

3.4.5. The Warm Front Thermal Comfort Survey

The thermal comfort survey was carried out in about 80 % of the case study dwellings by providing thermal comfort diary sheets and temperature strips to the householders at the time of the property condition survey. A designated member of the household, usually the head of household or the spouse, was instructed to record his or her thermal comfort perception and the room temperatures by reading from Thermochromic Liquid Crystal thermometers – inexpensive thermometers that contain heat-sensitive liquid crystals in a plastic strip which change colour at different temperatures – twice daily at 8 a.m. and 8 p.m. in the main living room and in the main bedroom over 11 consecutive days. The purpose of the thermal comfort survey was to record the changes in household thermal comfort perception following the *Warm Front* upgrade. All the thermal comfort data was stored in Microsoft Excel format. The findings from the thermal comfort survey have been published in a separate paper (Appendix 4) [38]. A thermal comfort diary is included in Appendix 7.

3.4.6. The Warm Front Energy Efficiency Survey

Detailed energy efficiency surveys were undertaken by the UCL Bartlett team in 8 % of the property condition surveyed dwellings. The energy efficiency survey involved measuring the whole house air infiltration rate using the Retrotec Model R43 blower door equipment and assessing the quality of loft and cavity wall insulation using a FLIR infrared camera. The air infiltration rate was monitored to understand the impact of measures such as draught proofing and insulation in reducing ventilation associated heat loss while images obtained from the infrared camera were used to estimate building surface areas that were still missing in insulation following the *Warm Front* intervention. The fan-pressurization method is described in detail section 4.3.1 and the findings from the blower-door test results have been published in a separate paper (Appendix 3) [3]. The results obtained from the infrared surveys are presented in Section 6.2.

3.5. The *Warm Front Data* Size

The actual number of dwellings from which the property and household condition data was collected fell short by 3 % and 9 % respectively compared to the original target number of 3200 dwellings with an inevitable a knock on effect on the fuel consumption, environment and thermal comfort sample size. The actual sample size obtained from the *Warm Front Study* is summarized in Table 3.1.

Several reasons contributed to the *shortfall* in the sample size. Some of which are failure to respond to telephone call, wrong contact number, refusal to participate, work already having been carried out prior to the survey and failure to follow up on householders who did not respond to the invitation to participate in the survey. There was also a considerable delay in the start of the wave 1 survey resulting in a 34 % drop in the number of property surveyed dwellings and a 47 % drop in the number of household surveyed dwellings relative to the original winter 1 target of 1600 dwellings. Although a large part of this *shortfall* was made up in winter 2, the small winter 1 sample contributed to reduced longitudinal cases (indicated in parenthesis) falling far short of the 800 dwellings originally intended thereby losing much statistical power in all longitudinal comparisons. Consequently, the thesis is largely based on cross-sectional analysis of pre- and post-intervention data.

Table 3.1: Classification of the *Warm Front Data* and the actual sample size (longitudinal sample).

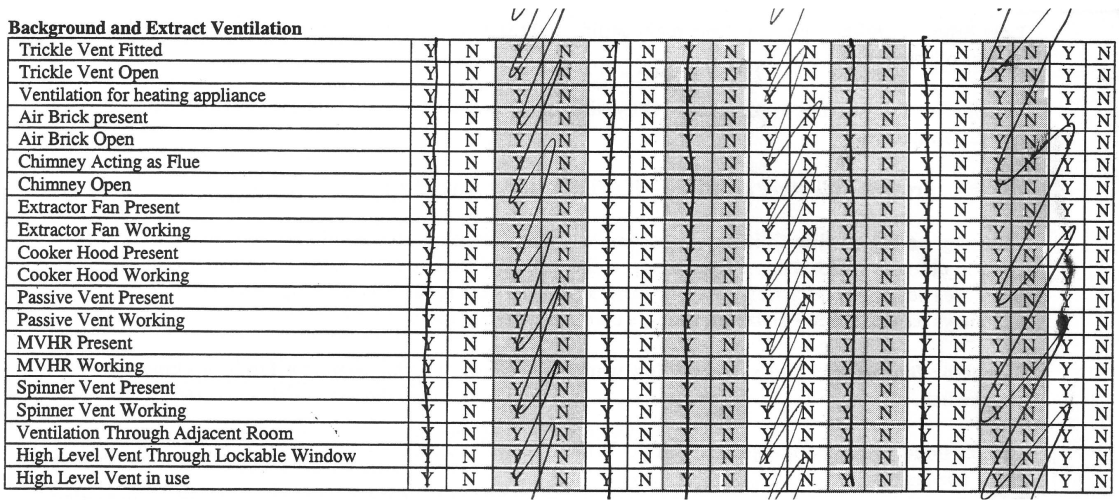
data (method of data collection)	wave 1 survey winter 2001/02		wave 2 survey winter 2002/03		total
	pre-WF	*post-WF*	*pre-WF*	*post-WF*	
property condition (inspection)	515 (269)	545	1073	966 (269)	3099
household condition (interview)	373 (230)	477	1051	1011 (230)	2912
environment (data loggers)	251 (125)	274	556	527 (125)	1608
fuel consumption (inspection)	492 (250)	527	1019	909 (250)	2947
thermal comfort (diary)	456 (223)	460	769	724 (223)	2409
energy efficiency (inspection)	59 (26)	27	55	95 (26)	236

3.6. The *Warm Front Data* Quality

This section discusses the quality of the property condition data which is extensively used in this study. About three months were dedicated in cleaning the property condition data prior to the start of the data analysis. The number and type of errors found were numerous although the sources can be narrowed down to two: poor quality survey and data entry error.

Although most of the survey and data entry errors detected from the data cleaning process seemed random, it was also evident that a lack of robust survey protocol was also a potential source of a significant number of errors such as confusion over the categorization of the rear extension from the main building, the inclusion of party walls as a part of exposed wall construction and the specification of exposed roof for lower ground flats. The data entry errors usually seemed to be a combination of misinterpretation of poor handwriting and keystroke error. However, a poor recording habit at the time of the survey, an example of which is shown in Figure 3.3, also resulted in some 1600 entry type errors.

Figure 3.3: An example of *Warm Front* surveyor sheet with confusing data entry.



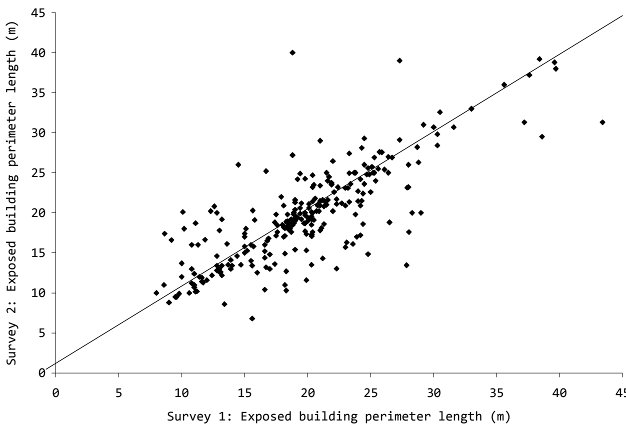
Background and Extract Ventilation																		
Trickle Vent Fitted	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Trickle Vent Open	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Ventilation for heating appliance	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Air Brick present	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Air Brick Open	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Chimney Acting as Flue	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Chimney Open	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Extractor Fan Present	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Extractor Fan Working	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Cooker Hood Present	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Cooker Hood Working	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Passive Vent Present	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Passive Vent Working	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
MVHR Present	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
MVHR Working	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Spinner Vent Present	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Spinner Vent Working	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
Ventilation Through Adjacent Room	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
High Level Vent Through Lockable Window	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
High Level Vent in use	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N

Using the database program MS Access, both survey and entry errors were detected by setting up a series of queries and filters which allowed discrepancies to be detected such as missing insulation data despite the presence of cavity wall or loft space; mismatch between the type of heating system and the boiler type; the presence of exposed roof in lower storey flats, unusually low or high outliers, etc. In most cases, errors were corrected by referring to the original surveyor's sheet and images of dwellings taken by the surveyors and the Bartlett team.

Despite these corrections, more errors are suspected as can be inferred from Figure 3.4 which compares the exposed building (main building + rear extension) perimeter of 264 pairs of longitudinally surveyed dwellings. Since the *Warm Front Scheme* had no impact on the exposed building perimeter length, the measurements taken from the *pre*- and the *post-WF* surveys should in theory line up along the 45 degree line which is the line of perfect agreement. However, the actual results show considerable scatter reflecting poor consistency between the two surveys with an average root mean square difference of 2.5 m. This type of inconsistency is easily detectable in the longitudinal sample but difficult in other cases where cross comparison is not possible. On the other hand, despite the scatter, the average lengths of the two longitudinal samples were found to be nearly equal at 18 m illustrating no bias in the error.

The example in Figure 3.4 is selected as the worst case scenario since the figures represent continuous number with more room for error whereas in other case, the level of inconsistency is expected to be less since the surveyors were required to select from a list of options.

Figure 3.4: A comparison of exposed building perimeter lengh of longitudinal case study dwellings.



Other inconsistencies found in the longitudinal sample included 14 (5.3 %) mismatches in the building type, 64 (24.2 %) in the dwelling age, 55 (20.8 %) in the rear extension age, 30 (11.4 %) in the main wall construction and 29 (11.0 %) in the rear extension wall construction. In terms of gas meter reading, 21 (7.8 %) dwellings were found to have different meter type, i.e. imperial or metric, from survey 1 to survey 2 indicating either a switch in the meter type or survey error. Also, 13 (4.8 %) longitudinal cases were found where the cavity wall insulation reduced from survey 1 to survey 2 and similarly 49 (18.2 %) cases where the loft insulation decreased in wave 2. These inconsistencies were corrected mainly by referring to photographs taken by surveyors but when these were unavailable, the corrections were based on the assumption that the information collected in survey 2 is more accurate as a result of lessons gained from survey 1.

3.7. The *Warm Front Study* Publication

Much of the detailed research arising from the *Warm Front Study* have been published in peer-reviewed academic journals. The reports and publications are listed in Table 3.2 along with the main consortium(s) responsible for the investigation and the status of publication. This study makes references to many of these papers and in particular to *The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings* (the *Warm Front Energy Paper*) (Appendix 1) [1], *The impact of energy efficient refurbishment on the airtightness of English dwellings* (the *Warm Front Ventilation Paper*) (Appendix 3) [3], and *A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment* (the *Warm Front Thermal Comfort Paper*) (Appendix 4) [38].

Table 3.2: Scientific papers produced from the *Warm Front Study*.

no.	title of papers	WF Study Group	status
1	Creature Comforts: Home is where the hearth is: grant recipients' views of England's home energy efficiency scheme.	SHU/ LSHTM	published [47]
2	Dependence of winter- and cold-related mortality on winter temperature	LSHTM	completed
3	Potential for reducing winter mortality by improving domestic energy efficiency	LSHTM	completed
4	Determinants of winter indoor temperatures in low income households in England	LSHTM/ UCL	published [45]
5	Health Impact Analysis of *Warm Front*	LSHTM	completed
6	Can we improve the identification of cold homes for targeted home energy efficiency improvements	LSHTM /UCL	published [48]
7	The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings	UCL	published [1] (appendix 1)
8	The impact of energy efficiency refurbishment on the airtightness of English dwellings	UCL	published [3] (appendix 3)
9	Winter indoor temperatures, Energy Efficiency Improvements and Mental Health	LSHTM /SHU	completed
10	Determinants of winter indoor relative humidity & mould occurrence in low income households in England	UCL/ LSHTM	published [46]
11	The health benefits of home energy efficiency	LSHTM/UCL/SHU	completed
12	Analysis of the health impact of England's home energy efficiency scheme (*Warm Front*); mortality and non-mortality impacts.	LSHTM	completed
13	Living in cold homes after heating improvements	SHU	published [49]
14	The psychosocial route to health gain from England's Home Energy Efficiency Programme	SHU/LSHTM	completed
15	A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment	UCL/SHU	published [38] (appendix 4)
SHU = Sheffield Hallam University *LSHTM = London School of Hygiene & Tropical Medicine* *UCL = University College London*			

3.8. Discussion

Although the *Warm Front Study* was primarily aimed at investigating the scheme's impact on health the *Warm Front Data* collected as a part of the study provided an excellent opportunity to investigate the impact of energy efficiency upgrade on the building physics issues such as temperature and energy due to the available data type combined with impressive data size which is one of the largest of this type collected in a single study in the UK. This study makes extensive use of the *Warm Front Data*, particular those collected from the property condition, fuel consumption, environment and energy efficiency surveys.

One of the weaknesses, or rather a lost opportunity, in the *Warm Front Data* is the availability of a small number of longitudinal case study dwellings which represents only 17 % of the total sample compared to the original target figure of 50 %. The small sample size resulted in low statistical power of the longitudinal comparisons particularly when the comparison involved the combination of datasets such as indoor temperature and energy further reducing the sample size. As a result, only a limited number of longitudinal comparisons are presented while the longitudinal and the cross-sectional cases are in most cases combined.

The *Warm Front* property data was not readily suitable as input variables for BREDEM modelling without extensive data processing. One exemplary case is presented in Section 4.2.1 which describes how the exposed building surface area was determined from the surveyed exposed building perimeter length. Other critical input parameters such as those describing the heating practice, i.e. heating duration, demand temperature, combination of heating systems used, number of rooms heated, etc., were either missing or available from a small number of dwellings. There are other parameters such as the blower-door tested air infiltration rate data which if had been collected from a greater number of dwellings would have increased the accuracy of BREDEM performance. Although not an input parameter in BREDEM, no quantitative information was available on the controlled ventilation rate from occupancy behavior. On the other hand, it is often difficult to measure many of the input parameters with sufficient detail to allow robust calibration of BREDEM to the actual performance. Accordingly, no attempt was made in this study to calibrate the modelled result to the monitored result, but instead the analyses focus on changes in the energy consumption.

Shortcomings were also encountered with the monitored fuel consumption data due to the lack of end-user information on appliance use. This resulted in the estimation of energy consumption for space heating based on a method described in Section 4.5.2 introducing some uncertainty. Also no information was collected on how the householders used the different space heating appliances which meant that all dwellings owning any type of non-metered (solid, paraffin, oil) space heating appliances were subsequently omitted thereby reducing the property condition data available for analysis by 11 %. Limitations were also encountered with the monitored environmental data in that the living room and the bedroom temperatures were found to be inadequate in providing a representative snapshot of the mean dwelling temperature. Section 4.7.2 describes how a representative mean dwelling temperature was determined in this study.

Finally, extensive effort was spent in cleaning the property condition data, fuel consumption data and the environment data which is expected to have introduced significant improvement in the quality of the data. Additional cleaning was found to be difficult unless the properties were re-visited, but overall, the error types encountered did not reveal any evidence of bias and the dataset is considered to be a good representation of the case study dwellings as a result of the large sample scale.

CHAPTER 4 METHODOLOGY

This chapter describes the assumptions and the methods behind some of the important parameters used in the analyses. Section 4.1 describes the criteria used in classifying the case study dwellings; Section 4.2 describes the derived input parameters required for modeling in BREDEM; The different indicators of energy efficiency performance such as ventilation is described in Section 4.3, the heat loss parameter in Section 4.4, the space heating energy consumption in Sections 4.5 and 4.6 and the temperature in Sections 4.7 to 4.10 and finally the method used in determining the *comfort taking*, the *loss* and the *shortfall* which this thesis has set out to quantify are describes in Section 4.11.

4.1. Classification of the Case Study Dwellings

Seven criteria are used to classify the case study dwellings: space heating system by fuel type, householder age group, *Warm Front* intervention status, draught proofing status, insulation status, type of space heating system and the combination of insulation and space heating system. The purpose behind the classification based on space heating system by fuel type is primarily to filter out all dwellings owning any type of non-metered appliance from all energy related analysis to achieve greater accuracy. The classification into the householder age group separates the case study dwellings into the two *Warm Front* household age groups and will mainly be used to compare the *Warm Front* household characteristic to the national fuel poor in Chapter 5. The classification based on individual energy efficiency measures of draught proofing, insulation and space heating is to examine their impact on energy consumption (Chapter 7) and indoor temperature (Chapter 8). For these comparisons, the analyses are performed using multi-variable adjustment of the cross-sectional comparisons to reduce the effect of any imbalance stemming from other energy efficiency measures to determine the ‘estimated marginal mean values’. The ownership of double glazing is not used as a classification criterion due to the availability of this information from only 23 % of the property surveyed dwellings plus double glazing not being a *Warm Front* intervention. The impact of household and dwelling characteristics on the energy consumption has been examined in the *Warm Front Energy Paper* (Appendix 1) [1]. All the sample sizes presented in this section refer to the number of property condition surveyed dwellings.

4.1.1. Ownership of space heating appliance by fuel type

Information on the ownership of space heating appliance was obtained from 3099 dwellings. Of these 344 dwellings owned heating appliance(s) using non-metered fuel such as solid, paraffin or oil either without or in combination with metered fuel – gas electricity – heating appliance(s). The combination of different space heating fuel types found among the case study dwellings is compared between the *pre-* and the *post-WF* dwellings in Table 4.1. From the *Warm Front Study*, little information was collected on how occupants used their non-metered heating appliances. Therefore all dwellings owning any type of non-metered heating appliances will be excluded from all the analyses when examining energy consumption and indoor temperature.

Table 4.1: Case study dwellings disaggregated by the space heating fuel type.

(A) *Pre-WF*

metered fuel		non-metered fuel			no. of dwellings	% of total
gas	electricity	solid	paraffin	oil or other		
■	-	-	-	-	555	34.95
■	■	-	-	-	699	44.02
■	-	■	-	-	22	1.39
■	-	-	■	-	34	2.14
■	-	-	-	■	2	0.13
■	■	■	-	-	10	0.63
■	■	■	■	-	4	0.25
■	■	-	■	-	72	4.53
■	■	-	■	■	1	0.06
■	■	-	-	■	5	0.31
■	-	■	■	-	5	0.31
■	-	-	■	■	1	0.06
-	■	-	-	-	107	6.74
-	■	■	-	-	23	1.45
-	■	-	■	-	23	1.45
-	■	-	-	■	2	0.13
-	■	■	■	-	7	0.44
-	■	-	■	■	1	0.06
-	-	■	-	-	3	0.19
-	-	■	■	-	1	0.06
-	-	■	-	■	1	0.06
-	-	-	■	-	4	0.25
-	-	-	■	■	6	0.37
total					1588	100

(B) *Post-WF*

metered fuel		non-metered fuel			no. of dwellings	% of total
gas	electricity	solid	paraffin	oil or other		
■	-	-	-	-	881	58.32
■	■	-	-	-	487	32.27
■	-	■	-	-	36	2.39
■	-	-	■	-	24	1.59
■	-	-	-	■	5	0.33
■	■	■	-	-	13	0.86
■	■	■	■	-	1	0.07
■	■	-	■	-	28	1.86
■	■	-	-	■	3	0.20
■	-	■	■	-	1	0.07
-	■	-	-	-	26	1.66
-	■	■	-	-	1	0.07
-	■	-	■	-	1	0.07
-	■	-	-	■	1	0.07
-	-	■	-	-	1	0.07
-	-	-	-	■	2	0.14
total					1511	100

4.1.2. Vulnerable Householder Age

The vulnerable household members of the case study dwellings are aged either below 16 (u16) or 60 or above (o60). Two *Warm Front* grant schemes – *Warm Front* and *Warm Front Plus* – are available depending on whether the vulnerable household member classify as u16 or o60 with the two grant schemes mainly differing by the availability of a gas central heating system in *Warm Front Plus*. The householder age is used as a method of classifying the case study dwellings and Table 4.2 shows the definition and the corresponding sample size. The age based classification is mainly used in chapter 5 to understand the household characteristics of the case study dwellings.

Table 4.2: Case study dwellings disaggregated by the vulnerable household member age.

classification	definition	sample size, n = 3099		
		longitudinal	cross-sectional	total (% total)
u16	vulnerable household member aged below 16	102	1105	1207 (42.2)
o60	vulnerable household member aged 60 or over	167	1456	1623 (57.8)

4.1.3. Warm Front Intervention Status

The case study dwellings are classified into *pre*- or *post-WF* depending on the *Warm Front* intervention status with *pre-WF* representing those awaiting the *Warm Front* upgrade and *post-WF* those that have received the upgrade. A comparison between the *pre*- and the *post-WF* conditions is useful in understanding the effectiveness of the scheme as a whole but does not necessarily reflect the full potential of the *Warm Front* measures, i.e. the combination of draught proofing, insulation and central heating, since many of the *pre-WF* dwellings already owned insulation and/or gas central heating system while many of the *post-WF* dwellings were without wall insulation because they had solid walls.

An examination of the timing of the intervention relative to the day of the property inspection has shown that the *pre*- and *post-WF* classification originally used for targeting poorly reflected the actual *Warm Front* status because many of the dwellings already underwent partial or in a few cases even full upgrade prior to the *pre-WF* survey while many of the *post-WF* dwellings were still awaiting partial or full upgrade at the time of the survey. To complicate this further, many dwellings underwent partial or full upgrade during the two to four week period that the dwellings were being monitored for temperature and fuel consumption.

The timing of the intervention measures relative to the timing of the survey is shown in Table 4.3. It shows that the proportion of the *pre-WF* dwellings already owning insulation was high with 35 % having cavity wall insulation and 38 % loft insulation (>100 mm) prior to the survey with slightly less than half of these having been carried out by *Warm Front*. The table also shows 29 % of the *pre-WF* u16 households and 14 % of the *pre-WF* o60 households already owning gas central heating system with about 16 % in the o60 group already having been installed by *Warm Front* before the *pre-WF* survey. A large proportion of the *pre-WF* dwellings also underwent partial upgrade during the period that they were being monitored for temperature and fuel consumption with 8 % having received cavity wall insulation, 10 % loft insulation, 12 % of u16 dwellings room heater or boiler repair and 21 % of o60 either boiler repair or gas central heating.

In the case of *post-WF* dwellings, about 29 % of the cavity walled dwellings were found to have no wall insulation and 32 % no loft insulation (<=100 mm) due to a combination of incompletion of the scheme and those being labeled as ‘unknown’ by the surveyors being classified as being un-insulated in this study since the householders are assumed to have the knowledge if the work was performed.

Table 4.4 shows how the dwellings have been re-classified in this study to reflect the actual *Warm Front* status relative to the timing of the property survey: *pre-WF* if none of the originally scheduled *Warm Front* measures were installed; *post-WF* if all of the originally scheduled *Warm Front* measures were installed and in-between for the rest. Obviously the effect from the re-classification is reduced number of *pre*-WF dwellings from 1588 to 1243 and the *post-WF* dwellings from 1511 to 806. On the other hand, despite the reduced sample size, the assumption behind the re-classification is that an accurate reflection of the pre- and post-intervention status will result in increased accuracy in assessing the impact of the *Warm Front Scheme*.

Table 4.3: Case study dwellings disaggregated by the ownership of insulation and heating system in relation to the original *Warm Front* intervention status (n = 3099).

<table>
<tr><th colspan="2" rowspan="2">classification</th><th rowspan="2">installation of insulation relative to the Warm Front survey</th><th colspan="2">sample size (% total)
n = 3099</th></tr>
<tr><th>pre-WF</th><th>post-WF</th></tr>
<tr><td colspan="2" rowspan="4">dwellings with cavity wall</td><td>CWI installed by WF before survey</td><td>149 (15.8)</td><td>484 (44.4)</td></tr>
<tr><td>CWI installed by WF during survey</td><td>78 (8.3)</td><td>2 (0.2)</td></tr>
<tr><td>no CWI (incl. unknowns)</td><td>531 (56.4)</td><td>315 (28.9)</td></tr>
<tr><td>CWI present but no installation date assumed to be non-WF measure</td><td>184 (19.5)</td><td>290 (26.6)</td></tr>
<tr><td colspan="3">total</td><td>942</td><td>1091</td></tr>
<tr><td colspan="2" rowspan="4">dwellings with loft space</td><td>LI installed by WF before survey</td><td>243 (15.9)</td><td>453 (31.7)</td></tr>
<tr><td>LI installed by WF during survey</td><td>147 (9.7)</td><td>0 (0.0)</td></tr>
<tr><td>no LI, (incl. unknowns)</td><td>795 (51.9)</td><td>457 (31.9)</td></tr>
<tr><td>LI present but no installation date assumed to be non-WF measure</td><td>345 (22.5)</td><td>521 (36.4)</td></tr>
<tr><td colspan="3">total</td><td>1530</td><td>1431</td></tr>
<tr><td rowspan="8">u16</td><td rowspan="4">centrally heated dwellings</td><td>CH repaired by WF before survey</td><td>49 (6.8)</td><td>333 (56.8)</td></tr>
<tr><td>CH repaired by WF during survey</td><td>49 (6.8)</td><td>16 (2.7)</td></tr>
<tr><td>CH repaired after WF survey</td><td>136 (18.8)</td><td>35 (6.0)</td></tr>
<tr><td>CH condition unknown
pre-WF: assume not repaired
post-WF: assume repaired</td><td>163 (22.6)</td><td>96 (16.4)</td></tr>
<tr><td rowspan="4">non-centrally heated dwellings</td><td>RH installed by WF before survey</td><td>13 (1.8)</td><td>80 (13.7)</td></tr>
<tr><td>RH installed by WF during survey</td><td>39 (5.4)</td><td>0</td></tr>
<tr><td>RH installed by WF after survey</td><td>133 (18.4)</td><td>6 (1.0)</td></tr>
<tr><td>no installation date
pre-WF: assume uninstalled
post-WF: assume installed</td><td>140 (19.4)</td><td>20 (3.4)</td></tr>
<tr><td colspan="3">total</td><td>722</td><td>586</td></tr>
<tr><td rowspan="6">o60</td><td rowspan="4">centrally heated dwellings</td><td>CH repaired or installed by WF before survey</td><td>17 (2.0)</td><td>815 (88.3)</td></tr>
<tr><td>CH repaired or installed by WF during survey</td><td>54 (6.2)</td><td>2 (0.2)</td></tr>
<tr><td>CH repaired or installed after WF survey</td><td>223 (25.8)</td><td>8 (0.9)</td></tr>
<tr><td>CH condition unknown
pre-WF: assume unrepaired
post-WF: assume repaired</td><td>91 (10.5)</td><td>97 (10.5)</td></tr>
<tr><td rowspan="2">non-centrally heated dwellings</td><td>CH installed by WF during survey</td><td>114 (13.2)</td><td>0 (0.0)</td></tr>
<tr><td>CH installed after WF survey</td><td>367 (42.3)</td><td>1 (0.1)</td></tr>
<tr><td colspan="3">total</td><td>866</td><td>923</td></tr>
<tr><td colspan="5">WF: Warm Front
CWI: cavity wall insulation (50 mm)
LI: loft insulation (>100 mm)
CH: central heating
RH: room heater</td></tr>
</table>

Table 4.4: Case study dwellings disaggregated by the actual *Warm Front* intervention status (n = 3099).

classification	criteria	sample size		
		longitudinal	cross-sectional	total (% total)
pre-WF	no WF intervention	83	1160	1243 (40.1)
in-between	some WF intervention	-	-	1050 (33.9)
post-WF	full WF intervention	83	723	806 (26.0)

4.1.4. Draught Proofing

The case study dwellings are classified by the draught proofing condition classified into no draught proofing (*NDP*), partial draught proofing (*PDP*) and full draught proofing (*FDP*). Table 4.5 summarizes the sample size and the classification definition with dwellings grouped into *NDP* if less than 25 % of the openings (combination of doors and windows) are draught proofed, *FDP* if greater than 75 % is draught proofed and *PDP* for all others. Although the effect of insulation has not been taken into account, the statistically significant difference in the mean *heat loss parameters* (HLP) between the three draught proofing groups in Table 4.5 suggests that the criterion used in likely capturing different impact of the three draught proofing levels. The method used in determining the *heat loss parameter* is described in Section 4.4. The performance of the *NDP* and the *FDP* classified dwellings will be compared to examine the impact of draught proofing in this study while the effect of draught proofing will be isolated by statistically eliminating the effects of insulation and heating system (Section 4.1).

Table 4.5: Case study dwellings disaggregated by the ownership of draught proofing (n = 3099).

classification	criteria	sample size (% total) n = 3099	mean *HLP* (95%CI), W/m^2K
no draught proofing (*NDP*)	<25 % of openings draught proofed	496 (16.0)	3.98 (3.88, 4.08)
partial draught proofing (*PDP*)	>=25 % and <=75 % of openings draught proofed	656 (21.2)	3.77 (3.69, 3.85)
full draught proofing (*FDP*)	>75 % of openings draught proofed	1947 (62.8)	3.58 (3.53, 3.62)

4.1.5. Insulation

The case study dwellings are classified according to the insulation level grouped as no insulation (*NI*), partial insulation (*PI*) and full insulation (*FI*). Table 4.6 summarizes the classification definition and the sample size. Although *post-WF* loft insulation thickness is typically 200mm or above, thicknesses equal to or above 100mm was also considered as being fully insulated in this study because little difference was found in the mean *heat loss parameters* between the dwellings with 100mm loft insulation at 3.59 W/m^{2}K (SD: 0.94) and with 200mm or greater level of loft insulation at 3.45 W/m^{2}K (SD: 0.99). One explanation behind the lack of difference is that about 60 % of 100 mm loft insulated dwellings are solid walled compared to about 88 % of 200 mm or greater loft insulated dwellings thereby reducing the overall heatloss performance despite greater insulation thickness.

In general, the mean *heat loss parameters* in the table show that the classification is a fairly good representation of the insulation performance. The impact of insulation will be examined by comparing the performances of the *NI* and the *FI* dwellings while statistically eliminating the effects of draught proofing and heating (Section 4.1).

Table 4.6: Case study dwellings disaggregated by the ownership of insulation (n = 3099).

<table>
<tr><th colspan="2">insulation classification</th><th>criteria</th><th>sample size
(% total)
n = 3099</th><th colspan="2">mean HLP
(95%CI), W/m²K</th></tr>
<tr><td colspan="2">no insulation (NI)</td><td>no cavity wall insulation (0mm)
no loft insulation (≤25mm)</td><td>480 (15.5)</td><td colspan="2">4.55
(4.46, 4.66)</td></tr>
<tr><td rowspan="3">partial insulation (PI)</td><td>cavity wall insulation only (CWI)</td><td>full cavity wall insulation (50mm)
loft insulation (≤25mm)</td><td>61 (2.0)</td><td rowspan="3">3.97
(3.93, 4.02)</td><td>3.36
(3.21, 3.50)</td></tr>
<tr><td>loft insulation only (LI)</td><td>no cavity wall insulation (0mm)
full loft insulation (≥100mm)</td><td>1156 (37.3)</td><td>4.04
(3.99, 4.09)</td></tr>
<tr><td>other partial insulation</td><td>no or full cavity wall insulation (≤50mm)
some loft insulation (>25mm, <100mm)</td><td>438 (14.1)</td><td>3.88
(3.79, 3.96)</td></tr>
<tr><td colspan="2">full insulation (FI)</td><td>full cavity wall insulation (≥50mm)
full loft insulation (≥100mm)</td><td>964 (31.1)</td><td colspan="2">2.75
(2.72, 2.78)</td></tr>
</table>

4.1.6. Heating System

The case study dwellings are classified by the ownership of non-central heating (*non-CH*) and central heating (*CH*) system. The *non-CH* includes gas room heaters (condensing, non-condensing, open flue, balanced flue, coal effect), on-peak electric room heaters (panel, convector, bar or fan heaters), portable electric heaters and electric storage heaters if less than 3 units. The *CH* refers to a network of hot water radiators or warm air ducts with heat supplied by a central boiler (back boiler, normal, combination, condensing). The centrally heated dwellings are further classified into central heating only (*CHonly*), combination of central and non-central heating (*CH+nonCH*) and storage heating (*SH*) if there are three or more storage heaters. Table 4.7 summarizes the classification definition, the sample size and the approximate fuel conversion efficiency range with 100 % representing electric or storage heaters. In general the *nonCH* group will exhibit lower heating efficiency rate compared to the *CH* while within the *CH* group, the *CH+nonCH* group is expected to have lower overall heating efficiency than the *CHonly* group if some householders use a combination of central and non-central heating appliances. The impact of central heating will be examined by comparing the performances of the *nonCH* and the *CH* dwellings while statistically eliminating the effects of draught proofing and insulation (Section 4.1).

Table 4.7: Case study dwellings disaggregated by the ownership of heating system.

heating classification		criteria	sample size (% total) n = 3099	efficiency (SEDBUK %)
non-central heating (*nonCH*)		room heater(s) only	1143 (36.9)	20 ~ 100
central heating (*CH*)	central heating only (*CHonly*)	gas central heating only (condensing boiler: 38)	311 (10.0)	65 ~ 100
	central heating and room heaters (*CH+nonCH*)	gas central heating and room heater(s) (condensing boiler: 449)	1579 (51.0)	65 ~ 100
	storage heating (*SH*)	three or more storage heaters with or without room heater(s)	66 (2.1)	100

4.1.7. Insulation and Heating System

The case study dwellings are classified according to the combined ownership of insulation and heating system. Table 4.8 summarizes the classification definition and the sample size. The least energy efficient group is represented by the group with no insulation and no central heating *(NI+nonCH*) and the most energy efficient by the group with full insulation and central heating only (*FI+CHonly*). The ownership of draught proofing is deliberately excluded from this classification because its effect on the energy consumption, as will be shown in Chapter 7, is found to be marginal while its inclusion would have considerably reduced the sample size.

Table 4.8: Case study dwellings (% total) disaggregated by the combined ownership of insulation and heating system (n = 3099).

Heating \ Insulation	*NI* *(% total)	*PI* (% total)	*FI* (% total)
CHonly	30 (1.0)	165 (5.3)	116 (3.7) ‡
CH+nonCH	201 (6.5)	769 (24.8)	609 (19.7)
nonCH	238 (7.7) †	692 (22.3)	213 (6.9)
† *least energy efficient* ‡ *most energy efficient*			

4.2. BREDEM 8

Sufficient information was available from the property condition data to model 3099 case study dwellings in BREDEM which was primarily used to determine the following four parameters.

1. Modelled air leakage rate (Section 4.3.2)
2. Modelled space heating energy consumption (Section 4.5.1)
3. Modelled internal temperature (Section 4.7.1)
4. Temperature rise from incidental heat gains (Section 4.10)

There were two main challenges in modelling the case study dwellings in BREDEM. The first was preparing the raw data into useful formats for modelling and the second was modelling all 3099 case study dwellings. Both involved extensive use of Visual Basic programming in Microsoft Excel.

Most of the raw data obtained from the property condition survey required further derivation into formats suitable as input variables in BREDEM. The work ranged from simple tasks such as adding up the number flues and chimneys to as complex as estimating the zone 1 and zone 2 heat loss surface areas based on exposed building perimeter, floor height, dwelling type and window characteristic. Many of these procedures required assumptions to be made for missing variables and many of them required specifically programmed Visual Basic algorithms for the different dwelling type. Once the input data was prepared for all the dwellings, Visual Basic programming was used to automatically substitute the derived data into an Excel based BREDEM worksheet to model all 3099 dwellings.

The Microsoft Excel based BREDEM worksheet used in this study originally formed a part of the model titled the Condensation Targeter II [50] developed to predict the risk of surface condensation and mould growth in dwellings by incorporating a moisture algorithm into an Excel based BREDEM worksheet. For the purpose of this study, the moisture algorithm was dropped. The advantage of using an Excel based BREDEM worksheet was the flexibility it offered in allowing the substitution of different variables such as the actual monitored temperatures and in situ performance data in Chapter 10.

4.2.1. Exposed Building Surface Area

The exposed building surface area information is combined with thermal transmittance (U-value) to determine the building *heat loss parameter* described in Section 4.4. This section describes how the floor, roof, wall and window/door areas were determined from the surveyed property condition data.

Floor and Roof: The exposed floor area was directly available from the surveyed data. The exposed roof was assumed to have the same area as the floor except in mi-terraced dwellings with a passage. The living room floor area (zone 1) was measured from 21 % of the property surveyed dwellings, and from this information, the zone 1 floor area was estimated to take up approximately 38 % of the total ground floor area for the remaining case study dwellings.

Wall: The exposed wall area was determined by multiplying the building exposed perimeter with the building height. BREDEM requires separate exposed zone 1 and zone 2 wall areas but their actual exposed perimeter lengths were available from only a sub-sample of the case study dwellings. Consequently, the zones 1 and 2 exposed perimeter lengths for the rest of the dwellings were estimated by applying the proportional relationship of the zone 1 perimeter length to the total exposed perimeter length obtained from the sub-sample measurement as shown in Table 4.9 disaggregated according to the building type. This method assumes that zone 1 is always located on the ground floor and in the main part of the building.

Table 4.9: Proportion of zone 1 exposed building perimeter in relation to the main exposed building perimeter by dwelling type.

building type	% of main building exposed perimeter	
	rear extension present	no rear extension
end-terraced	67	59
terrace with passage	67	59
mid-terraced	67	50
semi-detached	63	53
detached	43	38
back-back (mid)	100	not applicable
back-back (end)	75	not applicable

Window and Door: The window and door areas were measured from 23 % of the property surveyed dwellings. From this information, the opening distribution for zones 1 and 2 was estimated by building type and the presence of a rear extension as shown in Table 4.10. The difference in the fenestration area according to the building age was found to be statistically insignificant most likely due to the small number of dwellings from which window and door data was collected. The window and door areas for the remaining 77 % of the dwellings were then estimated in accordance to these distribution figures.

Table 4.10: Proportion of zone 1 and zone 2 total estimated window and door opening area in relation to the total exposed wall area.

building type	% of total window & door area			
	rear extension present		no rear extension	
	zone 1	zone 2	zone 1	zone 2
all terraced	20	80	24	76
semi-detached	22	78	23	77
detached	30	70	25	75
all back-back	20	80	not applicable	

4.2.2. Surface U-value

The U-values are determined for all building surfaces exposed to the external environment. The U-value is expressed in units of W/m^2K and describes the rate of thermal transmittance though a square meter area of a building fabric across a unit temperature gradient; the greater the U-value, the greater the rate of heat loss through the building fabric during the heating season. This section describes the U-values used for the floor, roof, wall, window and door construction.

In the case of roof and wall, two different U-values are presented, the modelled U-value assuming 100 % of exposed cavity wall and roof construction areas being insulated and the monitored U-value representing the in situ insulation condition of the *post-WF* dwellings with an average of 20 % of the exposed cavity wall and 13 % of the exposed loft areas missing in insulation. The in situ insulation condition was determined using the results of thermographic images taken from 85 *post-WF* case study dwellings that have received cavity wall and loft insulation. The results of the thermographic images are discussed in detail in Section 6.2. .

Floor: The U-value of exposed floor is determined based on the ratio between the exposed perimeter length and the floor area while taking into account the floor insulation condition [51]. Information on floor insulation was collected from only 21 % of the property surveyed dwellings which indicated only 2 % having some floor insulation. Accordingly, no floor insulation was assumed for the rest of the dwellings from which no floor insulation data was collected.

Roof: Pitched roof was the predominant roof construction type with 95 % of the case study dwellings falling into this group. The rest were mainly of flat roof construction most of which had no roof insulation. The *modelled* and the *monitored U-values* used are presented in Table 4.11 for the pitched and flat roofs for 6 different loft insulation thicknesses based on the values provided in BREDEM 8 manual [33]. The *monitored U-values* are determined by adjusting the *modelled U-values* by the reduced insulation performance observed from the thermographic studies (Section 6.2) undertaken as a part of the *Warm Front Study* (Section 3.4.6).

Table 4.11: Estimated U-values of exposed roof by insulation thickness.

insulation thickness (mm)	U-value (W/m^2K)		
	flat/other roof	pitched roof	
		modelled #	monitored
no insulation or unknown	2.30	2.30	
50	0.67	0.67	0.88
100	not applicable	0.40	0.65
150		0.29	0.55
200		0.22	0.49
> 200		0.18	0.46

 # source: BREDEM-8 Model description, 2001 update [33]
modelled: 100 % exposed loft area insulated
monitored: 87 % of exposed loft area insulated

Wall: 97 % of the case study dwellings were of brick masonry construction with 32 % having solid wall (typical: 225 mm brick masonry) and 64 % cavity wall (typical: 105 mm external brick work – 50 mm air space – 105 mm internal brick or concrete masonry) construction. The U-values for the two wall types are shown in Table 4.12 based on the values provided in BREDEM 8 manual [33]. For the cavity wall, the *monitored* and the *modelled U-values* are presented where the *monitored U-values* take into account the reduced insulation performance observed from the thermographic studies (Section 6.2) undertaken as a part of the *Warm Front Study* (Section 3.4.6). Only two solid-walled dwellings had 25 mm wall insulation.

Table 4.12: Estimated U-values of exposed wall by insulation thickness.

<table>
<tr><td colspan="2">wall type</td><td colspan="2">solid wall</td><td colspan="2">cavity wall</td></tr>
<tr><td colspan="2">insulation thickness (mm)</td><td>0</td><td>25</td><td>0</td><td>50</td></tr>
<tr><td rowspan="2">U-values (W/m^2K)</td><td>modelled #</td><td>2.10</td><td>0.90</td><td rowspan="2">1.60</td><td>0.60</td></tr>
<tr><td>monitored</td><td colspan="2">not applicable</td><td>0.80</td></tr>
<tr><td colspan="6"># source: BREDEM-8 Model description, 2001 update [33]
modelled: 100 % exposed cavity wall area insulated
monitored: 80 % of exposed cavity wall area insulated</td></tr>
</table>

Window and Door: The typical window and door U-values used in this study are shown in Table 4.13 based on the values provided in BREDEM 8 manual [33]. These U-values do not take into account the insulating effect of emissivity coatings or inert gas. None of the 23 % of the case study dwellings from which window data was available was found to own triple glazing. The window and door U-values for the rest of the dwellings from which no data was collected were estimated based on the similarity in building age. Table 4.14 shows the combined average U-values of windows and doors for different dwelling age groups. With decreasing dwelling age, the average U-values are found to decrease reflecting increased ownership of double glazed windows.

Table 4.13: Estimated U-values of windows and doors

frame type	U-value (W/m^2K)						
	window type		door type				
	single glazing	double glazing*	solid	half glazed		fully glazed	
				single glazing	double glazing*	single glazing	double glazing*
wood	4.8	2.7 ~ 3.1	3.0	3.6	2.8 ~ 2.6	4.8	2.9 ~ 2.7
metal	5.7	3.3 ~ 3.7	2.8	4.3	3.5 ~ 3.1	5.7	3.8 ~ 3.2
pvc	4.8	2.7 ~ 3.1	2.5	3.6	3.1 ~ 2.9	4.8	3.3 ~ 3.0

** range includes double glazing spacing from 8 mm to 12 mm*
source: BREDEM-8 Model description, 2001 update [33]

Table 4.14: Estimated area weighted average window and door U-values by dwelling age

dwelling age	mean U-value (W/m^2K)
pre-1900 ~ 1929	3.75
1930 ~ 65	3.74
1966 ~ 95	3.58

4.2.3. Space Heating Appliance Efficiency

Space heating appliance fuel conversion efficiency, expressed in percentage, describes the efficiency of a space heating appliance in converting delivered fuel into useful heat. The fuel conversion efficiencies used in this study are based on the SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) figures [52]. These are shown in Table 4.15 for different heating appliances using metered fuel. BREDEM allows two heating systems – primary and secondary – to be designated as the source of space heating with contribution from the secondary system determined by the parameter ‘fraction of heat from secondary appliance’. Central heating is always designated as the primary system and in the case of non-centrally heated dwellings the heating appliance in the living room is designated as the primary system. For most modelling work, the primary system is assumed the only source of heating while in chapter 10, the potential impact from the combined use of the primary (central heating) and the secondary system (non-central heating) on the energy saving is examined.

Table 4.15: Estimated space heating appliance fuel conversion efficiency.

heating system		fuel type	efficiency (%)
central heating	back boiler	gas	65
	normal boiler	gas	65(o, b), 71(f)
	combination	gas	65(o, b), 71(f)
	condensing	gas	83
	storage heater	electricity	100
non-central heating	coal effect fire (open)	gas	20
	coal effect fire (flued)	gas	50
	non-condensing room heater	gas	40
	condensing room heater	gas	85
	open flue room heater	gas	60
	balanced flue room heater	gas	70
	modern heater with back boiler	gas	65
	portable electric heater	electricity	100
other	gas warm air	gas	70
	gas warm air with heat recovery	gas	85

o: open flue
b: balanced flue
f: fan-assisted flue

4.3. Ventilation Rate

Ventilation is often quantified as the number of whole house air changes per hour at 50 Pascals pressure gradient between the outside and the inside of a building. Ventilation in a building is normally categorized into two types: controlled and uncontrolled ventilation.

Controlled ventilation refers to the intentional ventilation by mechanical means or by window operation and is necessary to remove indoor pollutants such as odour and moisture. Uncontrolled ventilation refers to the unintentional air leakage – term used in this study – which if high is a statement about a building's poor construction quality and poor energy performance.

The controlled ventilation is usually difficult to monitor and quantify because it involves monitoring the occupant behavior. BREDEM estimates the controlled ventilation rate as a function of the uncontrolled ventilation rate under the assumption that occupants will deliberately open windows for fresh air if the uncontrolled ventilation rate is low. Controlled ventilation was not measured in the *Warm Front Study*.

In the *Warm Front Study*, the air leakage rate was measured from a sub-sample of dwellings using the blower-door technique as a part of the *Energy Efficiency Survey* (Section 3.4.6). This section describes how the actual air leakage rate was measured using the blower-door technique – *blower door tested air leakage rate* – and the method used in determining the air leakage rates – *modelled air leakage rate* and *monitored air leakage rate* – of dwellings from which no actual air leakage rate measurement was taken.

4.3.1. Blower-door Tested Air Leakage Rate

The *blower-door tested air leakage rate* refers to the 212 separate air leakage rate measurements taken from 191 case study dwellings using the fan pressurization method which involved mounting a calibrated fan into an open external doorway using an adjustable door panel system and applying a series of steady-state pressure differences across the building envelope by changing the fan speed. The tests were undertaken using the Retrotec fan pressurization equipment [53] and in accordance to the CIBSE TM23: 2000 recommended procedure [54]. All the tests were carried out with chimney openings sealed while leaving all flues and vents in open condition in order to measure the air leakage rate close to the normal dwelling condition.

4.3.2. Modelled Air Leakage Rate

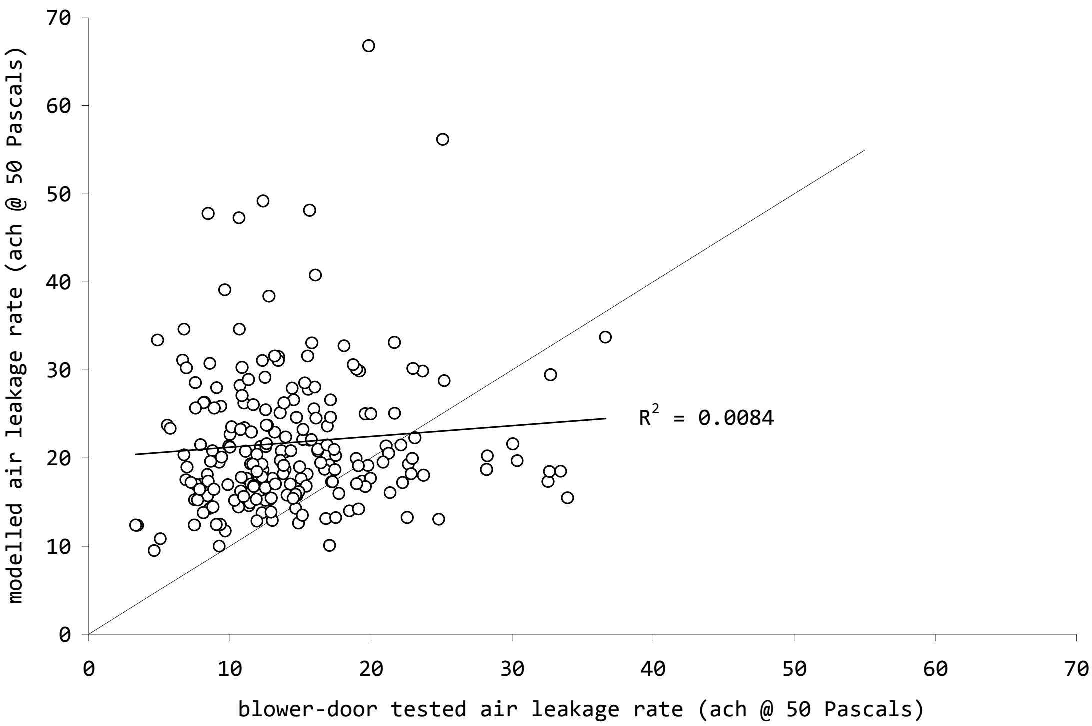
The *modelled air leakage rate* refers to the air leakage rate estimated using the BREDEM ventilation algorithm which takes into account the effect of the building exposure to wind and the building physical characteristic describing leakiness such as the building construction type, door and window conditions and the number of openings such as fans, flues, chimneys [33]. The *modelled air leakage rate* was determined for 3099 case study dwellings.

Table 4.16 and Figure 4.1 compare the *blower-door tested air leakage rate* of the 212 tested dwellings in relation to the *modelled air leakage rate* of the same dwellings. Along with the poor coefficient of determination, the flat slope of the regression line in relation to the y = x line indicates that the modelled rate is a poor representation of the actual air leakage rate. .

Table 4.16: Comparison of *blower-door tested* and *modelled air leakage rates*

air leakage rate	no.	air leakage rate (ach @ 50 Pascals)
		mean (SD)
blower-door tested	212	14.4 (6.1)
modelled (BREDEM8)		21.8 (8.1)

Figure 4.1: Comparison *of blower-door tested* and *modelled air leakage rates* (n = 212)



4.3.3. Monitored Air Leakage Rate

The *monitored air leakage rate* refers to the air leakage rate calculated from a regression equation determined from the 212 *blower-door tested air leakage rates*. The term *monitored air leakage rate* is used because it is assumed to be a closer representation of the actual air leakage rate than the BREDEM predicted *modelled air leakage rate*.

The *monitored air leakage rate* was estimated using a multiple regression as a function of 9 statistically significant dwelling physical characteristics as the independent predictor variables ($p < 0.001$) as shown in Eqn. 4.1. The effect of draught proofing is included in the 'loose windows' variable. The purpose of developing this equation was one, to understand the parameters that influence the actual air leakage rate in a domestic dwelling [2] and two, to estimate the *monitored air leakage rate*s for the 2896 case study dwellings from which no actual air leakage rate measurement was taken.

Monitored air leakage rate = 6.44 x loose windows + 0.29 x radiator(s)
+ 4.37 x chimney(s) + 2.44 x unfilled cavity wall + 2.65 x attic room
- 0.14 x lowest floor area + 1.63 x suspended floor area + 1.34 x fans
+ 0.83 x open flues + 17.76 (Eqn. 4.1)

where the parameters are

monitored air leakage rate	air change rate at @ 50 Pascals
loose windows (opening dimension)	% total
radiator(s)	number
chimney(s)	number
unfilled cavity wall	% total
attic room	yes (1) or no (0)

lowest floor area	m^2
suspended floor area	% total
fans	number
open flues	number

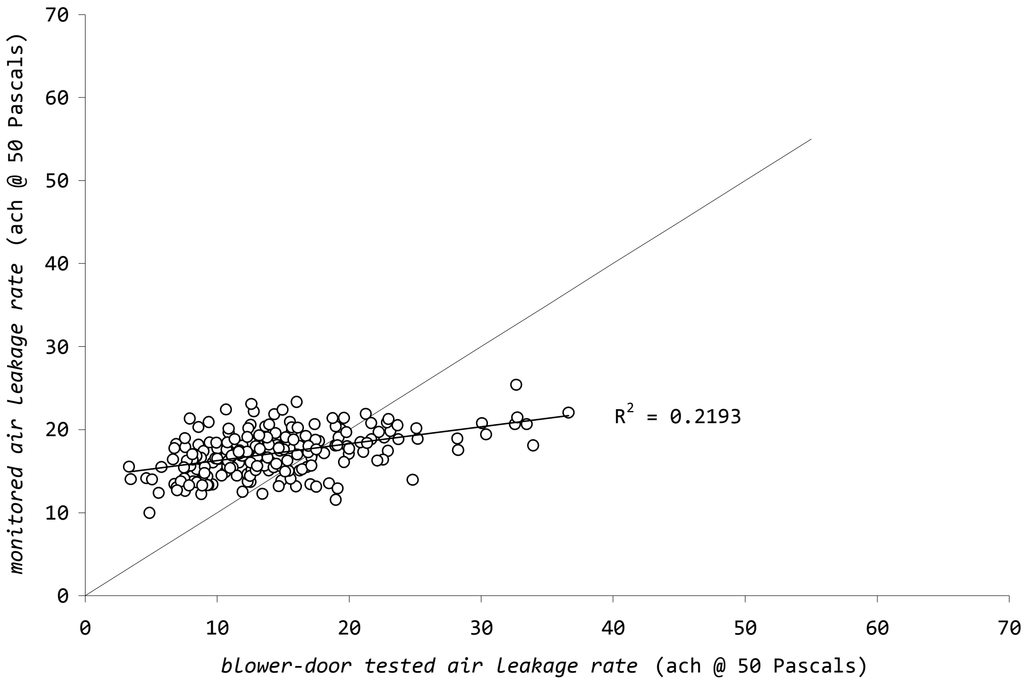
Many of these parameters determining the *monitored air leakage rate* are also found to be determinants of the BREDEM ventilation algorithm although their degrees of impact on the two air leakage rates are likely to be different. There are three parameters in the *monitored air leakage rate* which are not included in the BREDEM algorithm: the increase associated with radiators - unique to a retrofit scheme, an increase associated with the presence of an attic room and a decrease associated with increasing floor area.

A comparison between the *blower-door tested* and the *monitored air leakage rates* in Table 4.17 shows that the mean *monitored air leakage rate* is about 19 % greater than the mean *blower-door tested air leakage rate*. The higher standard deviation shown in the table and the wider distribution associated with the *blower-door tested air leakage rate* shown in Figure 4.2 also indicates the *monitored air leakage rate* is only partially effective in explaining the variation in the *blower-door tested air leakage rate* (R^2 = 21 %). On the other hand, a comparison of the mean and the r-squared values indicates that the *in situ air leakage rate* is a more accurate representation of the *blower-door tested air leakage rate* than the *modelled air leakage rate* as observed in Table 4.16.

Table 4.17: Comparison of *blower-door tested* and *monitored air leakage rates*

air leakage rate	no.	air leakage rate (ach @ 50 Pascals)
		mean (SD)
blower-door tested	212	14.4 (6.1)
monitored (Eqn. 4.1)		17.2 (2.6)

Figure 4.2: Comparison of *blower-door tested* and *monitored air leakage rates* (n = 212)



4.4. *Heat Loss Parameter*

The *heat loss parameter* (*HLP*) describes the rate of conductive and convective heat loss across a building fabric at a unit temperature gradient between the interior and the exterior normalized to internal floor area. Simply, the *heat loss parameter* is an indicator of how well a building is insulated and sealed with a low value describing a well insulated and airtight building fabric and a high value describing a poorly insulated and a leaky building fabric (Table 4.5 & Table 4.6). The heat loss parameter is expressed in the units of W/m^{2}K, and it is quantified by the relationship shown in Eqn. 4.2.

$$HLP = \frac{\sum_{n=1}^{i} U_i A_i + 0.33NV}{A_f} \qquad \text{(Eqn. 4.2)}$$

where the parameters are

U_i U-value of each type of exposed building construction (W/m^{2}K)

A_i Surface area of each type of exposed building construction (m^2)

N whole-house (controlled + air leakage) ventilation rate (ach) (Section 4.3.)

V building internal volume (m^3)

A_f internal floor area (m^2)

Three different *heat loss parameters* are determined by varying the U-value and the air leakage rate component of the ventilation rate in Eqn. 4.2. The first is the *modelled heat loss parameter* (HLP_{mod}) which is determined using the *modelled U-values* (Table 4.11) and the *modelled air leakage rate* (Section 4.3.2); the second is the *ventilation adjusted heat loss parameter* ($HLP_{mod(v)}$) which is determined using the *modelled U-value*s (Table 4.11) and the *monitored air leakage rate* (Section 4.3.1) and the third is the *ventilation and insulation adjusted heat loss parameter* ($HLP_{mod(vi)}$) which is adjusted by both the *monitored air leakage rate* and the *monitored U-values*. The latter is expected to be the closest representation of the actual building heat loss performance.

The mean values of the three *heat loss parameters* are compared in relation to draught proofing and insulation in Table 4.18 and Table 4.19 respectively. The results show both measures effective in reducing the *heat loss parameter* with full draught proofing (FDP) by 10 % and full insulation (FI) by 40 %. The introduction of the *monitored U-values* and the *monitored air leakage rate* resulted in reduced *heat loss parameter* performance indicating a *shortfall* in the actual performance of insulation and draught proofing, a topic to be discussed in detail in Chapter 11. The *heat loss parameter* will be used in Chapter 1 to examine its relationship to the indoor temperature.

Table 4.18: Mean *heat loss parameters* related to the draught proofing level.

dwellings classified by draught proofing status	*heat loss parameter* (95%CI), W/m^{2}K		
	HLP_{mod}	$HLP_{mod(v)}$	$HLP_{mod(vi)}$
NDP (no draught proofing), (n = 497)	4.0 (3.9, 4.1)	3.9 (3.8, 4.0)	4.0 (3.9, 4.1)
PDP (partial draught proofing), (n = 659)	3.8 (3.7, 3.9)	3.7 (3.6, 3.8)	3.8 (3.7, 3.9)
FDP (full draught proofing), (n = 1952)	3.6 (3.5, 3.6)	3.4 (3.4, 3.5)	3.6 (3.6, 3.6)

Table 4.19: Mean *heat loss parameters* related to the insulation level.

dwellings classified by insulation status	*heat loss parameter* (95%CI), W/m^{2}K		
	HLP_{mod}	$HLP_{mod(v)}$	$HLP_{mod(vi)}$
NI (no insulation), (n = 480)	4.6 (4.5, 4.6)	4.5 (4.4, 4.5)	4.5 (4.4, 4.6)
PI (partial insulation), (n = 1659)	4.0 (3.9, 4.0)	3.9 (3.8, 3.9)	4.0 (3.9, 4.0)
FI (full insulation), (n = 969)	2.8 (2.7, 2.8)	2.6 (2.6, 2.7)	2.9 (2.9, 3.0)

4.5. Space Heating Energy Consumption

The impact of energy efficiency measure on the energy consumption is investigated by determining the changes in the space heating energy consumption. Three types of space heating energy consumption are determined in this study and these are described in this section.

4.5.1. Modelled Space Heating Energy Consumption

Two different methods are used to determine the model predicted space heating energy consumption using BREDEM. The first method assumes a standard heating regime (zone 1: 21 °C (weekdays: 9 hrs, weekend: 16 hrs); zone 2: 18 °C (weekdays: 7 hrs, weekend: 11 hrs)) for the internal condition, and the energy usage obtained is described as the *modelled space heating energy consumption* (Q_{mod}). Because the same internal temperature condition is assumed for both the pre and post upgrade conditions, this method does not take into account the effect of the *comfort taking* and is therefore useful in examining the maximum potential saving that can be obtained from an energy efficiency upgrade. The *modelled space heating energy consumption* is examined in detail in Chapter 7.

In the second method, the modelled energy usage is determined by directly substituting the monitored zone 1 and zone 2 temperatures (Section 4.7.2) into BREDEM. Because the actual temperature condition is assumed in the model, any variation in the energy usage attributable to the *comfort taking* is eliminated leaving other factors to explain any difference between the monitored and the modelled energy saving. The modelled energy consumption determined from this method is described as the *modelled space heating energy consumption with monitored temperature* ($Q_{mod(mt)}$) and examined in Chapter 10 when determining the *loss*.

When determining the two types of modelled space heating energy consumption, the monitored external temperature is used in both cases while the primary heating system, usually the most efficient, is assumed as the only source of space heating.

4.5.2. Monitored Space Heating Energy Consumption

Although three to four week gas and electricity consumption data were obtained from the *Warm Front* survey, no information was collected on how much of this was consumed for space heating. The *monitored space heating energy consumption* (Q_{mon}) is derived from the monitored total gas and electricity consumption data based on Eqn. 4.3 and is meant to be the closest representation of the actual energy consumed for space heating.

$$Q_{mon} = Q_{total} – Q_{non\text{-}heating} \qquad \text{(Eqn. 4.3)}$$

where the parameters are

Q_{mon}	monitored space heating energy consumption
Q_{total}	monitored total energy consumption

$Q_{non\text{-}heating}$ non-space heating related energy consumption

Q_{total} is the actual energy consumption data obtained from the gas and electric meters in winter, and $Q_{non\text{-}heating}$ is predicted using two regression models, gas and electricity, based on the actual summer utility data obtained from small sub-samples of case study dwellings.

Eqn. 4.4 shows the summer gas consumption model developed from 130 actual summer gas meter readings obtained from 73 dwellings. Five variables were found to be the significant predictors in explaining 47 % of the variance in summer gas consumption ($p<0.001$). Eqn. 4.4 was used to predict the non-heating related gas loads in 2705 case study dwellings.

Summer gas consumption (kWh/day) = 3.66 x household size
- 3.14 x dwelling age + 4.59 x gas cooker - 0.14 x total floor area
+ 3.70 x gas water heater + 15.81 (Eqn. 4.4)

Eqn. 4.5 shows the summer electricity consumption model developed from 55 actual summer electricity meter readings obtained from 29 dwellings. Four variables were found to be significant predictors in explaining 53 % of the variance in summer electricity consumption ($p<0.001$). Eqn. 4.5 was used to predict the non-heating related electricity loads in 2737 case study dwellings.

Summer electricity consumption (kWh/day) = 0.76 x household size
+ 3.14 x electric water heater + 1.87 x electric cooker
+ 1.0 x number of television + 0.96 (Eqn. 4.5)

The units in some of the parameters in Eqns. 4.4 and 4.5 are

household size	number of occupants
dwelling age	pre-1900 = 1, 1900-1964 = 2, 1965-1990 = 3, post-1990 = 4
gas cooker	0 if not present, 1 if present
electric cooker	0 if not present, 1 if present
total floor area	in square meters
gas water heater	0 if not present, 1 if gas central heating, 2 if other gas fueled appliance
electric water heater	0 if not present, 1 if present

The non-space heating gas load in winter is assumed to differ little from summer gas consumption; seasonal adjustment is introduced to the summer electricity consumption by multiplying a coefficient of 2 to the household size to take into account the likelihood of extended lighting use in winter [55]. Increased heat loss from immersion heaters in winter is not taken into account since most of this is lost to the indoor environment.

The monitored space heating energy consumption predicted from Eqn. 4.3 was found to constitute 66 % of the total energy consumption. Although not a direct comparison (since this figure is relative to total winter energy use) space heating accounted for 62 % of the total annual energy consumption for the UK dwelling stock in 2001 [15] suggesting potential over-estimation in the monitored space heating energy consumption. On the other hand, since about half of the case study dwellings were pre-intervention with their heating system most likely to be in a substandard condition, the estimated figure could be considered to be reasonable.

4.6. *Quantifying Energy Consumption*

Energy consumption is quantified in this study based on the delivered energy, energy cost and carbon emissions. This section describes how these are quantified.

Delivered Energy: The delivered energy is expressed in kilowatt-hours (kWh). In the case of the monitored gas consumption, a conversion process is required from volumetric units of either 100's cubic feet or cubic meter to kWh. The 100's cubic feet meter type was found in 80 % of the case study dwellings and the rest were of the cubic meter type. Eqns. 4.6 and 4.7 are used to convert these volumetric readings into kWh [56].

volumetric unit in 100's ft^3: *units x (2.83 x 1.02264 x 39.25) / 3.6* (Eqn. 4.6)

volumetric unit in m^3: *units x (1.00264 x 39.25) / 3.6* (Eqn. 4.7)

where the parameters are

2.83	conversion factor from 100's cubic feet to cubic meter
1.02264	volume conversion factor
39.25	calorific value
3.6	conversion factor from MJ to kWh

Energy Cost: The energy cost associated with energy consumption is determined by applying the estimated energy cost factor to the amount of natural gas and electricity used. The 2002 cost factors are shown in Table 4.20 according to the geographic region and the fuel type [57]. The cost factors are based on standard tariff rates without taking into account standing charges or VAT or dual fuel rates or two-tier system.

Table 4.20: Fuel cost factor for natural gas and electricity.

fuel type	fuel cost factor for 2002* (pence/kWh)		
	Southampton (South-East)	Birmingham (Midlands)	Liverpool, Manchester Newcastle (Northern)
electricity (standard tariff)	6.21	6.48	6.17
electricity (off-peak)	2.74	2.71	2.56
gas (metered)	1.49		
* *source: Sutherland Tables (2008)* [57]			

Carbon Emissions: The carbon dioxide emissions from fuel consumption are determined by applying the estimated carbon emissions factor to the amount of gas and electricity used. Table 4.21 shows the carbon emissions factors used [58, 59].

Table 4.21: Carbon emissions factor for natural gas and electricity.

fuel type	CO2 emissions factor for 2002 and 2003 (kgCO2/kWh)
electricity	0.518*
gas (metered)	0.185†
* *source: Defra (2007)* [58] † *source: Defra (2004)* [59]	

4.7. *Internal Temperature*

Different rooms in a dwelling normally maintain different temperatures with the living room typically being the warmest. Determining a representative dwelling internal temperature becomes difficult when the temperature data is available from only two rooms such as in the *Warm Front Study*. Two methods are used to determine the internal temperature in this study: one, the *modelled internal temperature* based on the BREDEM prediction and two, the *monitored internal temperature* based on the monitored temperature data.

4.7.1. Modelled Internal Temperature

The *modelled internal temperature* represents the mean monthly steady state internal temperature of a dwelling determined from BREDEM predicted zone 1 (main living room) and zone 2 (rest of the dwelling) temperatures under a standard heating regime (zone 1: 21 °C, weekdays: 9 hrs, weekend: 16 hrs; zone 2: 18 °C, weekdays: 7 hrs, weekend: 11 hrs) while using the *Warm Front* monitored external temperature as the external condition. The monthly mean temperature of each zone is predicted in BREDEM by taking into account the demand temperature, the background temperature and the time taken for the dwelling temperature to fall from the demand to the background temperature. In BREDEM, the zone 2 temperature is determined by further adjusting for the heated and the unheated zone 2 regions based on a weighted sum. The *modelled internal temperature* is determined by combining the predicted zone 1 and zone 2 temperatures based on room volume weighted method as shown in Eqn. 4.8.

$$T_{mod.int} = \left[(T_{zn1} \times V_{zn1}) + (T_{zn2} \times V_{zn2}) \right] / V_{tot} \qquad \text{(Eqn. 4.8)}$$

where the parameters are

$T_{mod.\,int}$	*modelled internal temperature* (°C)
T_{zn1}	modelled zone 1 (living room) temperature (°C)
T_{zn2}	modelled zone 2 temperature (°C)
V_{zn1}	zone 1 (living room) volume (m^3)
V_{zn2}	zone 2 volume (m^3)
V_{tot}	total dwelling volume (m^3)

4.7.2. Monitored Internal Temperature

The *monitored internal temperature* is derived based on a method which involves determining the zone 1 and the zone 2 temperatures from the monitored main living room ($T_{mon.lv}$) and main bedroom temperatures ($T_{mon.bd}$) using a volume weighted method as shown in Eqn. 4.8. The zone 1 temperature is simply represented by the monitored living temperature but the zone 2 temperature is estimated from the monitored bedroom temperature using the between-room temperature profile obtained from studies undertaken by Hunt and Gidman [60] and the Carbon Reduction in Buildings Project [61, 62].

In the Hunt and Gidman study, spot temperature measurements of every room in 1000 UK dwellings were measured. The analysis includes disaggregation of the temperature measurements according to the type of heating system but not according to the insulation status most likely since most of the case study dwellings were not likely to have been insulated in 1978 when the study took place.

In the Carbon Reduction in Buildings Project, continuous temperature measurements of every room were taken from 15 dwellings in Milton Keynes Energy Park in 2005 to 2006. All of the case study dwellings were of conventional residential design in the UK but constructed to better energy performance specification each with a gas central heating system and a higher insulation level than the level required by the 1985 building regulations in force at the time of construction.

The temperatures of rooms typically comprising the zone 2 in UK dwellings are compared relative to the main bedroom in Figure 4.3 based on the measurements from the two studies. It is evident from the figure that there exists great variation in room temperatures with insulated and centrally heated dwellings exhibiting more uniform temperature distribution with a maximum temperature difference of 1.3 °C (excluding circulation) compared to poorly insulated dwellings exhibiting a greater temperature gradient of 3.5 °C for those that are non-centrally heated and 2.1 °C for those that are centrally heated.

Figure 4.3: Zone 2 room temperatures relative to the main bedroom temperature based on two temperature studies of English dwellings.

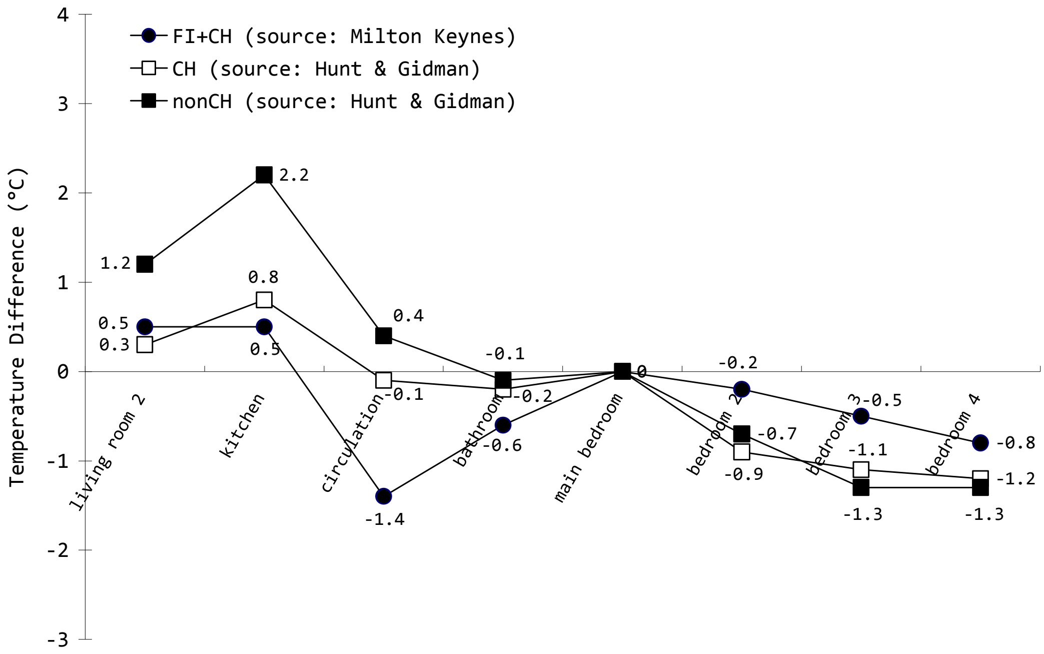


Table 4.22 shows how the zone 2 room temperature profiles from Figure 4.3 are matched to the case study dwellings according to the level of insulation and the type of heating system. The non-centrally heated profile from the Hunt & Gidman study has been adopted to represent the non-insulated and non-centrally heated *Warm Front* dwelling while the centrally heated profile from the Hunt & Gidman study has been applied to the centrally heated case study dwellings and also to the non-centrally heated but insulated dwellings under the assumption that temperature profile associated with central heating might be similar to that of insulation. The temperature profile of the Carbon Reduction in Buildings Project is used to represent the well insulated and centrally heated case study dwellings.

Table 4.22: Zone 2 room temperature profiles matched to the case study dwellings according to the insulation level and the ownership of central heating system.

zone 2 temperature profile		*Warm Front*			
		nonCH		*CH*	
		NI	*PI & FI*	*NI*	*PI & FI*
Hunt & Gidman	*nonCH*	X			
	CH		X	X	
Milton Keynes	*FI + CH*				X

By adjusting the monitored bedroom temperature by the zone 2 room temperature profile and the ownership of insulation and central heating, the temperatures of other zone 2 rooms were then estimated followed by the determination of the *monitored internal temperature* using a volume weighted averaging method as shown in Eqn. 4.9.

$$T_{mon.int} = \left[(T_{lv} \times V_{lv}) + \sum_{n=1}^{i} (T_{rm} \times V_{rm})_i \right] / V_{tot} \qquad \text{(Eqn. 4.9)}$$

where the parameters are

$T_{mon.int}$	monitored internal temperature (°C)
$T_{mon.lv}$	monitored living room temperature (°C)
T_{rm}	zone 2 room temperatures (°C)
V_{lv}	living room volume (m^3)
V_{rm}	zone 2 room volumes (m^3)
V_{tot}	total dwelling volume (m^3)
i	number of zone 2 rooms

The impact of applying the zone 2 room temperature profile on the zone 2 and the *monitored mean internal temperature* is shown in Table 4.23. Although the zone 1 temperature is unaffected by this application, it is included in the table to show why the *monitored internal temperature* which includes the effect of the zone 1 temperature is therefore higher than the zone 2 temperature.

The monitored bedroom temperature is found to range from as low as 15.0 °C in *NI+nonCH* dwellings to as high as 18.6 °C in *PI+CH* & *FI+CH* dwellings. This is also the temperature that would be expected in zone 2 if not adjusted by the zone 2 temperature profile. The impact of applying the zone 2 room temperature profile on the zone 2 and the *monitored internal temperature* is evident in that the zone 2 temperature is less by 3.9 °C (95%CI: 3.8, 3.9) and the *monitored internal temperature* less by 3.0 °C (95%CI: 2.9, 3.0) compared to the zone 2 temperature which assumes the same temperature condition as the main bedroom.

Table 4.23: Impact of room temperature profile on the monitored zone 2 and *monitored internal temperature* ($T_{mon.int}$) (°C).

temperature		*nonCH*		*CH*	
		NI (95%CI) n ≈ 111	*PI* & *FI* (95%CI) n ≈ 450	*NI* (95%CI) n ≈ 111	*PI* & *FI* (95%CI) n ≈ 880
zone 1 (living room) $T_{mon.lv}$		17.8 (17.2, 18.4)	18.7 (18.1, 18.6)	19.2 (18.8, 19.7)	19.6 (19.4, 19.7)
zone 2	not applied (bedroom)	15.0 (14.4, 15.6)	16.2 (15.9, 16.4)	17.6 (17.0, 18.1)	18.6 (18.4, 18.7)
	applied	11.9 (11.4, 12.4)	12.8 (12.6, 13.0)	13.7 (13.2, 14.2)	14.4 (14.3, 14.6)
$T_{mon.int}$	not applied	15.5 (15.0, 16.1)	16.7 (16.5, 16.9)	17.9 (17.5, 18.4)	18.8 (18.6, 18.9)
	applied	13.2 (12.7, 13.6)	14.1 (13.9, 14.3)	14.9 (14.5, 15.3)	15.6 (15.5, 15.7)
applied: zone 2 room temperature profile applied *not applied: zone 2 room temperature profile not applied*					

4.8. *Standardized Internal Temperature*

When comparing the internal temperature of dwellings across different times and geographical areas, the external temperature must be taken into account particularly if the dwellings are poorly insulated and heated as in many of the case study dwellings. The mean internal temperature determined in Section 4.7 is therefore standardized to the external temperature as shown in Eqns. 4.10 and 4.11 in order to increase the relationship between the temperature change and the energy efficiency measure.

$$T_{mod} = T_{mod.int} - T_{mon.ext} \quad \text{(Eqn. 4.10)}$$

$$T_{mon} = T_{mon.int} - T_{mon.ext} \quad \text{(Eqn. 4.11)}$$

where the parameters are

T_{mod}: *modelled standardized internal temperature* (°C)

T_{mon}: *monitored standardized internal temperature* (°C)

$T_{mod.int}$: *modelled internal temperature* (°C)

$T_{mon.int}$: *monitored internal temperature* (°C)

$T_{mon.ext}$: *monitored external temperature* (°C)

4.9. *Room Volume*

The room volumes are required when determining the mean internal temperature which is determined by volume weighted averaging method as shown in Eqns. 4.8 and 4.9. Since individual room dimensions were not measured in the *Warm Front* survey, these were estimated based on a representative volumetric proportion that each room type typically takes up in a UK dwelling based on information provided in the EHCS 1996 [25].

The proportion of the typical room volumes relative to the total volume is shown in Table 4.24. Any variation in the volumetric proportion arising from difference in the number of bedrooms was small compared to the variation among dwellings with equal number of bedrooms indicating that other factors such as the dwelling type and the floor plan may have a greater effect. However, no consideration was made for the different dwelling type due to the small sample size from which the volumetric proportion was estimated.

Table 4.24: Volumetric proportion of typical room types relative to the total dwelling volume.

Room type	Volumetric proportion relative to total dwelling volume (%)
living room	28
kitchen	11
circulation	15
bathroom	8
bedroom	38
* *source: Defra (2007)* [58]	

4.10. *Temperature Rise from Incidental Gains*

The internal heat generated in a dwelling is not all supplied by the space heating appliance. Useful heat is also generated from solar radiation, water heating and occupant activities such as cooking, lighting and metabolism all contributing to a sufficient temperature rise in a dwelling to maintain comfortable conditions without the aid of heating appliance when the external temperature is greater than 15.5 °C, a threshold temperature termed the base temperature, in the case of UK dwellings.

This form of temperature gain is termed the temperature rise from incidental gains (T_{gain}) and is estimated for each of the case study dwelling using BREDEM which takes into account the useful heat gains from solar radiation, water heating, cooking and metabolism. The usefulness of these gains is of course greater in winter and smaller in summer which BREDEM takes into account by applying a utilization factor [33]. The temperature rise from incidental gains are summarized in Table 4.25. The greater temperature rise in the insulated dwellings relative to the non-insulated dwellings is due to heat being retained longer in an insulated dwelling. In contrast, the difference between the non-central and the centrally heated dwellings is not significant.

Table 4.25: Mean *temperature rise from incidental gains* associated with different energy efficency measures (°C) (95%CI).

intervention									
NDP	*FDP*	*NI*	*FI*	*nonCH*	*CHonly*	*NI+ nonCH*	*FI+ CHonly*	*Pre-WF*	*Post-WF*
2.38 (2.26, 2.51)	2.54 (2.48, 2.59)	2.06 (1.93, 2.18)	2.98 (2.90, 3.05)	2.41 (2.33, 2.49)	2.71 (2.59, 2.83)	1.93 (1.72, 2.14	3.25 (3.02, 3.48)	2.24 (2.16, 2.32)	2.69 (2.59, 2.78)

4.11. *Energy Saving and Shortfall*

The results from the *Warm Front Energy Study* (Appendix 1) [1] have shown an increase in the energy consumption following upgrade which is not attributable to the internal temperature rise. The method of investigation used in the preliminary study involved normalizing the energy consumption to the internal temperature which meant that any change in the energy usage associated with temperature change, i.e. from the *comfort taking*, could not be determined.

One of the primary aims of this study is to build upon the findings from that preliminary study by examining how much of the difference between the theoretically expected and the actually observed energy saving is attributable to the *comfort taking* and the *loss*. The method used is illustrated in Figure 4.4 which essentially involves examining the change in the energy consumption or cost or carbon emissions (*monitored space heating energy consumption* (Q_{mon}) and *modelled space heating energy consumption* (Q_{mod})) before and after energy efficiency upgrade to the change in the *monitored standardized internal temperature* (T_{mon}).

The actual energy performance prior to the energy efficiency upgrade is described by the function as $Q_{mon.pre} = f(T_{mon.pre})$ in Figure 4.4. If the internal temperature were to rise, the energy consumption would be expected to increase linearly along this line described by this function. If the energy performance of a property is improved, then the gradient of the line is expected to reduce as shown by the function $Q_{mon.post}$ =

$f(T_{mon.post})$. Measures such as draught proofing and insulation which result in decreased fabric heat loss should also result in higher *temperature rise from incidental gains* thereby moving the intercept along the x-axis from the lower pre-intervention *temperature rise from incidental gains* ($T_{gain.pre}$) to a higher post-intervention *temperature rise from incidental gains* ($T_{gain.post}$) thereby resulting in shifting the line to a lower energy consumption range.

The level of improvement that in theory should have been achieved following energy efficiency upgrade is described by the change in the slope from the pre-intervention *modelled space heating energy consumption* function $Q_{mod.pre} = f(T_{mon.pre})$ to the post-intervention *modelled space heating energy consumption* function $Q_{mod.post} = f(T_{mon.post})$. The change in the modelled gradient is greater in order to reflect the greater saving that is theoretically expected.

Along with the linear functions, the mean values of the monitored (solid geometry) and the modelled (non-solid geometry) energy usage and internal temperature are plotted. The post-intervention hypothetical energy consumption level which assumes no *comfort taking* (dashed square) is estimated from the monitored post-intervention function $Q_{mon.post} = f(T_{mon.post})$ by substituting the monitored standardized internal temperature (T_{mon}) which takes into account temperature rise from improved heat loss performance but prior to the *comfort taking*. The post-intervention hypothetical energy consumption level is an important parameter against which the increase in energy consumption from the *comfort taking* is determined.

The relationship shown in Figure 4.4 is idealized in the sense that the functions describing the monitored and the modelled pre-intervention conditions, $Q_{mon.pre}$ and the $Q_{mod,pre}$, are shown as being perfectly aligned whereas in reality this is difficult to achieve because it requires the calibration of the BREDEM predicted pre-intervention condition to the monitored, a difficult task to carry out if in a sample size as large as in the *Warm Front Study*. This also dictates why the analyses in this study focus on the change in the energy consumption and the temperature. The definition of the parameters in Figure 4.4 is as follows:

$T_{gain.pre}$ Pre-intervention *temperature rise from incidental gains* (°C).

$T_{gain.post}$ Post-intervention *temperature rise from incidental gains* (°C).

$T_{mon.pre}$ Pre-intervention *monitored standardized internal temperature* (°C).

$T_{mon.post}$ Post-intervention *monitored standardized internal temperature* (°C).

$T'_{mon.post}$ Counterfactual post-intervention *standardized internal temperature* taking into account temperature rise from improved heat loss performance but not taking into account temperature rise from the *comfort taking*.

$Q_{mon.pre}$ Pre-intervention *monitored space heating energy consumption* (delivered energy, energy cost or carbon emissions).

$Q_{mod.pre}$ Pre-intervention *modelled space heating energy consumption* (delivered energy, energy cost or carbon emissions).

$Q_{mon.post}$ Post-intervention *monitored space heating energy consumption* (delivered energy, energy cost or carbon emissions).

$Q_{mod.post}$ Post-intervention *modelled space heating energy consumption* (delivered energy, energy cost or carbon emissions).

$Q'_{mon.post}$ Counterfactual post-intervention *monitored space heating energy consumption* (delivered energy, energy cost or carbon emissions) taking into account energy saving from improved heat loss performance but not taking into account increased consumption from the *comfort taking*.

$Q'_{mod.post}$ Post-intervention *modelled space heating energy consumption* (delivered energy, energy cost, carbon emissions) taking into account energy saving from improved heat loss performance but not taking into account increased consumption from the *comfort taking*.

□Q_{SVmon} *Monitored saving* (Eqn. 4.12).

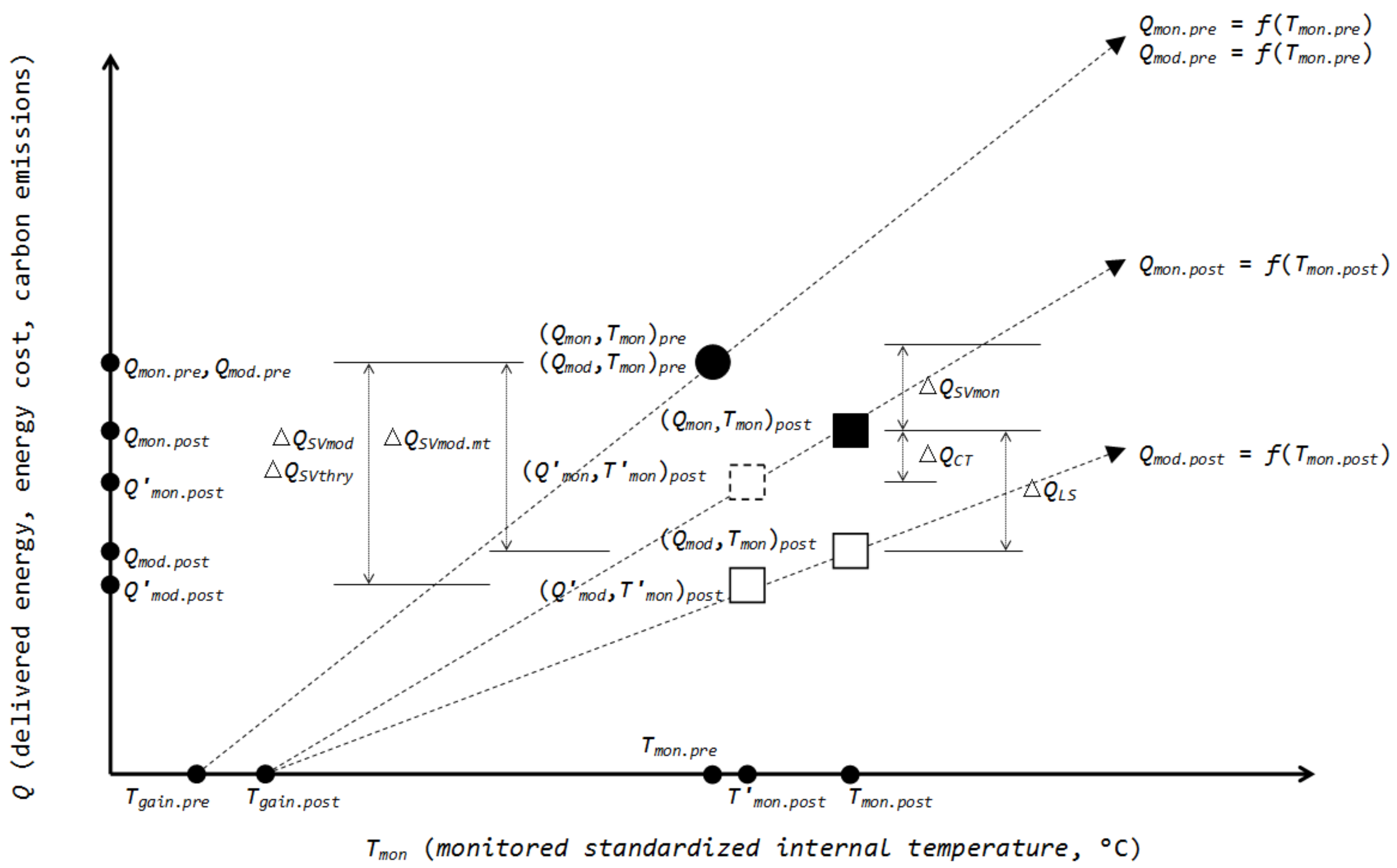
□Q_{SVmod} *Modelled saving* (under standard heating regime) (Eqn. 4.13).

□$Q_{SVmod.mt}$ *Modelled saving with monitored temperature* (Eqn. 4.14).

□Q_{CT} *Comfort taking* (Eqn. 4.18).

□Q_{LS} *Loss* (Eqn. 4.20).

Figure 4.4: Idealized diagram describing the impact of energy efficiency measure on energy consumption and internal temperature.



4.11.1. The Saving and the Saving Factor

The *saving* refers to the reduction in the space heating energy consumption (delivered energy, fuel cost, carbon emissions) following energy efficiency improvement. Four methods are used to determine the *saving*: the *monitored saving* (ΔQ_{SVmon}), the *modelled saving* (ΔQ_{SVmod}), the *modelled saving with monitored temperature* ($\Delta Q_{SVmod.mt}$) and the *theoretical saving* (ΔQ_{SVthry}) using Eqns. 4.12, 4.13, 4.14 and 4.15 respectively. The *monitored saving* (ΔQ_{SVmon}) refers to the saving in the *monitored space heating energy consumption* (Q_{mon}) (Section 4.5.2) following energy efficiency improvement; the *modelled saving* (ΔQ_{SVmod}) refers to the BREDEM predicted saving under standard heating regime (Section 4.5.1), the *modelled saving with monitored temperature* ($\Delta Q_{SVmod.mt}$) refers to the BREDEM predicted saving following the substitution of actual monitored temperature and the *theoretical saving* (ΔQ_{SVthry}) is determined as the sum of the *monitored saving* (ΔQ_{SVmon}), the *comfort taking* (ΔQ_{CT}) and the *loss* (ΔQ_{LS}), i.e. by combining the three components that make up the theoretically expected saving.

The reason for determining the two predicted savings, i.e. the *modelled saving* and the *theoretical saving*, is to examine how these two, which in theory ought to be the same as illustrated in the idealized diagram in Figure 4.4, actually compare. However, as the findings in Chapter 11 (Table 11.1 and Table 11.2) show there is a great difference between these two resulting in a large variation in the *shortfall* depending on the choice of the predicted saving.

The *saving factor* (*SVF*) is expressed in percentage and measures the actual saving in relation to the potential saving. A 100 % *saving factor* is therefore achieved if all of the potential saving is observed in actual condition. Two types of *saving factor* are determined depending how the potential saving are determined: the *modelled saving* *factor* (SVF_{mod}) is measured by relating the *monitored saving* (ΔQ_{SVmon}) to the *modelled saving* (ΔQ_{SVmod}) based on Eqn. 4.16 and the *theoretical saving factor* (SVF_{thry}) is measured by relating the *monitored saving* (ΔQ_{SVmon}) to the *theoretical saving* (ΔQ_{SVthry}) based on Eqn. 4.17.

$$\Delta Q_{SVmon} = Q_{mon.pre} - Q_{mon.post} \qquad \text{(Eqn. 4.12)}$$

$$\Delta Q_{SVmod} = Q_{mod.pre} - Q'_{mod.post} \qquad \text{(Eqn. 4.13)}$$

$$\Delta Q_{SVmod.mt} = Q_{mod.pre} - Q_{mod.post} \qquad \text{(Eqn. 4.14)}$$

$$\Delta Q_{SVthry} = \Delta Q_{SVmon} + \Delta Q_{CT} + \Delta Q_{LS} \qquad \text{(Eqn. 4.15)}$$

$$SVF_{mod} = (\Delta Q_{SVmon} / \Delta Q_{SVmod}) * 100 \qquad \text{(Eqn. 4.16)}$$

$$SVF_{thry} = (\Delta Q_{SVmon} / \Delta Q_{SVthry}) * 100 \qquad \text{(Eqn. 4.17)}$$

4.11.2. The Comfort Taking and the Comfort Taking Factor

The *comfort taking* (ΔQ_{CT}) is one of the two components, identified in this study, that contribute to the *shortfall* (ΔQ_{SF}) and refers to the increase in the *monitored space heating energy consumption* (Q_{mon}) (delivered energy, fuel cost, carbon emissions) from increased demand temperature following energy efficiency upgrade. The *comfort taking* is determined as the difference between the post-intervention *monitored space heating energy consumption* ($Q_{mon.post}$) and a hypothetical pre-*comfort taking* space heating energy consumption ($Q'_{mon.post}$) as shown in Eqn. 4.18. The *comfort taking factor* (*CTF*) is measured in percentage and quantifies the *comfort taking* (ΔQ_{CT}) relative to the *theoretical saving* (ΔQ_{SVthry}) and is determined by Eqn. 4.19.

$$\Delta Q_{CT} = Q_{mon.post} - Q'_{mon.post} \qquad \text{(Eqn. 4.18)}$$

$$CTF = (\Delta Q_{CT} / \Delta Q_{SVthry}) * 100 \qquad \text{(Eqn. 4.19)}$$

The hypothetical pre-*comfort taking* space heating energy consumption, $Q'_{mon.post}$, is determined by solving the relationship $Q_{mon.post} = f(T_{mon.post})$ for the temperature $T'_{mon.post}$, a level prior to the *comfort taking* but taking into account the temperature rise from improved fabric heat loss performance associated with insulation and air tightening measures.

4.11.3. The Loss and the Loss Factor

Along with the *comfort taking* (ΔQ_{CT}), the *loss* (ΔQ_{LS}) is the other component identified in this study that contributes to the *shortfall* (ΔQ_{SF}) and describes the difference between the *monitored* and the *modelled space heating energy consumption* which is attributable to factors other than the *comfort taking*. The *loss* is shown as the difference between $Q_{mon\ post}$ and $Q_{mod\ post}$ in Fig. 4.4 which can then be expressed as the difference between the *monitored saving* (ΔQ_{SVmon}) (Eqn. 4.12) and the *modelled saving with monitored temperature* ($\Delta Q_{SVmod.mt}$) (Eqn. 4.14) as shown in Eqn. 4.20. The *loss* can also be determined as the difference between $Q'_{mon\ post}$ and $Q'_{mod\ post}$ if the former parameter is known. The *loss factor* (*LSF*) is measured in percentage and measures the *loss* (ΔQ_{LS}) relative to the *theoretical saving* (ΔQ_{SVthry}) and is determined by Eqn. 4.21.

$$\Delta Q_{LS} = \Delta Q_{SVmod.mt} - \Delta Q_{SVmon} \qquad \text{(Eqn. 4.20)}$$

$$LSF = (\Delta Q_{LS}\ /\Delta Q_{SVthry}) * 100 \qquad \text{(Eqn. 4.21)}$$

4.11.4. The Shortfall and the Shortfall Factor

The *shortfall* (ΔQ_{SF}) refers to the unrealized potential saving in the space heating energy consumption (delivered energy, fuel cost, carbon emissions) following energy efficiency improvement. Two types of *shortfall* are determined: the *modelled shortfall* (ΔQ_{SFmod}) and the *theoretical shortfall* (ΔQ_{SFthry}) using Eqns. 4.22 and 4.23 respectively.

Although in theory, the two methods should result in the same *shortfall*, this is not likely to be the case if there is a difference between the *modelled saving* (ΔQ_{SVmod}) (Eqn. 4.13) and the *theoretical saving* (ΔQ_{SVthry}) (Eqn. 4.15) against which the *modelled shortfall* and the *theoretical shortfall* are measured against.

The *theoretical shortfall* (ΔQ_{SFthry}) is determined using Eqn. 4.23 as the sum of the *comfort taking* (ΔQ_{CT}) and the *loss* (ΔQ_{LS}), the two components contributing to the difference between the model predicted and the actual energy saving.

The *shortfall factor* (*SFF*) is expressed in percentage and measures the *shortfall* in relation to the potential saving. Two types of *shortfall factor* are determined depending on how the potential saving are determined: the *modelled shortfall factor* (SFF_{mod}) is measured by relating the *modelled shortfall* to the *modelled saving* (ΔQ_{SVmod}) as shown in Eqn. 4.24 and the *theoretical shortfall factor* (SFF_{thry}) is measured by relating the *theoretical shortfall* to the *theoretical saving* (ΔQ_{SVthry}) based on Eqn. 4.25.

$$\Delta Q_{SFmod} = \Delta Q_{SVmod} - vQ_{SVmon} \quad \text{(Eqn. 4.22)}$$

$$\Delta Q_{SFthry} = \Delta Q_{CT} + \Delta Q_{LS} \quad \text{(Eqn. 4.23)}$$

$$SFF_{mod} = (\Delta Q_{SFmod} / \Delta Q_{SVmod}) * 100 \quad \text{(Eqn. 4.24)}$$

$$SFF_{thry} = (\Delta Q_{SFthry} / \Delta Q_{SVthry}) * 100 \quad \text{(Eqn. 4.25)}$$

CHAPTER 5 CHARACTERISTICS OF THE CASE STUDY DWELLINGS

The *Warm Front Scheme* grant eligibility criteria means that the case study households are receiving some type of means tested benefit, living in a dwelling that is privately owned or rented and having a household member in the vulnerable age group either below 16 (u16) or 60 or above (o60).

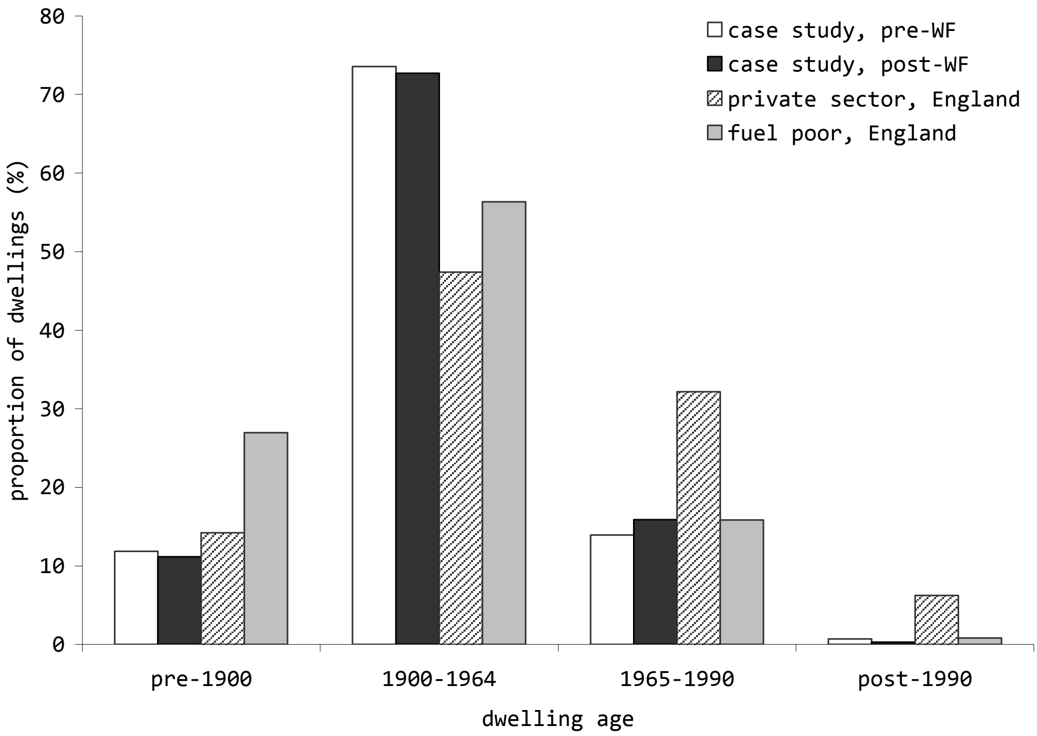
This chapter examines a number of representative property and household characteristics of the case study dwellings in relation to the average private sector English dwellings and the average private sector English dwellings classified as being in fuel poverty. The aim of this analysis is to explore how representative the case study dwellings are of the national fuel poor. The property and the household characteristics selected for the comparisons are dwelling age, dwelling type, floor area, energy efficiency, insulation, central heating, household size, household type, income and ratio of energy cost to income. These variables were selected under the basis that they were found to be statistically significant ($p <= 0.05$) indicators of dwelling energy performance [1]. The data for the national sample is based on the 2001 English House Condition Survey [18] (rather than the more recent 2003 to 2007 EHCS data) due to a greater compatibility with the *Warm Front Data* collected in winters of 2001 to 2002.

Seven property related characteristics are compared in Sections 5.1 to 5.7, dwelling age, dwelling type, floor area per person, energy efficiency, ownership of cavity wall insulation, ownership of loft insulation and ownership of central heating system; four household characteristics are compared in Sections 5.8 to 5.11, household size, householder type, income and fuel poverty; Section 5.12 summarizes the findings.

5.1. Dwelling Age

The dwelling age (excluding dwelling extension) is compared in Figure 5.1. The case study dwellings are of older stock with 85 % pre-dating 1965 compared to 62 % in England. Little difference in the dwelling age distribution is found between the *pre*- and *post-WF* dwellings. The proportion of the English fuel poor dwellings pre-dating 1965 make up 83 % which is similar to the case study condition, but more of the fuel poor are of the older stock with 27 % pre-1900 compared to only 12 % among the case study. When the case study dwellings are disaggregated by the household age group, u16 and o60 (not shown), 89 % of the o60 pre-dated 1965 compared to 81 % in the u16 group.

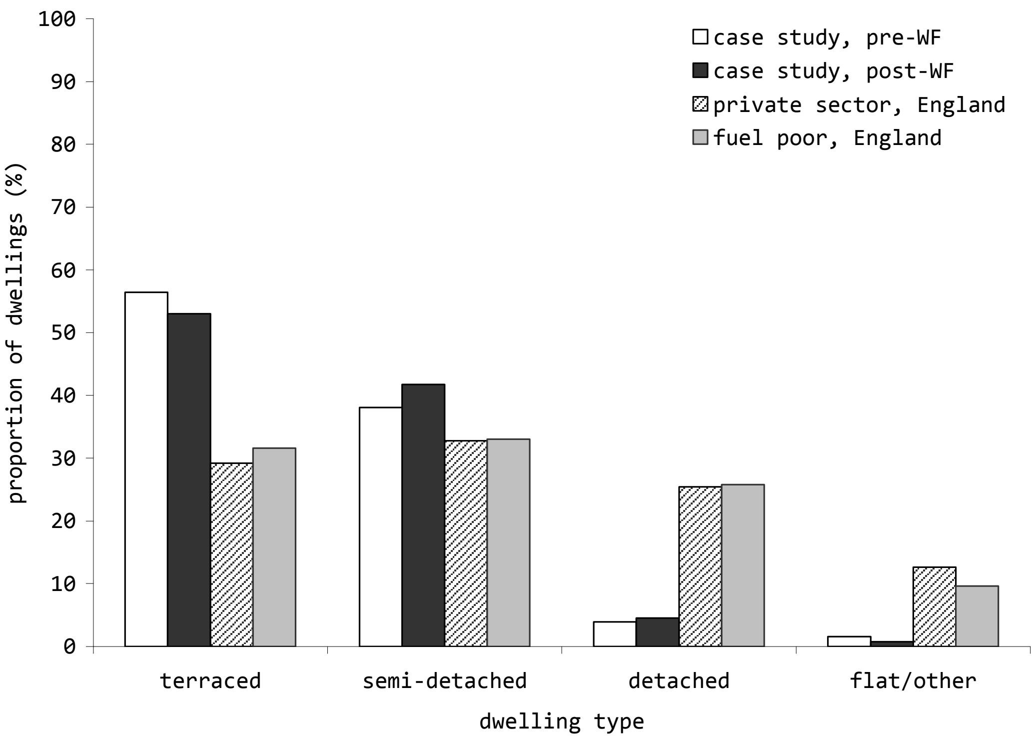
Figure 5.1: Case study dwelling age compared to the private sector and the fuel poor.



5.2. Dwelling Type

The dwelling type is compared in Figure 5.2. The dwelling type is grouped as terraced, semi-detached, detached and flat/other. Terraced dwellings make up the largest group in the case study dwellings at 52 % compared to 29 % in the private sector and 32 % in the fuel poor. Detached dwellings, on the other hand, make up only 4 % in the case study dwellings compared to 25 % in the private sector and 26 % in the fuel poor. Likewise, flats and other types are also under-represented at 7 % among the case study dwellings compared to 13 % in the private sector and 10 % in the fuel poor. Little difference in the dwelling type distribution is found between the *pre*- and *post-WF* dwellings.

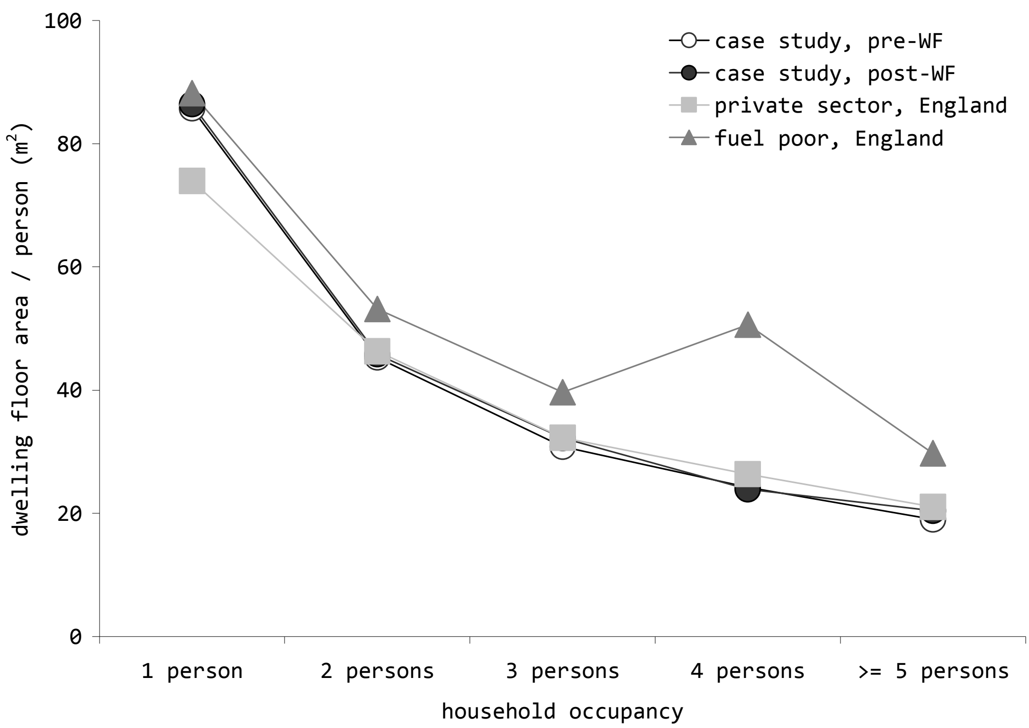
Figure 5.2: Case study dwelling type compared to the private sector and the fuel poor.



5.3. Floor Area Per Person

The mean dwelling floor area per person is compared in relation to the number of household members in Figure 5.3. The distribution of the case study dwellings was found to closely match the English private sector except for the single occupancy which is similar to the fuel poor. Since only the o60 households consisted of single occupancy among the case study dwellings, the dwelling size of the o60 group can be considered to be in close agreement to the fuel poor. The mean floor area per person in fuel poverty was found to be the highest at 70.7 m^2 (SD 49.3 m^2) followed by the case study at 51.6 m^2 (SD 29.5 m^2) followed by the private sector at 45.6 m^2 (SD 31.2 m^2). The distribution shows little difference in the floor area per person between the *pre*- and *post-WF* dwellings with *pre-WF* mean floor area of 50.4 m^2 and *post-WF* mean floor area of 53.2 m^2 respectively.

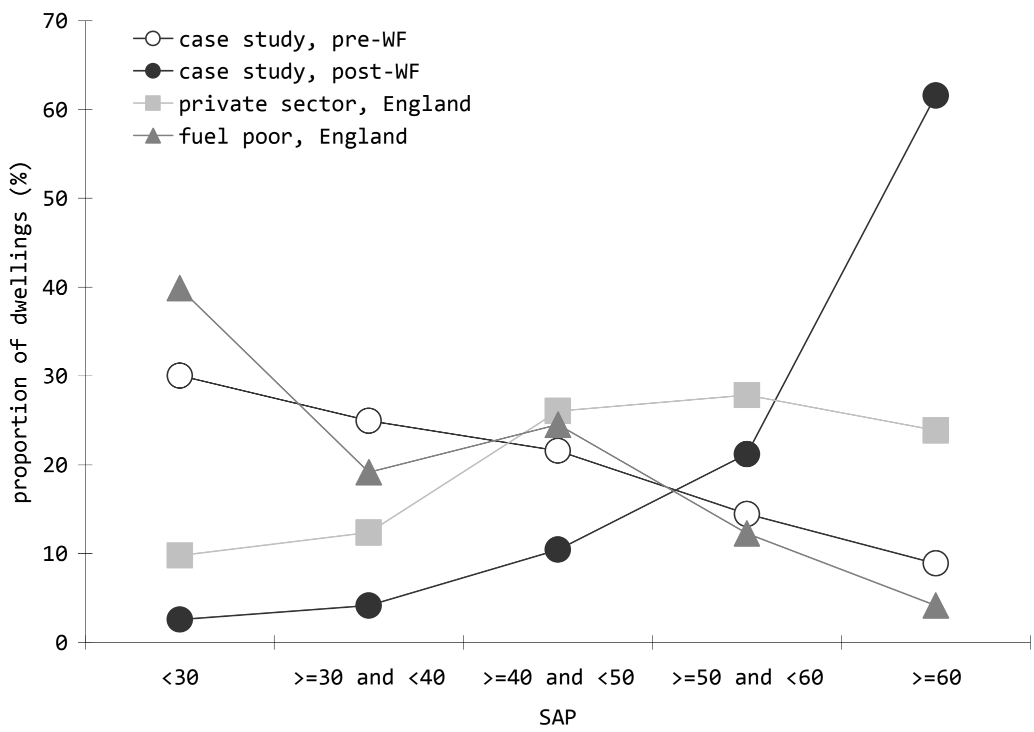
Figure 5.3: Case study dwelling floor area per person compared to the private sector and the fuel poor



5.4. Energy Efficiency

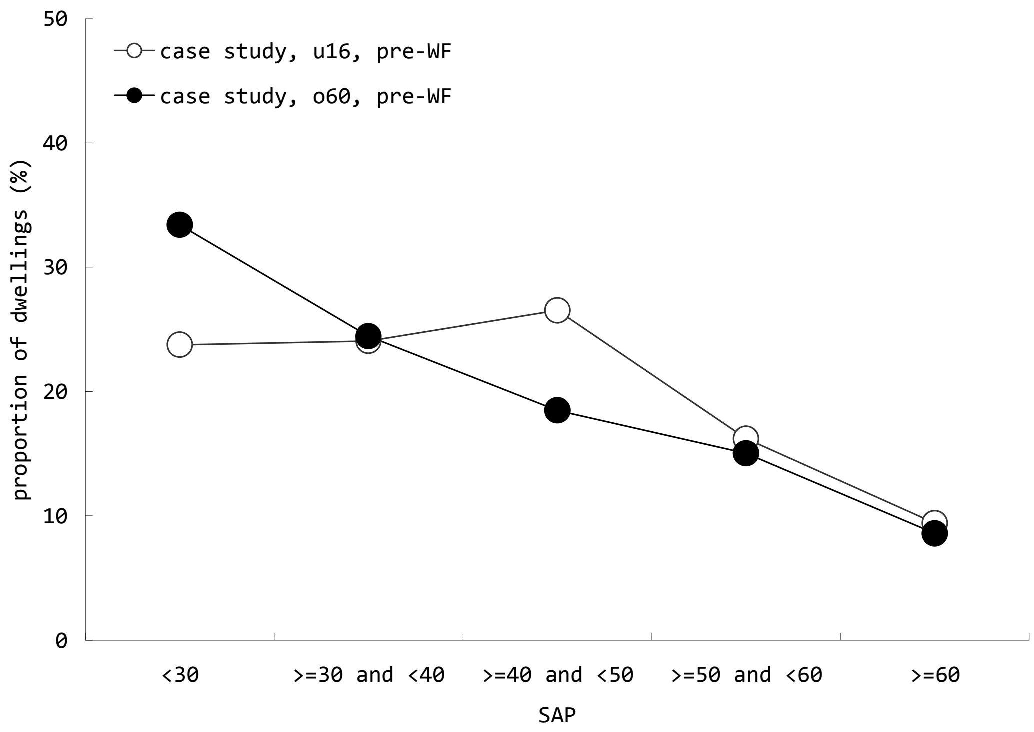
The dwelling energy efficiency is compared in Figure 5.4. Energy efficiency is measured in SAP (Standard Assessment Procedure, v. 2001) which is the UK Government's standard domestic energy performance rating system scored based on a logarithmic scale ranging from 1 (poor) to 120 (excellent) and calculated on the basis of energy cost for space and water heating normalized for floor area. A comparison between the *pre*- and the *post-WF* distribution shows the *pre-WF* clustered in the lower region and the *post-WF* in the higher region. The *pre*-WF distribution is found to be similar to the fuel poor whereas in the case of *post-WF* the proportion of case study dwellings with SAP above 60 increased to 62 % which is well above the private sector average of 24 %. The mean SAP value of the fuel poor was the lowest at 32.4 (SD 19.1) followed by *pre-WF* at 37.6 (SD 16.6) followed by the private sector at 49.3 (SD 15.6) followed by *post-WF* at 63.0 (SD 14.4).

Figure 5.4: Case study dwelling SAP compared to the private sector and the fuel poor



The *pre-WF* case study dwellings are disaggregated into the u16 and o60 households in Figure 5.5. The distribution shows a greater proportion of the o60 households below SAP 30 at 33 % compared to 24 % in the u16 households. The mean SAP rating of the *pre-WF* o60 households was slightly lower at 36.9 (SD 16.6) compared to 39.4 (SD 16.3) for the u16 households.

Figure 5.5: *Pre-WF* case study dwelling SAP compared between the two hosehold age groups

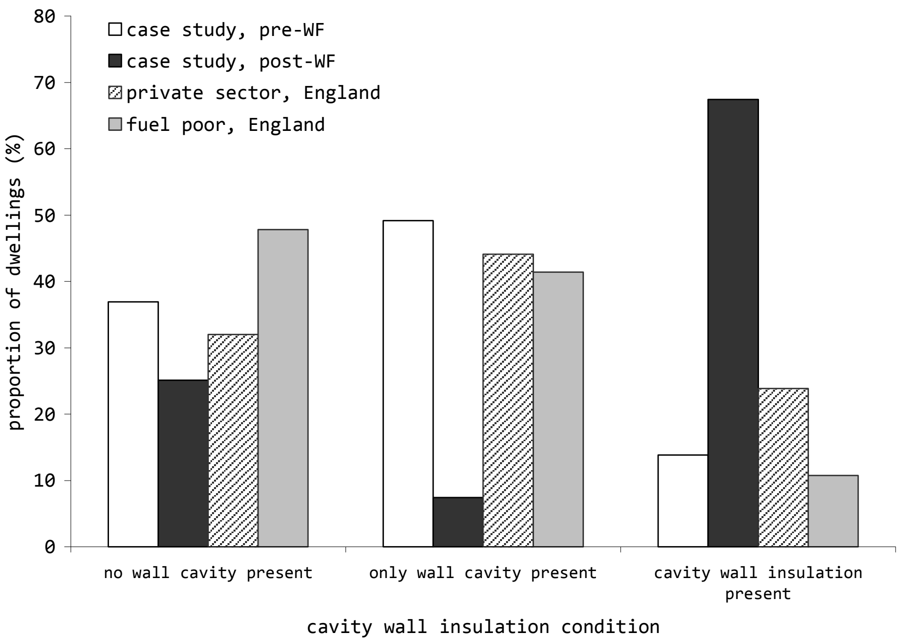


5.5. Cavity Wall Insulation

Figure 5.6 compares the ownership of cavity wall insulation. 86 % of the *pre-WF* case study dwellings (no wall cavity present + only wall cavity present) were found to have no wall insulation which is similar to 89 % in the fuel poor and higher than 76 % in the private sector. The higher proportion of solid-walled dwellings in the *pre-WF* at 37 % and the fuel poor at 48 % compared to the private sector at 32 % partly explains the lower ownership of wall insulation.

68 % of the *post-WF* dwellings were found to own cavity wall insulation, a level much higher than the private sector at 24 % and the fuel poor at 11 %. However, 33 % of the *post-WF* dwellings were still missing in insulation mainly due to solid walled dwellings making up 25 % of the *post-WF* group. When excluding the solid walled dwellings, the ownership of cavity wall insulation in the *post-WF* group was found to be 90 %.

Figure 5.6: Case study dwelling ownership of cavity wall insulation compared to the private sector and the fuel poor.

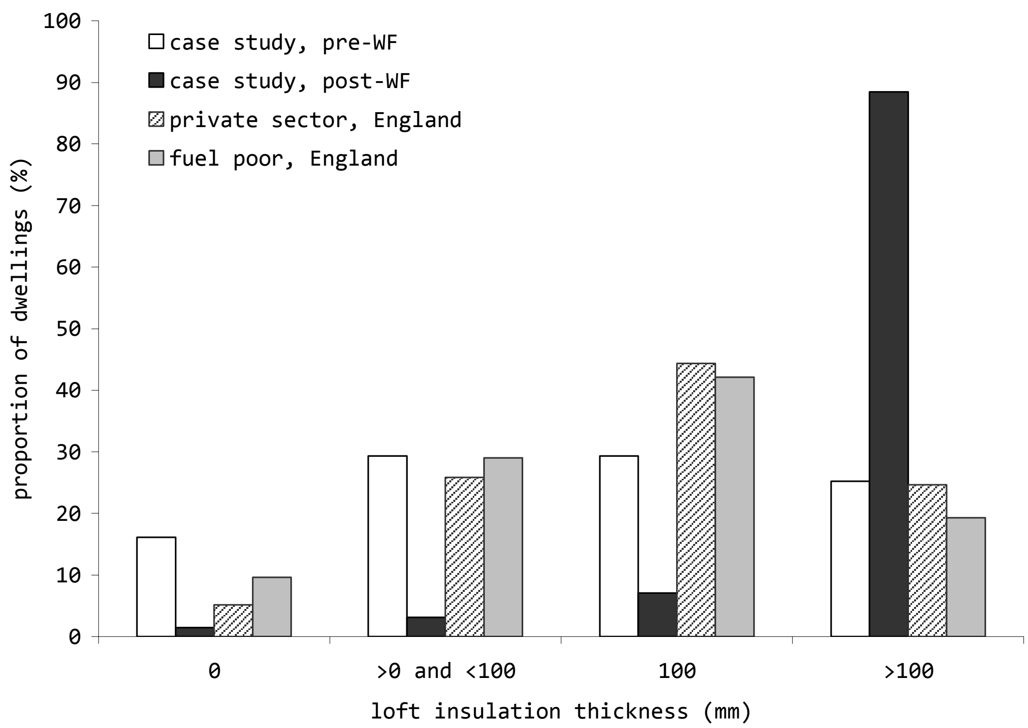


5.6. Loft Insulation

Figure 5.7 compares the ownership of loft insulation. Dwellings with unknown insulation thickness (165 dwellings) are classified as having no loft insulation while all dwellings without loft space are excluded. The *Warm Front Scheme* aims to increase the loft insulation thickness to a level higher than 100 mm.

The ownership of loft insulation thickness greater than 100 mm was 25 % in *pre-WF* which is similar to the private sector but higher than the fuel poor at 19 %. On the other hand, the proportion of *pre-WF* dwellings without loft insulation was the highest at 16 % compared to 5 % in the private sector and 10 % in the fuel poor, but this may be due to unknown cases having been classified as having no loft insulation in this comparison. The ownership of loft insulation greater than 100mm was found to be the greatest in the post-WF group at 89 %.

Figure 5.7: Case study dwelling ownership of loft insulation compared to the private sector and the fuel poor.



5.7. Central Heating

Figure 5.8 compares the ownership of central heating system. 57 % of the *pre-WF* u16 households owned central heating compared to 31 % in the o60 group both of which are lower than the 66 % found with the fuel poor. In *post-WF,* the central heating ownership was 95 % in the o60 group which is even greater than 87 % in the private sector. Central heating in the *post-WF* u16 households was also found to be high at 84 %.

Figure 5.8: Case study dwelling ownership of central heating compared to the private sector and the fuel poor.

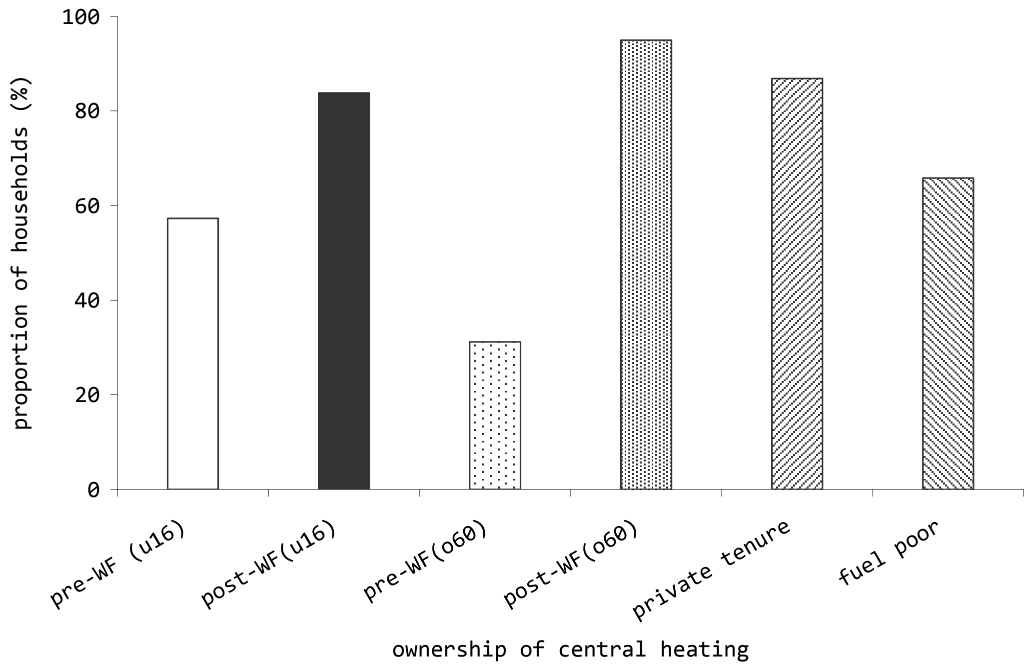


Table 5.1 examines the impact of the *Warm Front Scheme* on the central heating boilers efficiency among the centrally heated case study dwellings. The boilers are grouped as condensing, combination, normal and back boilers broadly reflecting the SEDBUK fuel conversion efficiencies with the condensing boilers representing the most efficient (80 % ~ 85 %) followed by the combination boilers (70 % ~ 75 %) followed by

the normal boilers (60 % ~ 65 %) followed by the back boilers which are likely to be the least efficient due to old age (μ: <60 %).

Table 5.1 shows that the ownership of condensing boilers was higher at 36 % post-WF compared to 14 % pre-WF. The ownership of combination boilers was also higher at 38 % post-WF compared to 32 % pre-WF. In contrast, the ownership of normal boilers was less at 19 % post-WF compared to 41 % pre-WF and back boilers at 8 % post-WF compared to 14 % pre-WF.

This difference is more pronounced in the o60 group with 46 % *post-WF* o60 group owning condensing boilers, 40 % combination boilers while the ownership of normal boilers was much lower at 9 % and back boilers 5 %. The greater proportion of condensing and combination boilers found in the post-WF o60 dwellings in Table 5.1 compared to the u16 dwellings could partly by attributed to the effect of the *Warm Front Scheme* which provides grants for central heating only to o60 households.

Although not shown in the table, the ownership of condensing boilers among the centrally heated *pre-WF* case study dwellings is found to be greater than the centrally heated English private sector with only 2 % owning condensing boilers [15]. The comparison in Table 5.1 depend heavily on the cross-sectional sample and therefore may not provide an accurate assessment of the impact of the *Warm Front scheme*.

Table 5.1: A comparison of ownership of central heating boiler.

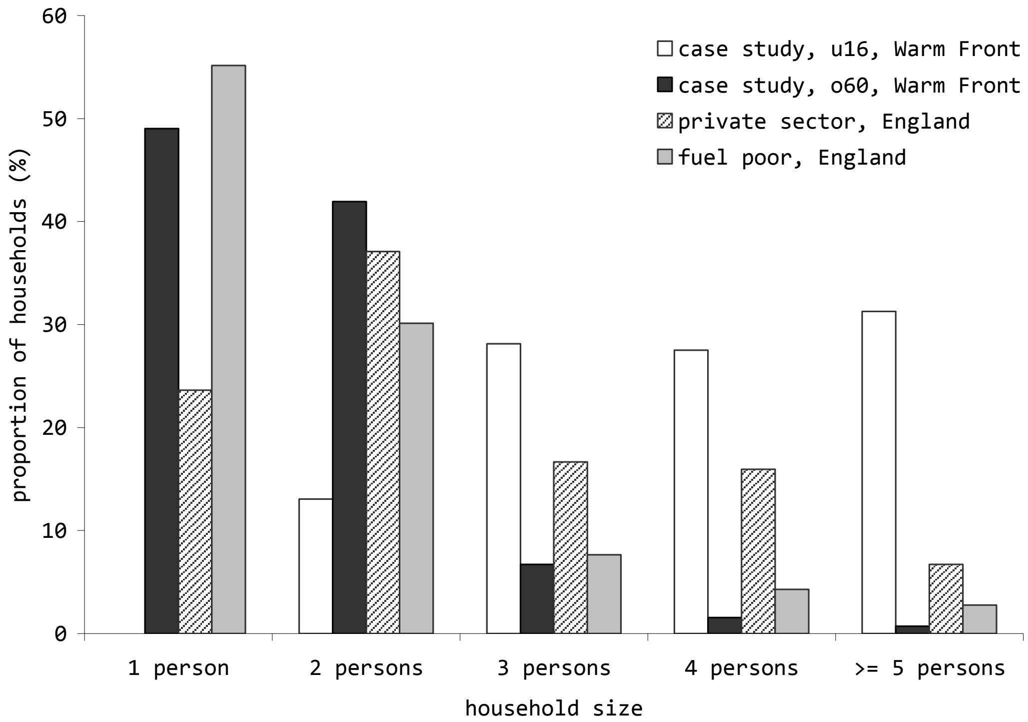
household group	WF status	gas cndns [#] (% total w/ ch)	gas combi. (% total w/ ch)	gas normal (% total w/ ch)	gas back (% total w/ ch)
u16	*pre-WF* (336)	9.8	30.4	43.5	16.7
	post-WF (338)	15.7	34.0	36.4	13.9
o60	*pre-WF* (222)	19.4	34.2	36.0	10.4
	post-WF (616)	46.4	40.3	8.8	4.5
total	*pre-WF* (558)	13.6	31.9	40.5	14.0
	post-WF (954)	35.5	38.1	18.6	7.9

[#] includes condensing combi boilers

5.8. Household Size

The household size is compared in Figure 5.9. Single occupancy households dominate the English fuel poor at 55 % followed by the case study o60 at 49 %. These figures show great difference to the average English private sector with only 24 % making up single occupancy household. The household size in the u16 households shows marked difference from the rest with 87 % having three or larger occupancy compared to only 9 % in the o60 households, 15 % in the fuel poor and 39 % in the private sector. Similarity is observed in the distribution pattern between the o60 and the fuel poor with one to two person households dominating both groups followed by a sharp drop in the larger households. Little difference was found in the household size distribution between the *pre*- and the *post-WF* dwellings (not shown) with single and double occupancy constituting about 31 % *pre-WF* and 34 % *post-WF* and for larger households showing negligible difference.

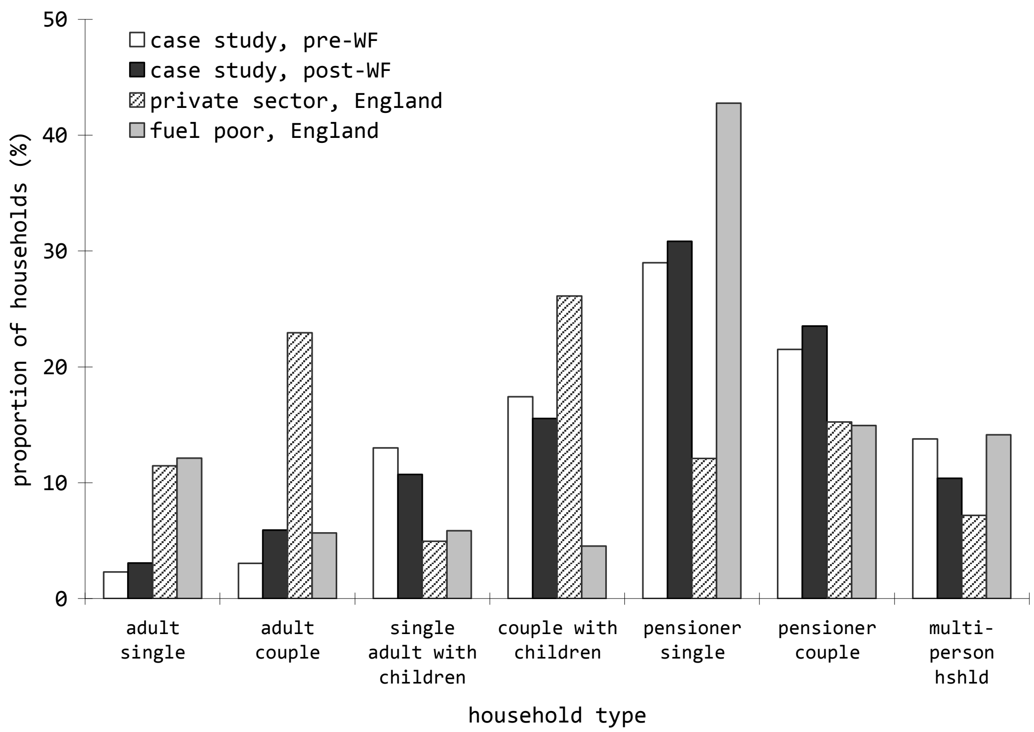
Figure 5.9: Case study household size compared to the private sector and the fuel poor.


60
50
40
30
20
10
0
proportion of households (%)
case study, u16, Warm Front
case study, o60, Warm Front
private sector, England
fuel poor, England
1 person
2 persons
3 persons
4 persons
>= 5 persons
household size

5.9. Household Type

The household type is compared in Figure 5.10. Single pensioner households make up the largest group among the English fuel poor and the case study dwellings at 43 % and 30 % respectively. In contrast, the single pensioner group constitutes only 12 % of the English private sector which is predominantly adult couple with or without children. Compared to the fuel poor, the case study dwellings was found to have a higher representation of single adult with children (case study: 12 %, fuel poor: 6 %), couple with children (case study: 17 %, fuel poor: 5 %) and pensioner couple (case study: 23 %, fuel poor: 15 %) while lower representation of non-pensioner single adult (case study: 3 %, fuel poor: 12 %) and single pensioner as observed above. Little difference is found in the distribution between the *pre*- and the *post-WF* dwellings.

Figure 5.10: Case study household type compared to the private sector and the fuel poor.

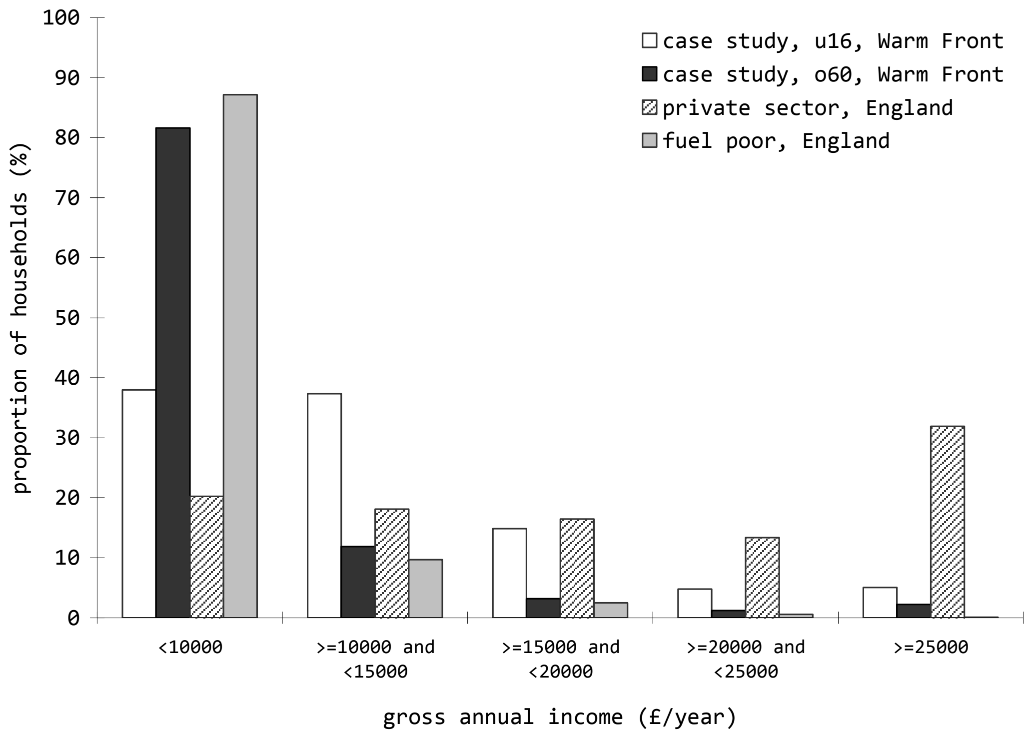


5.10. Income

The gross household annual income (incl. housing & council tax benefits, saving & investments investments and income support from all household members) is compared in

Figure 5.11. The income data was collected by requesting the householders to select an income range listed on a chart during the household interview (Section 3.4.2). The income distribution between the English fuel poor and the o60 households are found to be similar with the highest proportion earning below £10,000 (o60: 82 %, fuel poor: 87 %) and falling sharply in the higher income range. Comparatively lower proportion of the u16 households are found below the £10,000 range at 38 % but the majority fell below the £15,000 range at 75 %. A large proportion of the English private sector earned more than £25,000 at 32 % compared to only 5 % in the u16, 2 % in the o60 and none in the fuel poor. The mean income was the highest in the private sector at £19,906 (SD £22,923) followed by the u16 at £13,064 (SD £10,512) followed by the o60 at £8,171 (SD £5,438) followed by the fuel poor at £6,906 (SD £2,897). Little difference was found in the income distribution between the *pre*- and the *post-WF* dwellings (not shown).

Figure 5.11: Case study household gross annual income compared to the private sector and the fuel poor



5.11. Ratio of Energy Expenditure to Income

By definition, a household is classified as being fuel poor if, in order to maintain a satisfactory heating regime, the household is required to spend more than 10 % of its income on household fuel use. Determining Fuel Poverty 2001 [70] requires the knowledge of annual household net income – after deductions for tax and national insurance – , annual fuel costs – for space heating, water heating, lighting, cooking and appliances – and heating regime.

In the *Warm Front Study*, the fuel cost was determined using the domestic energy modeling software NHER Plan Assessor which is based upon BREDEM-12, the fuel cost model of choice in Fuel Poverty 2001 [70]. When determining the fuel cost, standard heating was assumed for all u16 households while all day heating (all dwelling or half dwelling depending on the dwelling floor area and the number of occupants) was assumed for all o60 dwellings [71]. On the other hand, only the gross household income data was collected in the *Warm Front Study* and therefore the net income data required for the determination of Fuel Poverty 2001 unavailable.

Figure 5.12 compares the ratio of energy expenditure to gross household income of the *Warm Front* dwellings to the ratio of energy expenditure to 'full' household income, i.e. measure of Fuel Poverty 2001, of the English dwellings from the EHCS 2001 database. Although the figure is not comparing like with like due to the difference in the income data, it is still hoped to provide some crude understanding of the level of fuel poverty among the Warm Front dwellings. Since, the *Warm Front Data* uses gross income, the actual level of fuel poverty among the Warm Front dwellings is likely to be greater than what the figures indicate.

Figure 5.12 suggests that about 30 % of the *pre-WF* dwellings are found to be in fuel poverty suggesting the scheme's limited effectiveness in targeting the fuel poor households. The lower proportion of *post-WF* households in fuel poverty at 13 % accompanied by a lower mean energy cost to gross income ratio of 7.2 % (SD 11.5 %) *post-WF* compared to 9.0 % (SD 7.5 %) *pre-WF* suggests *Warm Front Scheme* could be having an impact in reducing fuel poverty.

The *pre-WF* case study dwellings are disaggregated into the u16 and o60 households in Figure 5.13. The distribution shows a greater proportion of the o60 households in fuel poverty at 38 % compared to 18 % in u16. The mean energy cost to income ratio for the o60 households was also higher at 10.3 % (SD 8.7 %), just on the borderline of fuel poverty, and 6.9 % (SD 4.1 %) for the u16 households.

Figure 5.12: Case study household fuel cost to gross income ratio compared to the private sector and the fuel poor.

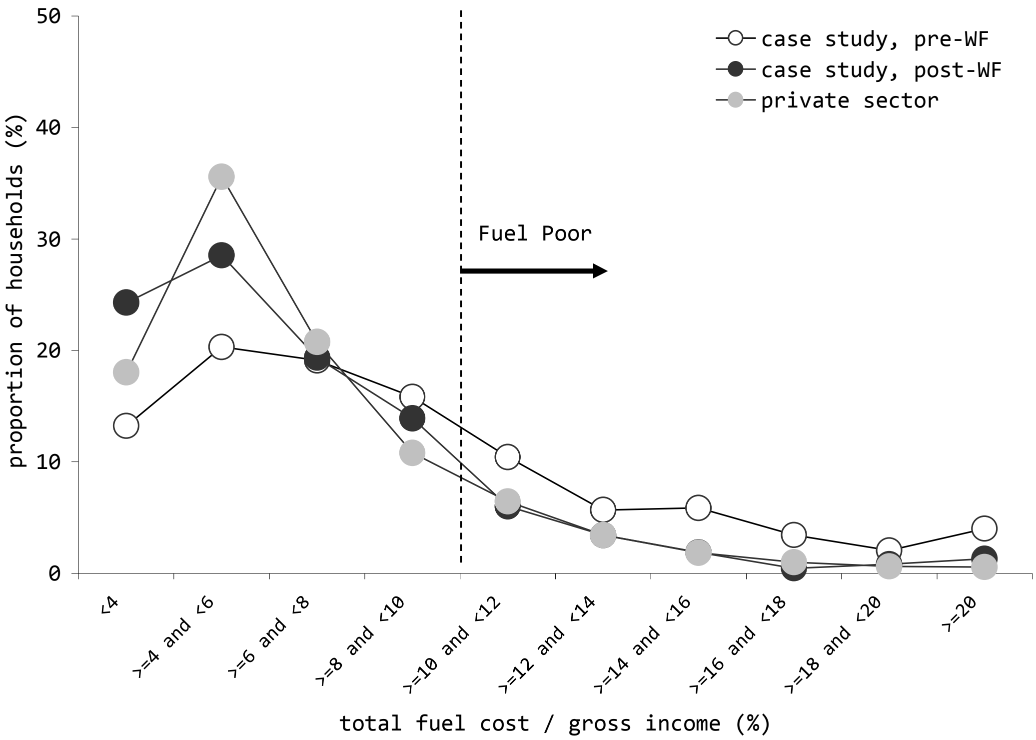
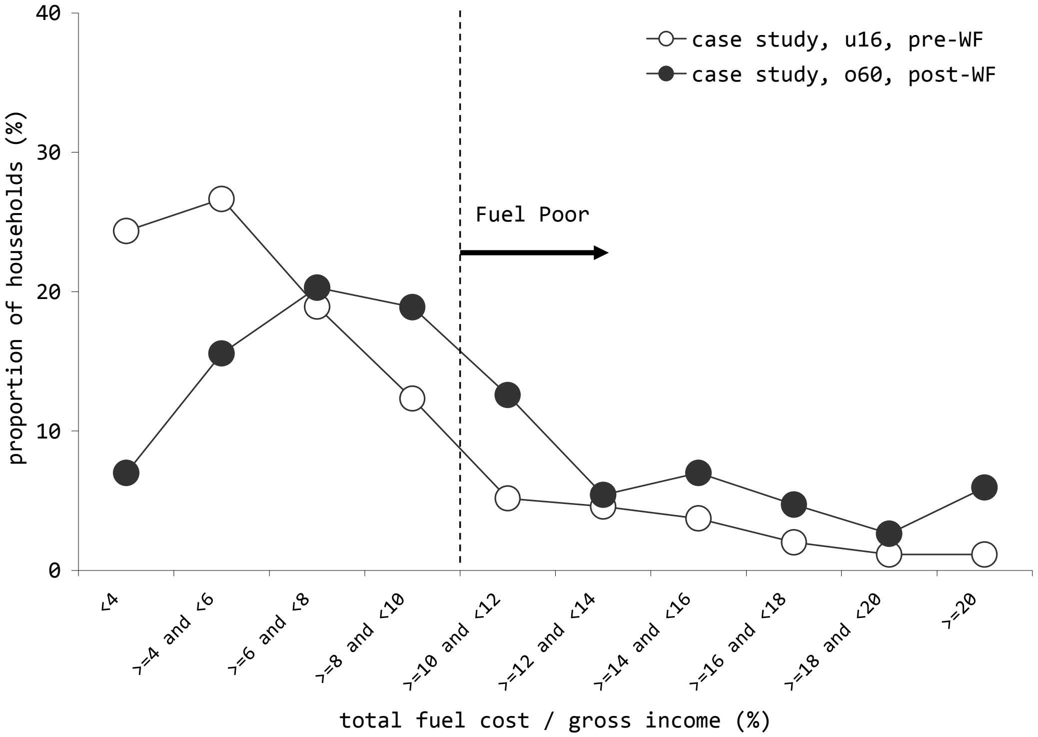


Figure 5.13:Case study u16 and o60 househol energy cost to income ratio compared.



40
30
20
10
0
proportion of households (%)
case study, u16, pre-WF
case study, o60, post-WF
Fuel Poor
<4
>=4 and <6
>=6 and <8
>=8 and <10
>=10 and <12
>=12 and <14
>=14 and <16
>=16 and <18
>=18 and <20
>=20
total fuel cost / gross income (%)

5.12. Discussion

The *Warm Front Scheme* is England's key policy designed to eliminate fuel poverty among the vulnerable households. However, the analysis in this chapter suggests that about 30 % of the *pre-WF* case study dwellings were in fuel poverty which in theory should be greater and be nearer 100 % if the scheme is well targeted. This may partly explain why many of the characteristics of the case study sample compared in this chapter differed from those of the fuel poor although there was more resemblance to the fuel poor than the national private sector.

One of the main reasons behind the *shortfall* in the proportion of the case study dwellings in fuel poverty is due to the scheme's failure to effectively target the fuel poor as pointed out in studies by the National Audit Office and Eaga Partnership Charitable. Their findings indicate factors such as the scheme's reliance on means tested benefit as fuel poor indicator, targeting criteria specific to particular household age groups and the exclusion of dwelling energy efficiency – a key indicator of fuel poverty – resulting in less than one fifth of the *Warm Front* grant recipients up to 2004 classifying as being fuel poor [31, 32].

Another reason behind the small proportion of the fuel poor households found in the case study group can be attributed to the sampling methodology used in the *Warm Front Study* which drew a balanced number of *Warm Front* and the *Warm Front Plus* schemes eligible households (Figure 3.2). This is evident in Table 5.2 which shows the young households (u16) being disproportionately represented in the case study sample at 42 % which is greater than the 36 % found with the national *Warm Front* sample [32] and much greater than the 10 % found with the national fuel poor thereby further skewing the sample to the group less likely to be in fuel poverty [18].

Table 5.2: Comparison of representative household and dwelling characteristics of the case study dwellings in relation to England's *Warm Front* national sample and fuel poor.

parameters	case study	*Warm Front* *	fuel poor †
% household income < £10,000	67 (u16: 38, o60: 82) [2]	-	87
% dwellings SAP < 30	30 (u16: 24, o60: 33) [1,3]	21	40
% in fuel poverty	32 (u16: 18, o60: 38) [1,3]	18	100
% u16 households	42 [1]	36	10
% o60 households	58 [1]	23	60

** Source: Sefton (2004) [32]*
† Source: EHCS 2001 [18]
[1] based on number property surveyed dwellings
[2] based on number of household surveyed dwellings
[3] pre-WF

This is evident when the case study dwellings are disaggregated into the two age groups of u16 and o60. Only 18 % of the u16 households are found to be in fuel poverty while the proportion is greater at 38 % for the o60 households explaining why some of the characteristics such as the SAP distribution, the floor are per person, the household size and the income distribution (Figure 5.5, 5.9, 5.11) of this group found better agreement with the fuel poor.

On the other hand, one of the benefits gained from the 'skewed' sampling of the *Warm Front Study* is that the proportion of the o60 households constituted 58 % of the case study dwellings which is similar to 60 % found in the national fuel poor and therefore showing a more realistic representation compared to only 23 % found in the national *Warm Front* sample.

Accordingly, the over-representation by the u16 households in the case study group means that there is a large range of households in fuel poverty that are left out from the *Warm Front Study* for not meeting the scheme's age criteria. As a result, the characteristics of the case study dwellings are sufficiently different from those of the fuel poor. Furthermore, the findings from this study may also not accurately reflect the impact of the *Warm Front Scheme* at the national level because of the greater representation of the younger households in the case study group.

No significant difference was found between the *pre*- and the *post-WF* dwellings in relation to the household and most of the property related variables strongly suggesting that there is little difference in the characteristic of the sample between the two groups. On the other hand, distinct differences were found between the two groups for variables which measure building energy performance such as SAP (Section 5.4), ownership of cavity wall insulation (Section 5.5), ownership of loft insulation (Section 5.6) and the ownership of central heating (Section 5.7) reflecting the impact of the *Warm Front* scheme.

No detailed study was undertaken as to why 10 % of the *post-WF* (cavity walled) dwellings were still without wall insulation and similarly 11 % with no full loft insulation. One likely explanation is survey error, but anecdotal evidence also indicated some householders may have refused wall insulation due to concern over possible moisture penetration. Inadequacy of the cavity space may also be a contributing factor as one householder was told by an installer.

CHAPTER 6 FACTORS CONTRIBUTING TO THE *SHORTFALL*

This chapter introduces three potential factors that have been identified in this study that can contribute to the *shortfall* in the energy saving. The simplified assumptions upon which theoretical air leakage rate is estimated is identified as one possible source in Section 6.1; the limitations associated with retrofit insulation measures is examined in Section 6.2; the occupancy behavior resulting in inefficient use of the heating system is examined in Section 6.3 and the impact of energy efficiency measures on the heating regime is examined in Section 6.4. The effect of adjusting for these elements on the *shortfall* and the *shortfall factor* will be examined in Chapters 11 and 12 respectively.

6.1. Monitored Air Leakage Rate

212 case study dwellings were blower doors tested to measure the actual *blower-door tested air leakage rate*. Using this data, the *monitored air leakage rates* were determined for the rest of the case study dwellings (n = 2896) from which no actual air leakage rate data was available using an algorithm (Eqn. 4.1) developed from the *blower-door tested air leakage rate*.

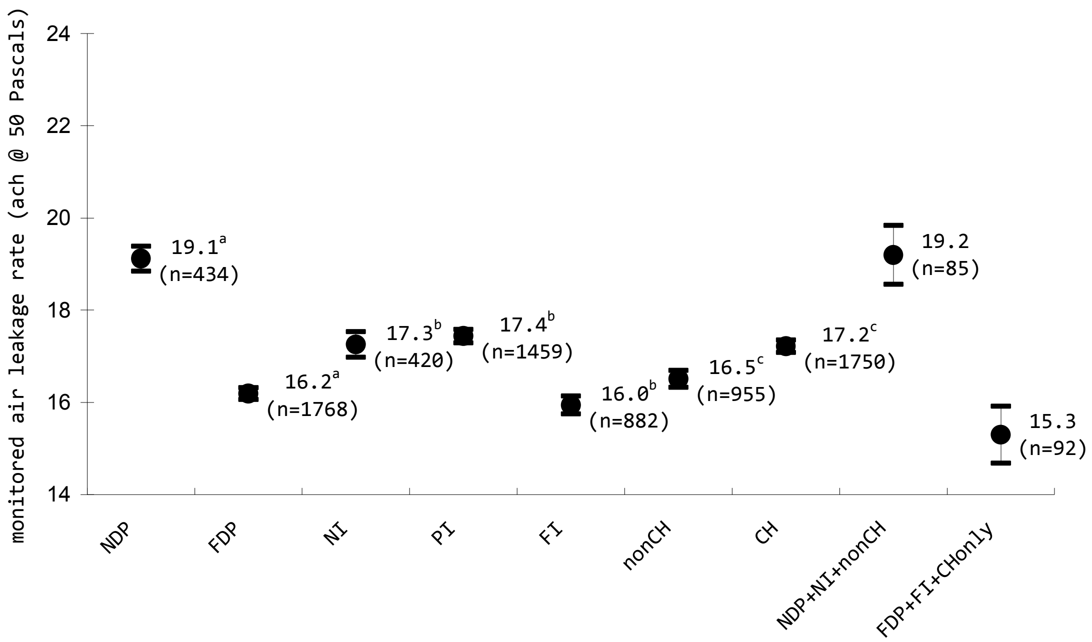
In Figure 6.1 the sensitivity of the *monitored* (Section 4.3.1) and the *modelled air leakage rates* (Section 4.3.2) are examined in relation to the energy efficiency measures of draught proofing, insulation and central heating. The comparison shows a 2.9 ach (95%CI: 2.6, 3.2) decrease in the *monitored air leakage rate* associated with draught proofing whereas no significant result is observed in the modelled result. Similarly, full insulation is found to reduce the *monitored air leakage rate* by 1.3 ach (95%CI: 1.0, 1.7) but little impact is observed in the *modelled air leakage rate*. Central heating, on the other hand, has a significant impact on the modelled result which decreased by 2.5 ach (95%CI: 1.9, 3.0) while a 0.7 ach (95%CI: 0.5, 0.9) increase is observed in the *monitored air leakage rate*. The decrease observed in the modelled result is assumed to be the result of centrally heated dwelling less likely to have an open flue.

Although the *modelled air leakage rate* takes into account the condition of draught proofing and insulation, it may not be assigning sufficient impact factor to these measures to reflect their actual performance as observed with the *monitored air leakage rate*. The presence of flues does not explain the observed increase in the *monitored air leakage rate* associated with central heating since these are most likely of either balanced or fan-assisted type. Instead, the rise is thought to be the result of piping installation which would have involved lifting of floor boards followed by poor refitting and sealing procedure. This possibility is supported from the *Warm Front Ventilation Paper* (Appendix 3) [2] which showed a significant association between the number of radiators and increased *blower-door tested air leakage rate*. This is in contrast to the large decrease in the *modelled air leakage rate* observed from nonCH to CH which is most likely due to a greater number of open flues in non-centrally heated dwellings.

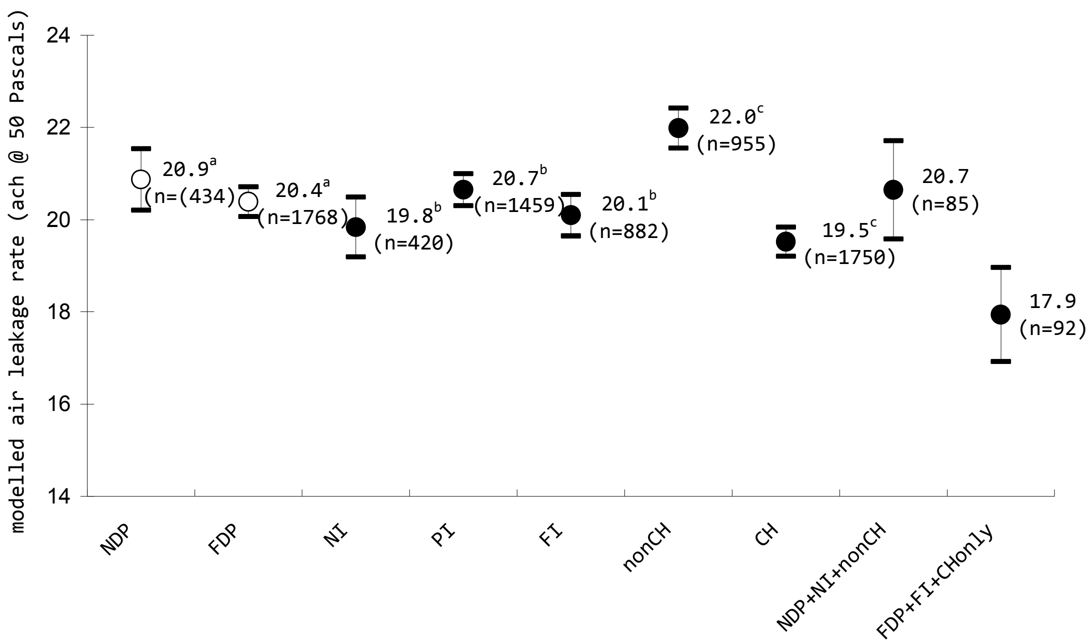
The analysis in this section showed that the parameters affecting the *modelled* and the *monitored air leakage rates* are significantly different. The sensitivity of the *monitored air leakage rate* can be assumed to be a closer representation of actual condition because its algorithm (Eqn. 4.1) is developed from the *blower-door tested air leakage rate*. By substituting the *monitored air leakage rate* into BREDEM, the accuracy of the model is expected to improve and contribute to reduced *shortfall*.

Figure 6.1: Impact of energy efficiency measures on the *monitored* and the *modelled air leakage rates* ([a] adjusted for insulation and heating, [b] adjusted for draught proofing and heating, [c] adjusted for draught proofing and insulation, *NDP*: no draught proofing, *FDP*: full draught proofing, *NI*: no insulation, *PI*: partial insulation, *FI*: full insulation, *CH*: central heating with non-central heating & central heating only, statistically significant relationships (p<0.05) are indicated in solid)

(A) *Monitored air leakage rate* (n = 3099)



(B) *Modelled air leakage rate* (n = 3099)



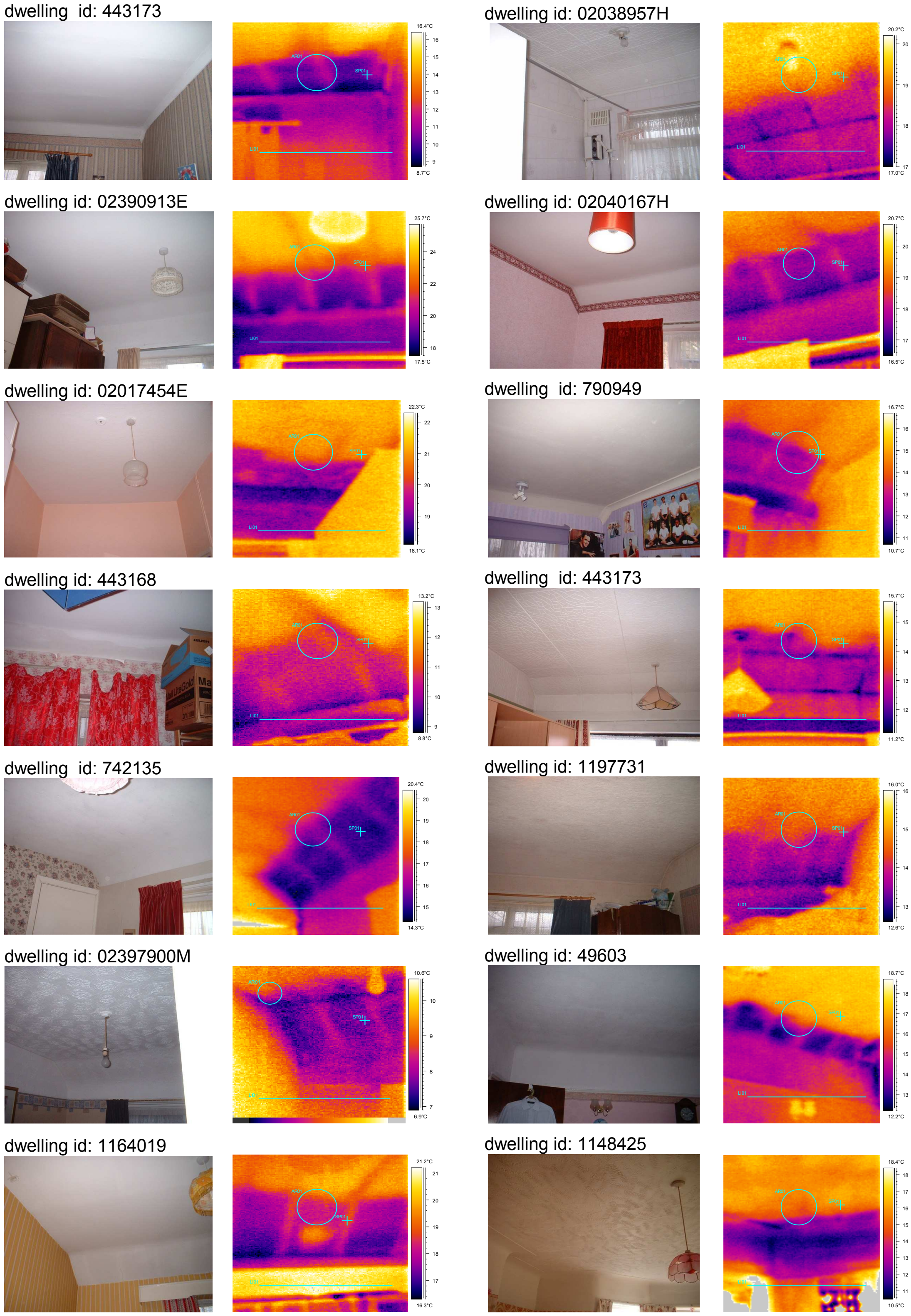
6.2. Monitored U-value

Thermal imaging was carried out using FLIR infrared camera to assess the quality of cavity wall and loft insulation in 85 *post-WF* dwellings. The infrared camera was an effective tool allowing the visualization and the assessment of the in situ insulation condition in a non-destructive way. Unfavorable climatic conditions and often low indoor temperatures in the case study dwellings meant that the tests were not always carried out in accordance to the recommended procedure outlined in ISO6781 [63].

The thermographic images thus obtained were then analyzed to quantify the areas of exposed wall and ceiling with missing insulation. The information provided by the images, on the other hand, were insufficient to assess the insulation thickness which is based on the surveyor’s data in this thesis. A frequently occurring pattern observed from the thermographic images was missing insulation along the joint where the exterior wall meets the roof indicating retrofit insulation measures having limited effect in reaching these areas most likely due to a combination of physical inaccessibility, precaution against blocking roof vents and blockage from window lintels. Some of these images, all taken from different *post-WF* dwellings, are shown in Figure 6.2.

The missing areas contributed to an average of 20 % of the exposed cavity wall and 13 % of the exposed ceiling area. No differentiation was made in these figures according to the house type due to the small sample size from which this information was derived. These conditions clearly reduce the thermal performance of the building fabric and unless taken into account when modelling will result in overestimation of the insulation performance. The *monitored U-values* adjusted for the in situ insulation condition is provided in Tables 4.11 and 4.12.

Figure 6.2: Images of insulated *post-WF* dwellings showing areas of missing insulation along the external wall and roof joint.



6.3. Monitored Central Heating Performance

The actual fuel efficiency of central heating boiler in converting the delivered energy into useful heat was not monitored in the *Warm Front Study*. However, some level of underperformance from its theoretical SEDBUK efficiency level is to be expected due to a combination of over-sizing, poor installation and occupant behavior [4] resulting in less energy saving than what is theoretically expected. This section focuses on one particular user behavior which can result in decreased central heating system performance.

The *Warm Front Scheme* does not require the removal of old non-central heating appliances as a pre-requisite for the installation of a gas central heating system. The scheme assumes that the benefits of increased indoor temperature and fuel efficiency to be gained from a new central heating system will encourage the householders to make the switch. However, for reasons such as unfamiliarity with a new system and the convenience of old habit, some householders may continue using the old heating appliances either alone or in combination with a new central heating system thereby reducing the potential energy efficiency benefit to be gained from a central heating system. Anecdotal evidence from a retrofit study indeed showed a 40 % higher energy consumption level in a centrally heated dwelling due to combined use of an inefficient gas fire [20].

In Table 6.1 the *pre-* and *post-WF* case study dwellings are disaggregated by the combination of the heating appliances found in the dwellings: non-central heating only (*nonCH*), combination of central and non-central heating (*CH+nonCH*) and centrally heating only (*CHonly*). The comparison shows the proportion of dwellings owning a central heating system (*CH+nonCH*, *CHonly*) is greater *post-WF* at 90 % compared to 43 % *pre-WF* with a greater difference observed in the o60 (elderly households) group

95 % *post-WF* compared to 31 % *pre-WF*. When the centrally heated *post-WF* dwellings are disaggregated into the two groups of *CHonly* and *CH+nonCH*, the majority are found to belong in the *CH+nonCH* group at 77 % compared to only 14 % in *CHonly*. Again, this proportion is found to be greater in the o60 group with 86 % in the *CH+nonCH* group compared to only 9 % in *CHonly*. These comparisons however depend heavily on the cross-sectional sample and therefore may not provide an accurate assessment of the impact of the *Warm Front scheme*.

Table 6.1: A comparison of the ownership of heating system

household group	WF status (total no.)	*nonCH* (% total)	*CH+nonCH* (% total)	*CHonly* (% total)
u16	*pre-WF* (644)	42.7	43.6	13.7
	post-WF (445)	16.2	63.6	20.2
o60	*pre-WF* (837)	68.8	27.7	3.5
	post-WF (657)	5.0	85.5	9.4
total	*pre-WF* (1481)	57.5	34.6	7.9
	post-WF (1102)	9.5	76.7	13.8
nonCH: no central heating, CHonly: central heating only, CH: central heating with or without local heating.				

Table 6.2 compares the ownership of various types of non-central heating appliances (gas, solid, paraffin and electric) between the pre- and the *post-WF*. The average number of gas room heater was the greatest in the *pre-WF* group with most dwellings likely to own at least one unit (1.3) followed by electric heaters (portable: 0.8, fixed: 0.4) followed by paraffin and solid room heaters (0.1). The average number of non-central heating units was lower across all types *post-WF* with the greatest difference observed among the portable units with electrical heaters lower by 63 % followed by paraffin heaters by 55 %. The reduction among the fixed units was comparatively less with the number of solid room heaters lower by 20 % and gas room heaters only by 13 %.

A *pre-WF* o60 dwelling is found to own at least 3 non-central heating units compared to 2 in the u16 group. However, a 37 % decrease in the average number of non-central heating appliance was observed in the o60 group compared to 17 % in the u16 group suggesting the introduction of a central heating system may have an impact in reducing dependency on the use of non-central heating appliances. On the other hand, despite the presence of a gas central heating system and a 19 % lower ownership of gas room heaters, a *post-WF* o60 household is still likely to own at least one gas room heater.

The large contrast in the difference between the portable and the fixed units from pre- to *post-WF* seems to suggest a hassle factor associated with the removal of the fixed heating units as a probable reason behind their continued presence in the *post-WF* dwellings. Furthermore, the short time period between the central heating installation and the *post-WF* survey, most of which took place within 6 month of the installation, would have given the householders little opportunity for their removal or settling into normal use of central heating system or both.

Table 6.2: A comparison of ownership of average number of non-central heating appliance.

hshld. group	WF status	solid	gas	# electric (fixed)	electric (portable)	paraffin	total
u16	*pre-WF*	0.05	1.06	0.37	0.60	0.07	2.15
	post-WF	0.05	1.00	0.41	0.27	0.05	1.78
	change	0%	-5.7%	+10.8%	-55.0%	-28.6%	-17.2%
o60	*pre-WF*	0.05	1.49	0.52	0.87	0.14	3.07
	post-WF	0.03	1.21	0.38	0.28	0.04	1.94
	change	-40.0%	-18.8%	-26.9%	-67.8%	-71.4%	-36.8%
both groups	*pre-WF*	0.05	1.30	0.44	0.75	0.11	2.66
	post-WF	0.04	1.13	0.33	0.28	0.05	1.82
	change	-20.0%	-13.1%	-25.0%	-62.7%	-54.5%	-31.6%
# *includes less than 3 storage heaters*							

Although the analysis in this study excludes all dwellings owning any type of non-metered heating appliance, household interviews have revealed about 3 % of households that have a combination of gas central heating and local appliances (n = 1625) continuing to use paraffin for space heating, 2 % coal and a very small number oil and wood. Although a similar data is not available on how local gas and electric appliances were used, this observation suggests the possibility of some householders continuing to use local gas or electric heating appliances considering the large proportion of dwellings falling into the *CH+nonCH* group. Whether the non-central heating appliance is used independently or in combination with the central heating system, its continued use will inevitably result in reduced overall heating efficiency and undermine the potential energy saving benefit to be gained from a central heating system. Chapter 7 shows how the energy consumption of the *CH+nonCH* dwellings is slightly higher than in the *CHonly* dwellings suggesting increased energy use from the use of non-central heating appliances but without any significant gain in terms of temperature rise which is shown in Chapter 8.

6.4. Impact of Energy Efficiency Measure on Heating Regime

The impact of the energy efficiency measure on the space heating regime is examined by comparing to the average number of daily hours that the rooms are heated and the thermostat setting. The information on the number of hours rooms heated was obtained from household interviews and the thermostat setting from the property survey.

The effect of draught proofing, insulation and central heating on the average number of daily daily hours that the rooms are heated is compared in

Table 6.3 to Table 6.5. All energy efficiency measures are found to have little effect on the heating hours except in the case of the bathroom whose heating hours are 4 hours less with insulation but 3 hours more with central heating. Table 6.5 shows that central heating may also slightly reduce the main living room heating hours.

Table 6.3: Mean number of hours per day rooms heated in winter by the draught proofing level (95%CI).

rooms	lv1	lv2	ktc	bath	crc	b1	b2	b3	b4
NDP	12.0 (1.4, >24)	7.7 (3.0, >24)	6.4 (2.7, 21)	3.3 (2.9, 20)	8.1 (4.1, 17)	6.3 (1.8, >24)	8.2 (3.1, 21)	8.6 (4.3, 7)	7.8 (4, 10.2)
FDP	11.3 (0.8, >24)	7.4 (1.7, >24)	6.7 (1.4, >24)	6.0 (1.3, >24)	11.2 (1.7, >24)	4.6 (1.0, >24)	5.5 (1.6, >24)	4.5 (2.0, >24)	3.2 (5, 8.4)
p-value	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
NDP: no draught proofing, FDP: full draught proofing									

Table 6.4: Mean number of hours per day rooms heated in winter by the insulation level (95%CI).

rooms	lv1	lv2	ktc	bath	crc	b1	b2	b3	b4
NI	11.2 (1.1, >24)	6.1 (2.2, >24)	5.7 (2.1, >24)	**7.9 (2.1, >24)**	9.7 (3.4, >24)	4.6 (1.3, >24)	5.9 (2.3, >24)	3.8 (3.4, 11)	5.5 (4, 6.9)
FI	11.7 (0.9, >24)	8.6 (1.9, >24)	7.2 (1.5, >24)	**4.3 (1.5, >24)**	11.0 (1.8, >24)	5.3 (1.1, >24)	6.3 (1.8, >24)	5.8 (2.1, >24)	4.0 (1, 13.7)
p-value	> 0.05	> 0.05	> 0.05	**< 0.05**	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
NI: no insulation, FI: full insulation									

Table 6.5: Mean number of hours per day rooms heated in winter by the heating type (95%CI).

rooms	lv1	lv2	ktc	bath	crc	b1	b2	b3	b4
nonCH	12.2 (0.8, >24)	7.2 (1.6, >24)	6.0 (1.6, >24)	**3.6 (1.8, >24)**	11.1 (2.3, >24)	4.3 (1.1, >24)	5.2 (1.8, >24)	3.9 (2.9, 20)	1.3 (3, 13.4)
CH	11.0 (1.0, >24)	7.7 (1.9, >24)	7.1 (1.7, >24)	**6.9 (1.5, >24)**	9.5 (1.8, >24)	5.6 (1.1, 24)	6.4 (1.7, >24)	7.1 (2.3, >24)	7.2 (6, 7.5)
p-value	> 0.05 (0.06)	> 0.05	> 0.05	**< 0.05**	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
nonCH: non-central heating, CH: central heating									

Table 6.6 examines the effect of draught proofing, insulation and central heating on the thermostat setting. None of the energy efficiency measures were found to have an impact on the thermostat setting. The impact of central heating is inconclusive as a result of the availability of set point data from only 4 *nonCH* dwellings.

Table 6.6: Mean thermostat setting by energy efficiency measures.

energy efficiency measure	draught proofing		insulation		heating	
	NDP	*FDP*	*NI*	*FI*	*nonCH*	*CH*
mean	21.9	22.2	22.1	22.2	21.6	22.2
95% CI	0.7	0.3	0.7	0.3	3.0	0.3
no.	79	376	85	370	4	451
p-value	> 0.05		> 0.05		> 0.05	
NDP: no draught proofing, FDP: full draught proofing, NI: no insulation, FI: full insulation, nonCH: non-central heating, CH: central heating						

6.5. Discussion

Based on the availability of information from the *Warm Front Study*, three possible factors have been identified that can contribute to the *shortfall* in the energy saving.

First, the *monitored* (Section 4.3.1) and the *modelled air leakage rates* (Section 4.3.2) were found to show different sensitivities in relation to the energy efficiency measures of draught proofing, insulation and central heating. This difference could potentially explain some of the *shortfall*.

Second, concrete evidence was found in retrofit insulation failing to deliver the level of performance that is theoretically expected due to missing areas of insulation above wall cavities and edges of the loft space thereby contributing to some of the *shortfalls* in the energy saving. Although the thermal imaging method was found to be an effective tool in locating areas with missing insulation, the effectiveness of this method was limited to the weather condition which resulted in thermographic images being taken from 85 dwellings out of 109 *post-WF* dwellings visited. The information obtained was also insufficient to determine other factors that can increase the U-value such as local variations in insulation thickness [5].

Third, the possibility of reduced central heating performance from continued use of local gas or electric space heating appliances was observed. Although no direct evidence was collected in the *Warm Front Study*, the possibility of this heating practice in dwellings owning both central and local space heating appliances was inferred from household interviews which revealed some householders with gas central heating continuing to use local appliances using non-metered fuel. It is thought that some households may continue to operate the old heating system as a result of familiarity and the hassle factor in learning the various controls associated with a central heating system. The analysis in Chapter 7 will indicate that the energy consumption in dwellings with both type of heating systems is about 2.5 % higher than those with central heating only indicating the possibility of continued use of local heating appliances resulting in increased energy consumption.

No clear evidence was found linking energy efficiency measures to the number of hours that the rooms were heated. Similarly, no evidence was found indicating a change in the demand temperature as a result of draught proofing or insulation. The impact of retrofit central heating system on the thermostat setting could not be verified due to the unavailability of set point information from most of the non-centrally heated dwellings. On the other hand, this relationship is examined in relation to the monitored internal temperature in chapter 9.

The BREDEM input variables will be adjusted by the three sources of the *shortfall* identified in this study and their effect on the *loss* and the *shortfall* examined in Chapters 10 and 11. The air leakage rate prediction will be improved by substituting the *monitored air leakage rate* (Section 4.3.1), the U-values will be improved by substituting the *monitored U-values* (Table 4.11 and Table 4.12) and the accuracy of the central heating performance will be improved by adjusting the parameter '*fraction of heat from secondary appliance*' in BREDEM which will be explained in detail in Section 7.4.

All parameters that have been adjusted by the *monitored air leakage rate* will be indicated by the subscript (*v*) and for the *monitored U-values* the subscript (*i*). All parameters that have been adjusted by all three monitored conditions, the *monitored air leakage rate*, the *monitored U-values* and the *monitored central heating performance* will be indicated by the subscript (*insitu*).

92 % of the pre-*WF* case study dwellings owned some type of local heaters. The ownership of gas heaters was the highest at an average of 1.3 units per dwelling followed by an average of 0.8 portable electric units. Following the upgrade, a 13 % drop in the ownership of gas heaters was observed compared to a 62 % drop in the portable electrical units reducing its mean ownership to 0.3 units per dwelling *post-WF*. The large drop in the electric units clearly indicates a significant shift in the fuel type from on-peak electricity to gas for space heating which is likely to have a beneficial impact on the fuel cost.

CHAPTER 7 SAVING

This chapter examines the impact of the *Warm Front Scheme* and energy efficiency measures on the *monitored space heating energy consumption* (Q_{mon}) (Section 4.5.2) and the *modelled space heating energy consumption* (Q_{mod}) (Section 4.5.1), i.e. BREDEM predicted saving under standard heating regime. The saving examined in this chapter has deliberately not been normalized to the internal temperature, a relationship which will be examined in Chapter 9 when determining the *comfort taking*. The impact of the *Warm Front Scheme* on the monitored and the modelled total delivered energy consumption is examined in Section 7.1 followed by the impact of the *Warm Front Scheme* and energy efficiency measures on the *monitored* and the *modelled saving* in Sections 7.2 and 7.3 respectively.

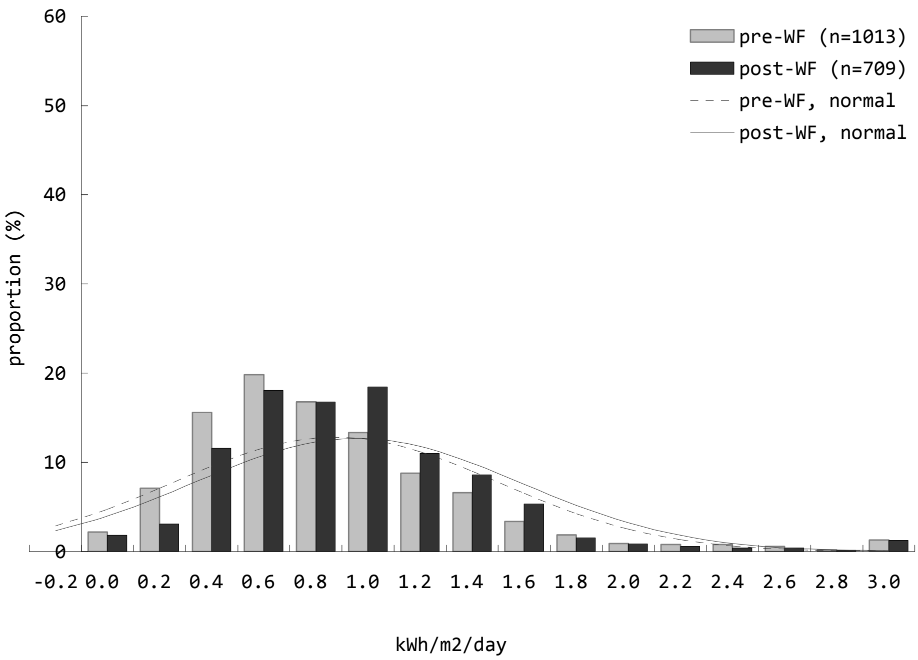
7.1. Total Delivered Energy Consumption

Figure 7.1A and B compare the monitored and the modelled total energy consumption between the pre- and the *post-WF* dwellings. The monitored total energy consumption refers to the sum of the gas and electricity consumption obtained from actual meter readings and the modelled total energy consumption refers to the modelled prediction which includes energy consumption for space heating, water heating, lighting, electrical appliances and cooking. No differentiation is made between the longitudinal and the cross-sectional case study dwellings in the figure.

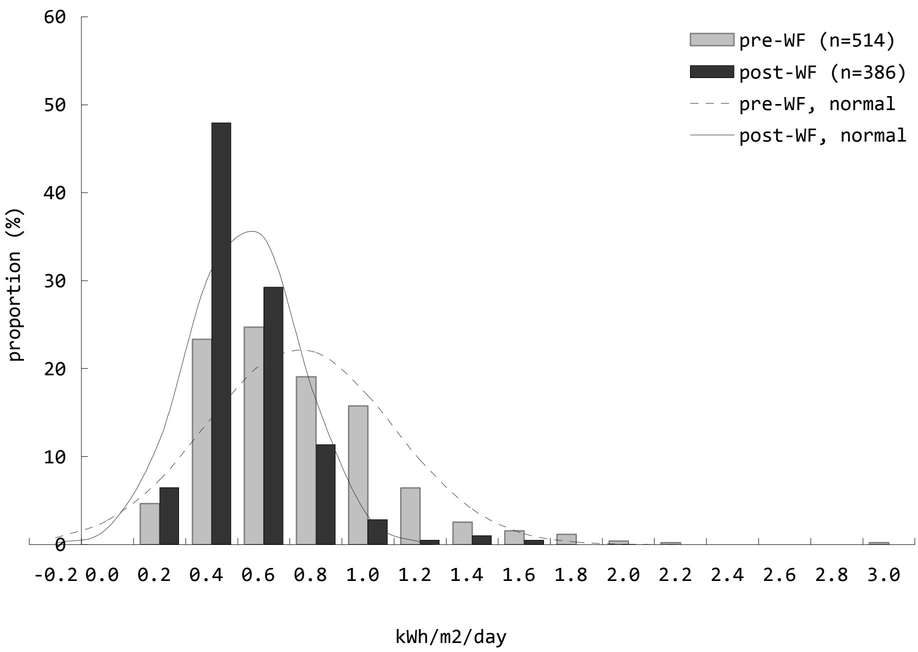
The distribution between the two figures is different in that the modelled result is clustered in the lower consumption range compared to the high variability observed in the monitored result. This difference can be explained by the difference in the usage of hot water, cooking and lighting but more importantly it is due to the model assuming a standard heating pattern whereas the monitored result reflects the varied energy consumption resulting from the different heating regimes actually found in the case study dwellings.

Figure 7.1: Distribution of the *pre*- and the *post-WF* monitored and modelled total delivered energy consumption.

(A) Monitored total delivered energy consumption



(B) Modelled total delivered energy consumption



The comparison of the mean values in Table 7.1 shows that the *post-WF* total fuel consumption is higher by 0.08 kWh/m^2/day (95%CI: 0.02, 0.14) than the pre-WF. This is in contrast to the model predicted -0.21 kWh/m^2/day (95%CI: -0.25, -0.17) decrease mainly because the model assumes standard heating regimes *pre-* and *post-WF* thereby excluding the effect of the comfort taking and its impact on the energy use.

When the monitored result is disaggregated into the longitudinal and cross-sectional groups, the longitudinal *post-WF* increase is higher by a mean of 0.22 kWh/m^2/day (95%CI: 0.04, 0.39) compared to the 0.08 kWh/m^2/day (95%CI: 0.02, 0.14) rise in the cross-sectional group although the difference is statistically not significant. The greater rise in the longitudinal group is mainly the effect of lower winter 2 external temperature which when adjusted for – along with region, dwelling age, dwelling type, household size and income – in a multi-variable analysis resulted in a longitudinal *post-WF* mean increase of 0.14 kWh/m^2/day (95%CI: -0.10, 0.38) (not shown) and the cross-sectional of 0.11 kWh/m^2/day (95%CI: 0.04, 019) (not shown). However, the impact of the multivariable adjustment is statistically not significant.

The same multi-variable adjustment to the modelled total energy consumption also showed similar results with little change observed in the cross-sectional group from a mean of -0.22 kWh/m^2/day (95%CI: -0.26, -0.18) to -0.21 kWh/m^2/day (95%CI: -0.25, -0.17) (not shown) following the adjustment while the longitudinal group showed a mean change from 0.03 kWh/m^2/day (95%CI: -0.06, 0.12) to -0.06 kWh/m^2/day (95%CI: -0.19, 0.06) (not shown). Again, much of the rise in the *post-WF* longitudinal energy use pre-adjustment can be explained by external temperature which when adjusted for shows a decrease in the longitudinal modelled energy use as in the cross-sectional comparison although the difference between the unadjusted and the adjusted longitudinal group is also statistically insignificant most likely due to the small sample size.

Table 7.1: A comparison of *pre*- and the *post-WF* monitored and the modelled total delivered energy consumption.

(A) Monitored total delivered energy consumption.

group	intervention status	mean (95%CI), kWh/m^2/day	difference to *pre-WF* group %	(95% CI), kWh/m^2/day	*p*-value
both groups	*pre-WF* (n = 1013)	0.97 (0.94, 1.01)	+8.2	+0.08 (0.02, 0.14)	<0.05
	post-WF (n = 709)	1.06 (1.01, 1.10)			
longitudinal	*pre-WF* (n = 65)	0.88 (0.74, 1.02)	+25.0	+0.22 (0.04, 0.39)	<0.05
	post-WF (n = 65)	1.10 (0.99, 1.20)			
cross-sectional	*pre-WF* (n = 948)	0.98 (0.94, 1.02)	+7.1	+0.07 (0.01, 0.14)	<0.05
	post-WF (n = 644)	1.05 (1.01, 1.10)			

(B) Modelled total delivered energy consumption.

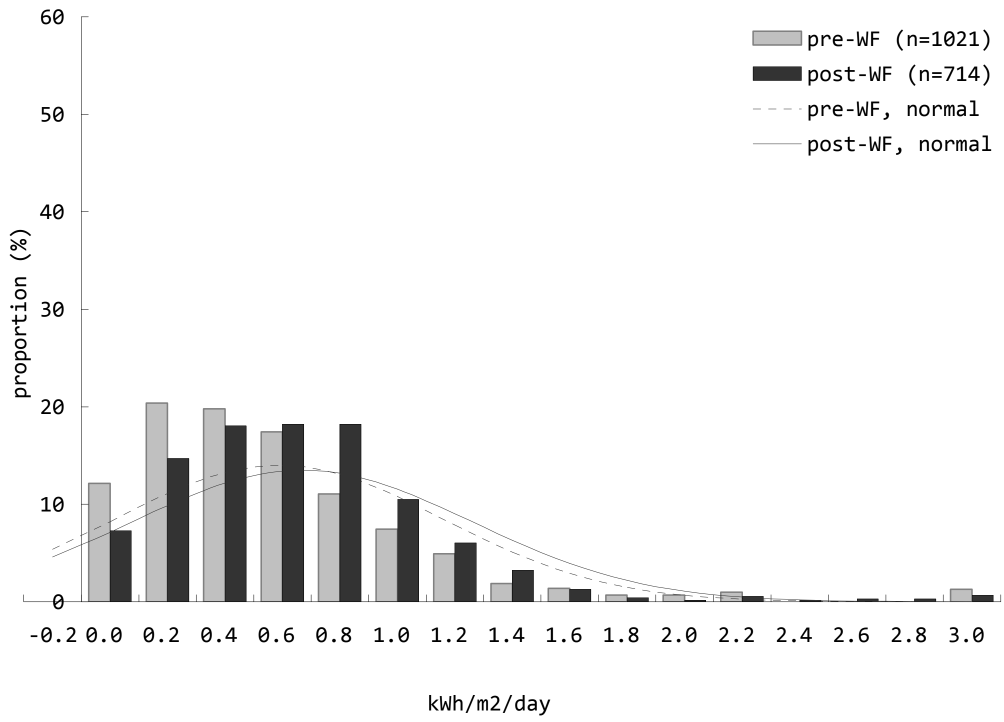
group	intervention status	mean (95%CI), kWh/m^2/day	difference to *pre-WF* group %	(95% CI), kWh/m^2/day	*p*-value
both groups	*pre-WF* (n = 514)	0.84 (0.80, 0.87)	-25.1	-0.21, (-0.25, -0.17)	<0.001
	post-WF (n = 386)	0.63 (0.60, 0.65)			
longitudinal	*pre-WF* (n = 28)	0.56 (0.49, 0.64)	+5.1	0.03 (-0.06, 0.12)	>0.05
	post-WF (n = 28)	0.59 (0.54, 0.65)			
cross-sectional	*pre-WF* (n = 486)	0.85 (0.82, 0.88)	-26.2	-0.22 (-0.26, -0.18)	<0.001
	post-WF (n = 358)	0.63 (0.61, 0.65)			

7.2. *Warm Front* and the *Space Heating Energy Consumption*

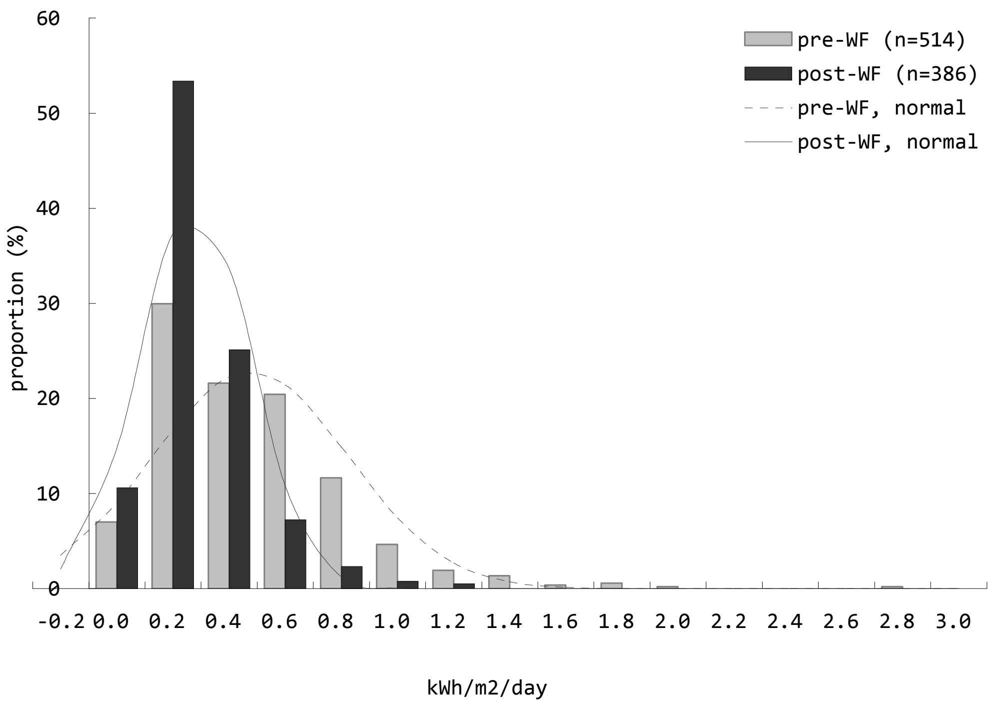
The *pre*- and the *post-WF monitored* (Q_{mon}) and the *modelled space heating energy consumption* (Q_{mod}) are compared in Figure 7.2. No differentiation is made between the longitudinal and the cross-sectional case study dwellings in this figure. As observed in the total energy consumption, the distribution of the *monitored space heating energy consumption* also shows a larger variability than the modelled result reflecting the wide temperature range found in the case dwellings in contrast to the standard heating regime assumed in the model.

Figure 7.2: Distribition of the *pre*-and the *post-WF monitored* and *modelled space heating energy consumption*.

(A) *Monitored space heating energy consumption* (Q_{mon}).



(B) *Modelled space heating energy consumption* (Q_{mod}).



The mean *pre-* and the *post-WF monitored* (Q_{mon}) and *modelled space heating energy consumption* (Q_{mod}) are compared

Table 7.2. The *post-WF* group shows a higher mean consumption level of 0.07 kWh/m^2/day (95%CI: 0.01, 0.13) in the cross-sectional group and 0.22 kWh/m^2/day (95%CI: 0.06, 0.38) in the longitudinal group. The increase in the post-WF group is mainly explainable by an increase in the gas usage which rose by an average of 0.12 kWh/m^2/day whereas the electricity use dropped by 0.05 kWh/m^2/day mainly from reduced reliance on electric appliance as shown in Table 6.2.

As observed in Section 7.1, the greater monitored rise of 0.22 kWh/m^2/day (0.06, 0.38) observed in the *post-WF* longitudinal group is mainly the impact of winter 2 external temperature which if factored in a multi-variable analysis – including other variables of region, dwelling age, dwelling type, household size and income – shows a less mean increase of 0.12 kWh/m^2/day (95%CI: -0.10, 0.34). Unlike in the longitudinal group, however, the cross-sectional group showed no significant change from a mean of 0.07 kWh/m^2/day (95%CI: 0.01, 0.13) pre-adjustment to 0.09 kWh/m^2/day (95%CI: 0.02, 0.16) post-adjustment indicating that there is little difference in the property, household and temperature distribution between the pre- and post-WF cross-sectional samples.

Similarly, the large difference between the longitudinal and the cross-sectional changes in the modeled result in Table 7.2B is again explained by the effect of external temperature on the longitudinal group which when corrected for showed a change from a mean of -0.04 kWh/m^2/day (-0.16, 0.08) to -0.12 kWh/m^2/day (95%CI: -0.23, -0.02) (not shown) while the same adjustment resulted in no change in the cross-sectional group.

Table 7.2: A comparison of *pre-* and the *post-WF* mean *space heating energy consumption*.

(A) *Monitored space heating energy consumption* (Q_{mon}).

group		intervention status	mean (95%CI), kWh/m^2/day	difference to *pre-WF* group □Q_{SVmon} (95% CI), kWh/m^2/day	*p*-value
both group	combined	*pre-WF* (n = 1021)	0.69 (0.65, 0.72)	+0.08 (0.03, 0.14)	<0.05
		post-WF (n = 714)	0.77 (0.73, 0.81)		
	gas	*pre-WF* (n = 1045)	0.61 (0.57, 0.64)	+0.12 (0.07, 0.18)	<0.001
		post-WF (n = 724)	0.73 (0.69, 0.78)		
	electricity	*pre-WF* (n = 1043)	0.08 (0.07, 0.09)	-0.05 (-0.06, -0.03)	<0.001
		post-WF (n = 734)	0.03 (0.02, 0.04)		
longitudinal		*pre-WF* (n = 66)	0.59 (0.46, 0.71)	+0.22 (0.06, 0.38)	<0.05
		post-WF (n = 66)	0.80 (0.71, 0.90)		
cross-sectional		*pre-WF* (n = 955)	0.70 (0.66, 0.73)	+0.07 (0.01, 0.13)	<0.05
		post-WF (n = 648)	0.77 (0.72, 0.81)		

(B) *Modelled space heating energy consumption* (Q_{mod}).

group	intervention status	mean (95%CI), kWh/m^2/day	difference to pre-WF group □Q_{SVmod} (95% CI), kWh/m^2/day	*p*-value
both groups	*pre-WF* (n = 514)	0.58 (0.55, 0.60)	-0.20 (-0.24, -0.16)	<0.001
	post-WF (n = 386)	0.38 (0.35, 0.41)		
longitudinal	*pre-WF* (n = 28)	0.36 (0.30, 0.42)	-0.04 (-0.16, 0.08)	>0.05
	post-WF (n = 28)	0.35 (0.30, 0.41)		
cross-sectional	*pre-WF* (n = 486)	0.59 (0.56, 0.62)	-0.21 (-0.25, -0.17)	<0.001
	post-WF (n = 358)	0.38 (0.36, 0.40)		

The *pre-* and *post-WF monitored* and *modelled savings* in energy cost and carbon emissions emissions are compared in

Table 7.3A and

Table 7.3B respectively. The longitudinal and the cross-sectional groups are combined in these comparisons. The model predicts a lower *post-WF* energy cost and carbon emissions by 0.4 pence/m^2/day (95%CI: -0.5, -0.3) and 44.6 g/m^2/day (95%CI: -52.0, -37.2) respectively. Despite the higher monitored space heating energy consumption observed *post-WF* in

Table 7.2A, the *post-WF* monitored energy cost is found to be 0.1 pence/m^2/day (95%CI: -0.2, 0.0) lower with a negligible difference in the monitored carbon emissions.

Table 7.3: A comparison of *pre-* and the *post-WF* mean space heating energy cost and carbon emissions.

(A) Space heating energy cost

group	intervention status (no.)	mean (95%CI) pence/m^2/day	difference to *pre-WF* group		
			%	(95% CI), pence/m^2/day	*p*-value
monitored	*pre-WF* (n = 1021)	1.37 (1.30, 1.44)	-7.3	-0.10 (-0.21, 0.01)	0.07
	post-WF (n = 714)	1.27 (1.18, 1.35)			
modelled	*pre-WF* (n = 514)	0.97 (0.93, 1.01)	-40.2	-0.39 (-0.46, -0.33)	<0.001
	post-WF (n = 386)	0.58 (0.53, 0.63)			

(B) Space heating carbon emissions

group	intervention status (no.)	mean (95%CI) g/m^2/day	difference to *pre-WF* group		
			%	(95% CI), g/m^2/day	*p*-value
monitored	*pre-WF* (n = 1021)	153.87 (146.20, 161.54)	-1.1	-1.73 (-13.69, 10.22)	>0.05
	post-WF (n = 714)	152.13 (142.96, 161.30)			
modelled	*pre-WF* (n = 514)	116.54 (111.70, 121.38)	-38.3	-44.63 (-52.02, -37.24)	<0.001
	post-WF (n = 386)	71.91 (66.33, 77.50)			

7.3. Energy Efficiency Measures and Saving

Figure 7.3 toFigure 7.5 compare the impact of different combination of energy efficiency measures on the *monitored monitored* (Q_{mon}) and the *modelled space heating energy consumption* (Q_{mod}) and their associated cost and carbon emissions.

The energy efficiency measures are classified according to the definition in Sections 4.1.3 to 4.1.7. The two centrally heated groups *CHonly* (central heating only) and *CH+nonCH* (central heating and room heaters) dwellings are combined as *CH* (central heating) in the modelled analysis since the model assumes no heating contribution from local heaters in centrally heated dwellings. Dwellings with storage heaters are excluded from the analysis. The mean values describing the effect of individual measures statistically reduce the impact of other energy efficiency measures through multi-variable adjustment (Section 4.1).

The impact on the *monitored* and the *modelled space heating energy consumption* is compared in Figure 7.3A and B respectively. Full insulation resulted in the mean *monitored saving* (□Q_{SVmon}) of -0.07 kWh/m^2/day (95%CI: -0.14, 0.01) while draught proofing is found to have no impact. Gas central heating, on the other hand, resulted in an increase in the mean monitored energy consumption by 0.18 kWh/m^2/day (95%CI: 0.11, 0.26) resulting in no saving. The increase associated with central heating is mitigated by the introduction of full insulation with *FI+CHonly* resulting in a mean increase of 0.11 kWh/m^2/day (95%CI: -0.04, 0.27).

In terms of the *modelled saving* (□Q_{SVmod}), draught proofing is also found to have no impact whereas in the case of full insulation the model predicts a greater mean saving of -0.26 kWh/m^2/day (95%CI: -0.31, -0.21) followed by a saving of -0.09 kWh/m^2/day (95%CI: -0.12, -0.06) from gas central heating. Unlike the gain in the monitored energy consumption, the combination of full insulation and central heating resulted in the greatest mean *modelled saving* of -0.31 kWh/m^2/day (95%CI: -0.42, -0.21).

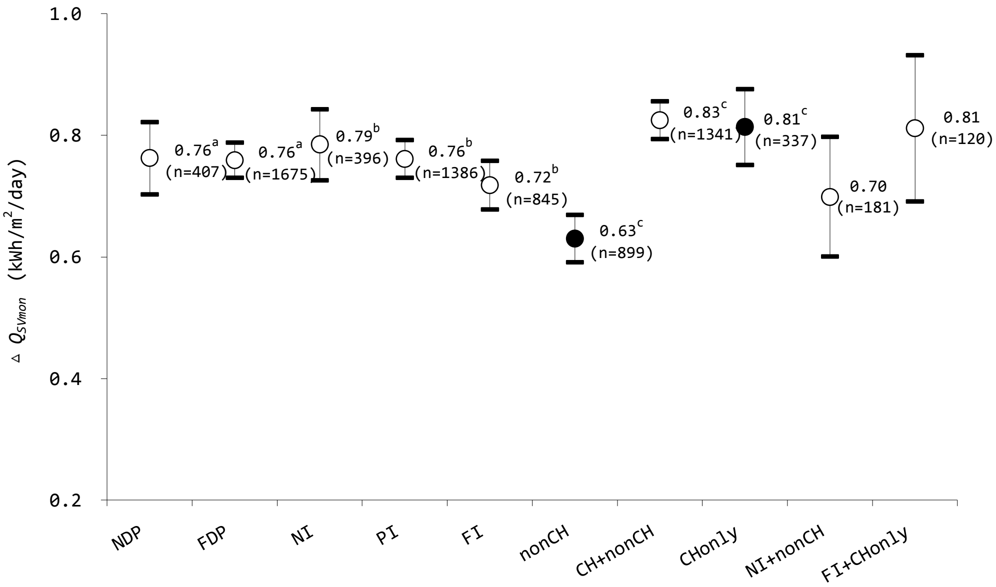
The same analyses carried out with multi-variable adjustment of region, dwelling age, dwelling type, household size, income and external temperature showed statistically no significant changes in both the *monitored* and the *modelled saving* (not shown) despite smaller sample sizes resulting from disaggregation.

In Figure 7.4, the impact of energy efficiency measures on the mean monitored and modelled space heating energy cost is compared. Again, draught proofing is found to have no impact on both the monitored and the modelled energy cost. Full insulation is found to reduce the mean monitored cost by -0.19 pence/m^2/day (95%CI: -0.33, -0.06) and, although statistically not significant, gas central heating is also found to reduce the mean energy cost by -0.13 pence/m^2/day (95%CI: -0.27, 0.01) despite its association with increased monitored energy consumption observed in Figure 7.3A. In comparison, the modelled result shows a greater reduction in the mean energy cost with full insulation reducing it by -0.42 pence/m^2/day (95%CI: -0.50, -0.34) and central heating by -0.30 pence/m^2/day (95%CI: -0.35, -0.25). The combination of full insulation and central heating also resulted in a greater reduction in the mean modelled energy cost by -0.66 pence/m^2/day (95%CI: -0.86, -0.46) compared to the monitored reduction of -0.34 pence/m^2/day (95%CI: -0.64, -0.04).

In terms of carbon emissions Figure 7.5 shows that full insulation resulted in a decrease in the mean monitored carbon emissions by 22.4 g/m^2/day (95%CI: -37.4, -7.5) while central heating resulted in its increase by 6.0 g/m^2/day (95%CI: -9.0, 21.2). In comparison, the model predicts greater saving from full insulation by a mean of 51.3 g/m^2/day (95%CI: -60.0, -42.6) and also a mean saving from central heating by 30.4 g/m^2/day (95%CI: -36.1, -24.7). The combination of full insulation and gas central heating resulted in its reduction by only 10.0 g/m^2/day (95%CI: -42.0, -22.0) compared to the mean modelled reduction of 70.6 g/m^2/day (95%CI: -84.7, -64.4).

Figure 7.3: A comparison of pre- and post-intervention space heating energy saving ([a] adjusted for insulation and heating, [b] adjusted for draught proofing and heating, [c] adjusted for draught proofing and insulation, *NDP*: no draught proofing, *FDP*: full draught proofing, NI: no insulation, *PI*: partial insulation, *FI*: full insulation, *nonCH*: non-central heating, *CH+nonCH*: combination of central and non-central heating, *CHonly*: central heating only, *CH*: *CH+nonCH* & *CHonly*, statistically significant relationships (p<0.05) are indicated in solid).

(A) *Monitored saving* in delivered energy (□Q_{SVmon})



(B) *Modelled saving* in delivered energy (□Q_{SVmod})

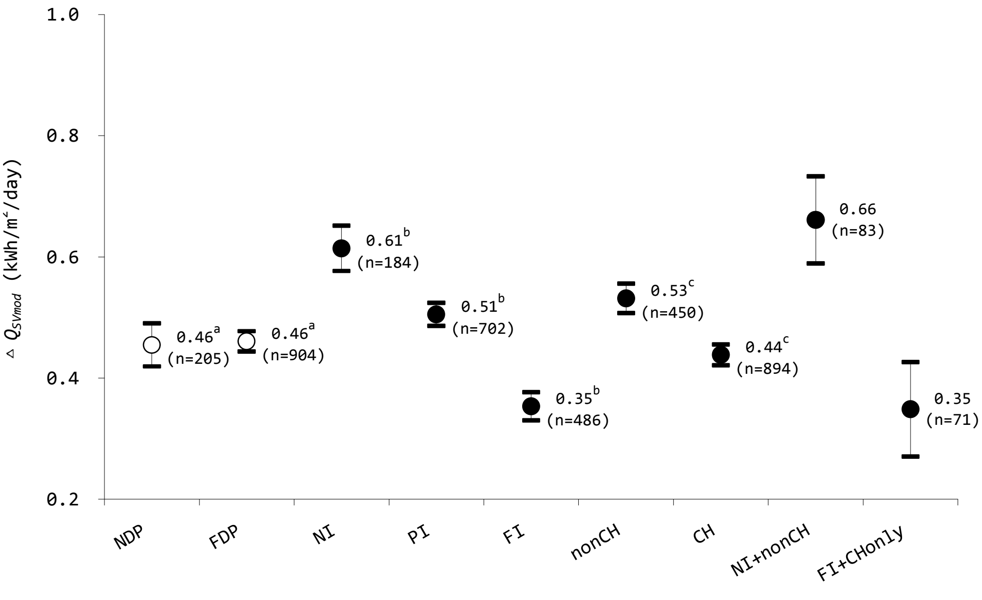
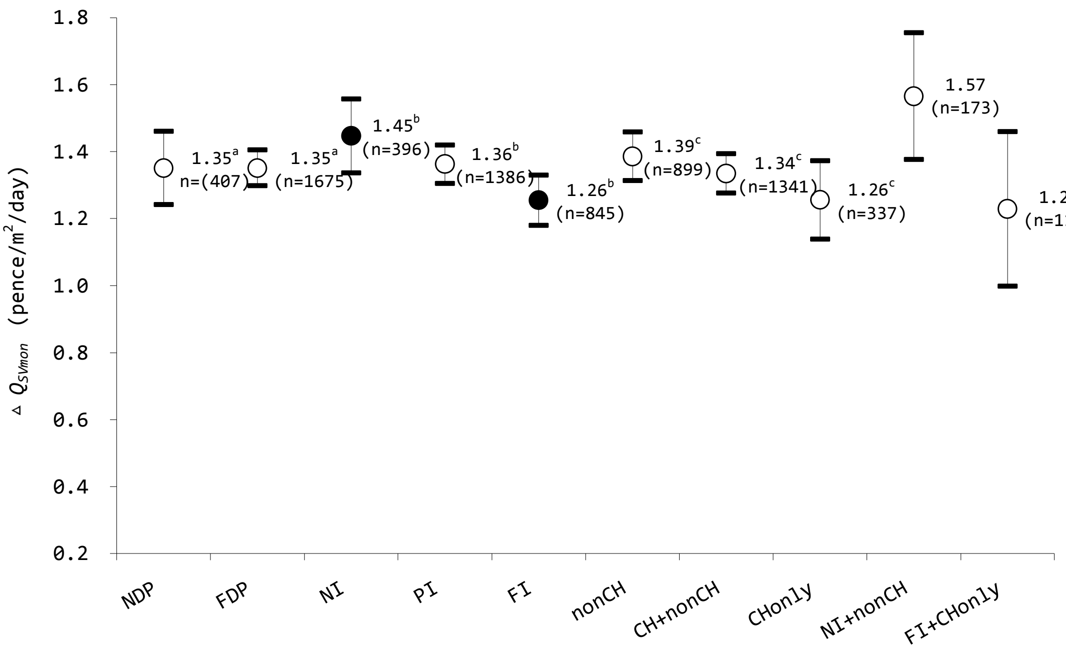


Figure 7.4: A comparison of pre- and post-intervention space heating energy cost saving ([a] adjusted for insulation and heating, [b] adjusted for draught proofing and heating, [c] adjusted for draught proofing and insulation, *NDP*: no draught proofing, *FDP*: full draught proofing, *NI*: no insulation, *PI*: partial insulation, *FI*: full insulation, *nonCH*: non-central heating, *CH+nonCH*: combination of central and non-central heating, *CHonly*: central heating only, *CH*: *CH+nonCH* & *CHonly*, statistically significant relationships (p<0.05) are indicated in solid).

(A) *Monitored saving* in energy cost (□$Q_{SVmon(cost)}$).



(B) *Modelled saving* in energy cost (□$Q_{SVmod(cost)}$).

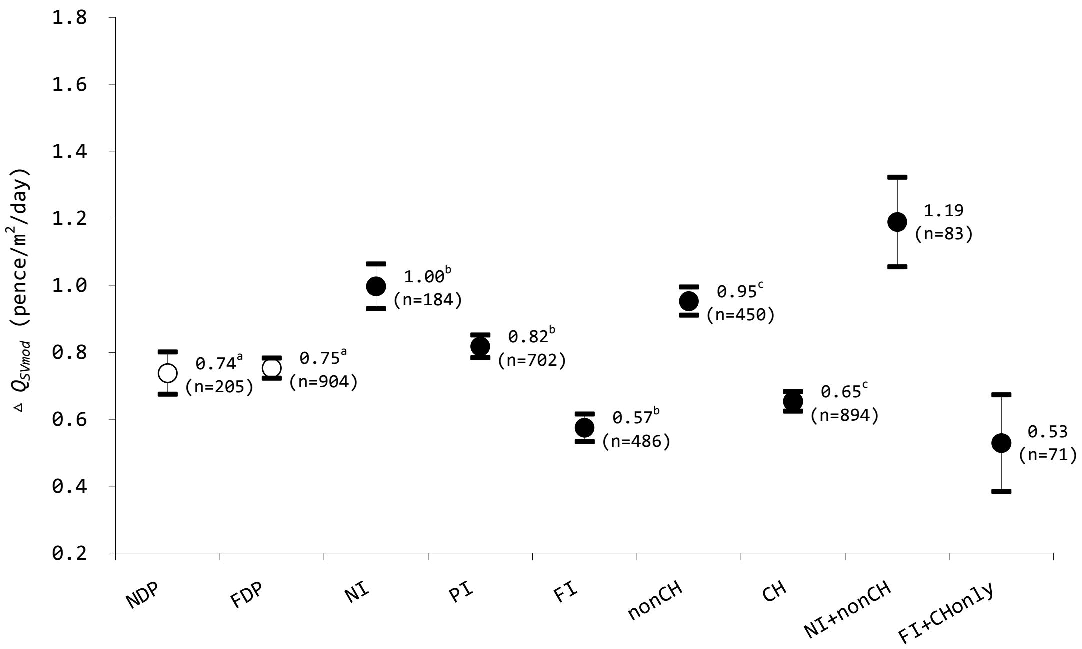
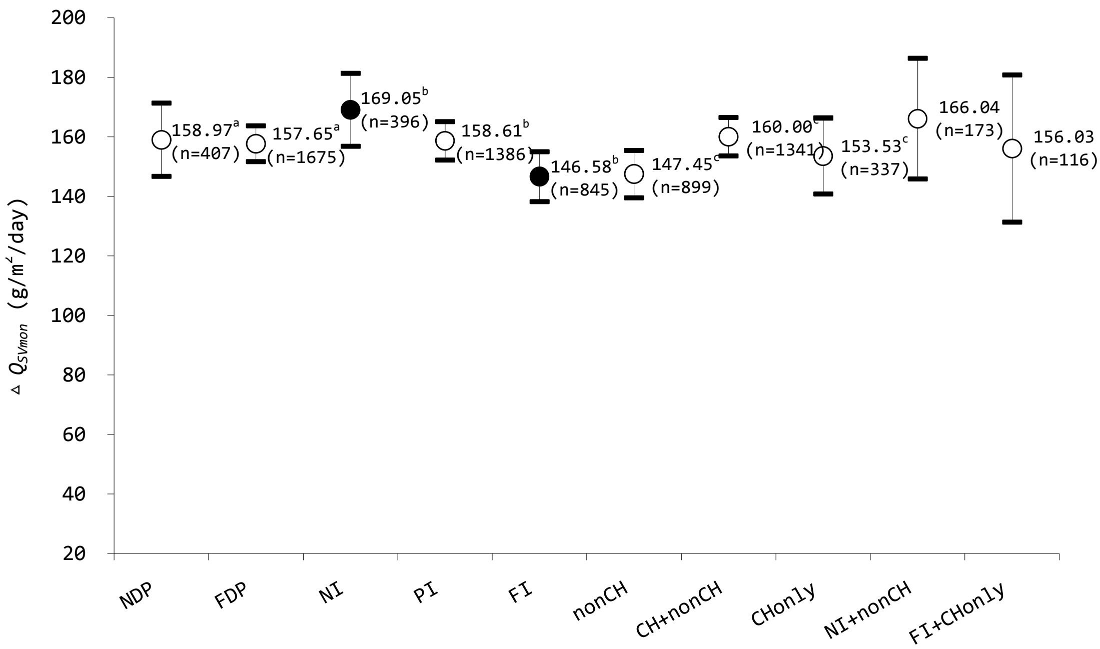
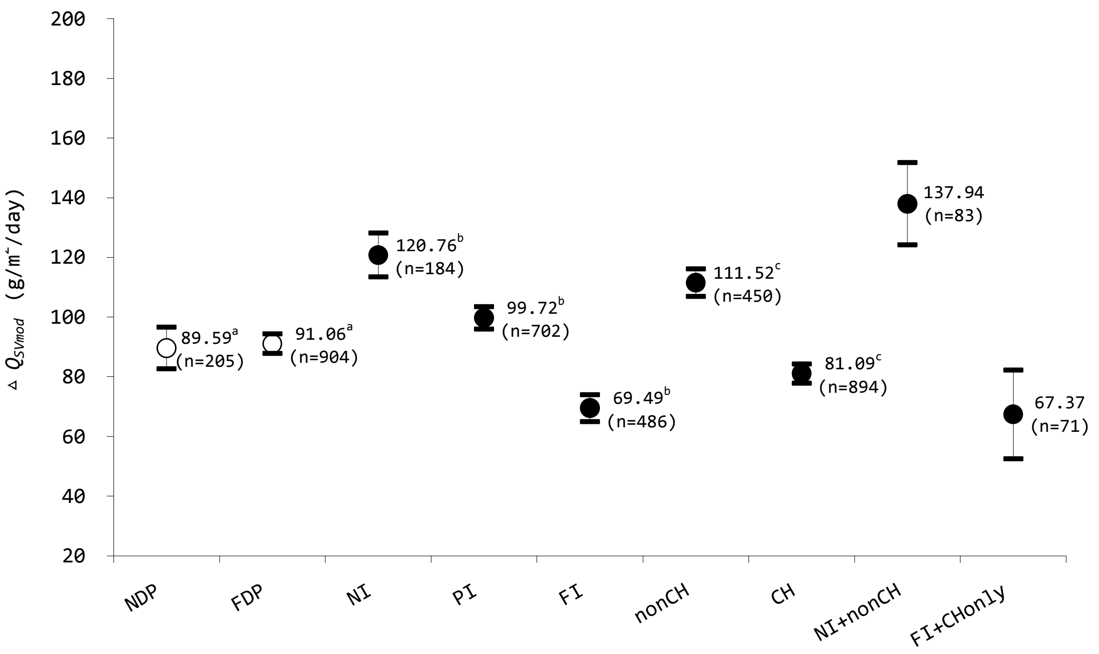


Figure 7.5: A comparison of pre- and post-intervention space heating carbon emissions saving ([a] adjusted for insulation and heating, [b] adjusted for draught proofing and heating, [c] adjusted for draught proofing and insulation, *NDP*: no draught proofing, *FDP*: full draught proofing, *NI*: no insulation, *PI*: partial insulation, *FI*: full insulation, *nonCH*: non-central heating, *CH+nonCH*: combination of central and non-central heating, *CHonly*: central heating only, *CH*: *CH+nonCH* & *CHonly*, statistically significant relationships ($p<0.05$) are indicated in solid).

(A) *Monitored saving* in carbon emissions (□$Q_{SVmon(co2)}$).



(B) *Modelled saving* in carbon emissions (□$Q_{SVmod(co2)}$).



7.4. Discussion

This chapter compared the *monitored space heating energy consumption* (Q_{mon}) (Section 4.5.2) and the *modelled space heating energy consumption* (Q_{mod}) (Section 4.5.1) between the *pre*- and the *post-WF* dwellings and the impact of different energy efficiency measures on these parameters and the associated energy cost and carbon emissions. The results are summarized in Table 7.4 where the saving is indicated as positive figures. The table also includes the *modelled saving* ($\Delta Q_{SVmod(insitu)}$) which has been adjusted for the *monitored air leakage rate* (Table 4.17, Section 6.1), the *monitored U-value* (Table 4.11, Table 4.12, Section 6.2) and the *monitored central heating performance* (Section 6.3).

The unrealized saving from *monitored central heating performance* is introduced by adjusting the BREDEM parameter '*fraction of heat from secondary appliance*' for the *CH+nonCH* case study dwellings until a 2.5 % increase in the energy consumption, i.e. the difference in the monitored energy consumption between the *CHonly* and the *CH+nonCH* dwellings (Figure 7.3) is achieved. The model predicts that the fraction of heating contribution from *nonCH* appliances required to attain a 2.5 % increase in the energy consumption in a centrally heated dwelling is about 8 %.

When examining the monitored saving, the greatest saving in energy cost is observed from *FI+CHonly* reflecting the sum of the saving associated with the individual measures of *FI* and *CH*. On the other hand, in terms of the delivered energy and carbon emissions, *FI* resulted in a greater saving than the combination of *FI+CHonly*. *CH* resulted in the least *monitored saving* across all three units of measurement.

The monitored energy consumption *post-WF* was found to be greater by a mean of 0.08 kWh/m^2/day (95%CI: -0.14, -0.03) (11.6 %) whereas in theory the *post-WF* consumption should have resulted in a mean *modelled saving* of 0.20 kWh/m^2/day (95%CI: 0.16, 0.24). When the analysis is disaggregated into the main energy efficiency measures the reason behind the lack of decrease in the *monitored saving* could partly be explained by the effect of the central heating measure which is found to result in a 0.18 kWh/m^2/day (95%CI: 0.11, 0.26) mean increase which in theory should have resulted in a mean *modelled saving* of 0.09 (95%CI: -0.12, -0.06). The lower performance of insulation which resulted in a mean *monitored saving* of only 0.07 kWh/m^2/day (95%CI: -0.14, 0.02) compared to a mean *modelled saving* of 0.26 kWh/m^2/day (95%CI: -0.31, -0.22) also seem to have contributed to the observed *shortfall*.

One of the main reasons explaining the large difference between the *monitore*d and the *modelled saving* observed in the central heating group (*CHonly*) is the difference in the internal temperatures assumed in the two saving. The monitored saving reflects the actual monitored temperature condition whereas the modelled saving is determined based on a standardized heating regime explaining why a greater saving is observed since the effect of *comfort taking* has been discounted. The external temperature, on the other hand, does not explain the difference between the *monitored* and the *modelled space heating energy consumption* since the monitored external temperature was substituted into BREDEM.

A comparison of the two *modelled savings* (□Q_{SVmod} and □$Q_{SVmod(insitu)}$) shows the latter figures to be lower and thereby approaching the *monitored saving* (□Q_{SVmon}) demonstrating the benefit of increasing the accuracy of BREDEM with in-situ energy efficiency performance (Chapter 6). On the other hand, despite the model adjustment, the main conclusions that can be drawn from the modelled findings still does not change in that the *Warm Front Scheme* and central heating should have led to energy saving while insulation should have led to a greater saving. This indicates that there are still other factors such as the *comfort taking* and other elements not identified in this study contributing to the difference between the *monitored* and the *modelled saving*.

Table 7.4: A comparison of mean *monitored saving* (□Q_{SVmon}), mean *modelled saving* (□Q_{SVmod}) and mean *in situ modelled saving* (□$Q_{SVmod(insitu)}$) adjusted by monitored energy efficiency performance (95%CI).

measurement	Intervention (baseline group)		change relative to baseline group (kWh/m^2/day)		
			□Q_{SVmon}	□Q_{SVmod}	□$Q_{SVmod(insitu)}$
delivered energy (kWh/m^2/day)	*FDP (NDP)*	*unadj*	0.00 (-0.07, 0.06)	-0.01 (-0.05, 0.03)	0.00 (-0.30, 0.04)
		*adj**	-0.22 (-0.10, 0.06)	-0.01 (-0.05, 0.03)	-
	FI (NI)	*unadj*	0.07 (-0.01, 0.14)	**0.26 (0.22, 0.31)**	**0.23 (0.18, 0.27)**
		*adj**	0.03 (-0.06, 0.11)	**0.23 (0.18, 0.27)**	-
	CHonly (nonCH)	*unadj*	**-0.18 (-0.26, -0.11)**	**0.09 (0.06, 0.12)**	**0.05 (0.02, 0.07)**
		*adj**	**-0.21 (-0.30, -0.11)**	**0.12 (0.08, 0.14)**	-
	FI+CHonly (NI+nonCH)	*unadj*	-0.11 (-0.27, 0.04)	**0.31 (0.21, 0.42)**	**0.26 (0.17, 0.36)**
		*adj**	-0.10 (-0.32, 0.11)	**0.27 (0.14, 0.41)**	-
	Post-WF (Pre-WF)	*unadj*	**-0.08 (-0.14, -0.03)**	**0.20 (0.16, 0.24)**	**0.16 (0.12, 0.19)**
		*adj**	**-0.11 (-0.18, -0.04)**	**0.21 (0.16, 0.25)**	-
energy cost (pence/m^2/day) (*cost*)	*FDP (NDP)*		0.00 (-0.12, 0.12)	-0.02 (-0.09, 0.06)	0.01 (-0.06, 0.07)
	FI (NI)		**0.19 (0.06, 0.33)**	**0.39 (0.33, 0.46)**	**0.38 (0.30, 0.45)**
	CHonly (nonCH)		0.13 (-0.01, 0.27)	**0.30 (0.24, 0.35)**	**0.26 (0.21, 0.31)**
	FI+CHonly (NI+nonCH)		0.33 (0.04, 0.64)	**0.66 (0.46, 0.86)**	**0.64 (0.45, 0.82)**
	Post-WF (Pre-WF)		0.10 (-0.01, 0.21)	**0.39 (0.33, 0.46)**	**0.36 (0.30, 0.43)**
carbon emissions (g/m^2/day) (*co2*)	*FDP (NDP)*		1.31 (-12.48, 15.11)	-1.47 (-9.20, 6.26)	0.89 (-6.60, 8.37)
	FI (NI)		**22.46 (7.49, 37.44)**	**51.28 (42.58, 59.97)**	**45.43 (36.96, 53.90)**
	CHonly (nonCH)		-6.08 (-21.18, 9.03)	**30.43 (24.73, 36.14)**	**23.78 (18.17, 29.39)**
	FI+CHonly (NI+nonCH)		10.01 (-21.97, 41.98)	**70.57 (50.30, 90.84)**	**65.05 (45.87, 84.23)**
	Post-WF (Pre-WF)		1.73 (-10.22, 13.69)	**44.63 (37.24, 52.02)**	**38.91 (31.75, 46.08)**

positive figures indicate saving.
statistically significant changes ($p < 0.05$) are highlighted in bold.
NDP: no draught proofing, FDP: full draught proofing, NI: no insulation, FI: full insulation, nonCH: no central heating, CHonly: central heating only,: CH: central heating with or without local heating.
**adjusted for region, dwelling age, dwelling type, household size and income.*
Insitu: adjusted for monitored air leakage rate, monitored U-value and monitored central heating performance

The examination of the total energy consumption in Section 7.1 was found to be useful in confirming the findings associated with the monitored space heating energy consumption. Both the mean monitored total and the mean *monitored space heating energy consumption* were found to be higher *post-WF* by 0.08 kWh/m^2/day (95%CI: 0.02, 0.14) (Table 7.1) and 0.08 kWh/m^2/day (95%CI: 0.03, 0.14) (Table 7.2) respectively supporting the view that the higher *post-WF monitored space heating energy consumption* is not the result of error introduced in determining the *monitored space heating energy consumption* using the method as described in Section 4.5.2.

Despite the higher energy consumption observed *post-WF*, the result is more encouraging when examined in terms of the energy cost which shows a small mean saving of 0.10 pence/m^2/day (95%CI: -0.01, 0.21) which can partly be explained by the decreased dependency on electricity for space heating as evidenced by the lower number of electrical space heating appliances ownership among the *post-WF* dwellings in table 6.4.

Table 7.4 shows that the multi-variable adjustment of the mean savings based on a representative property and household characteristics and external temperature showed statistically no significant differences in the results indicating that the distribution of the *pre-* and *post-WF* cross-sectional samples, which were predominantly compared in the analyses, is fairly similar providing good results even when the sample was disaggregated into smaller numbers.

CHAPTER 8 TEMPERATURE

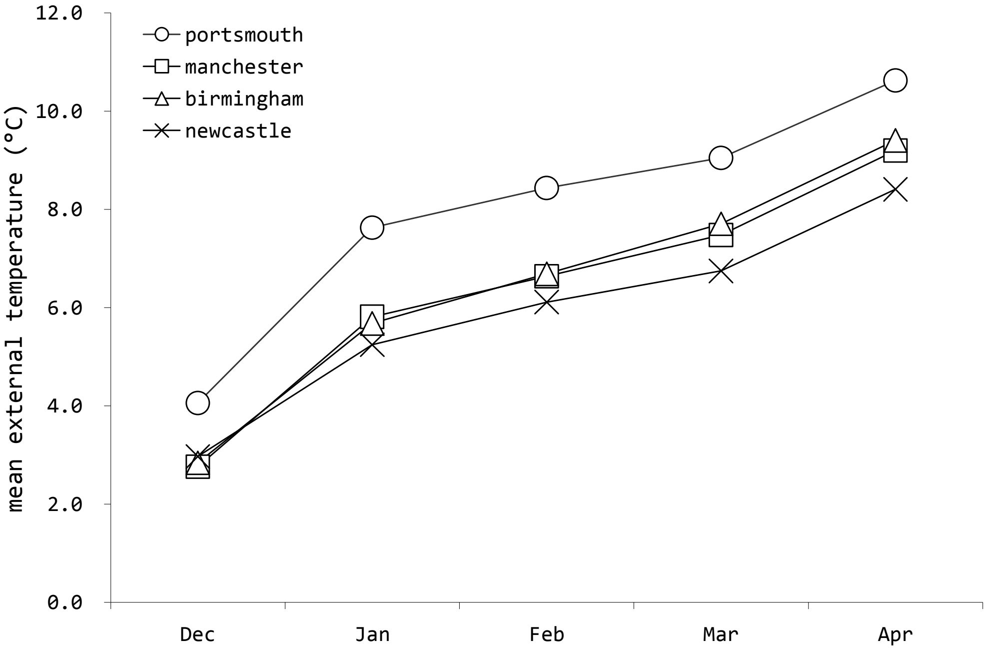
This chapter examines the impact of the *Warm Front Scheme* and energy efficiency measures on the indoor temperature. Section 8.1 compares the monthly external temperature of the two surveyed winters; Section 8.2 examines the *monitored living room temperature* ($T_{mon.lv}$), the *monitored bedroom temperature* ($T_{mon.bd}$) and the *monitored internal temperature* ($T_{mon.int}$) (Section 4.7.2, Eqn. 4.9) in relation to the *Warm Front Scheme* and energy efficiency measures; Section 8.3 compares the *monitored standardized internal temperature* (T_{mon}) (Section 4.8, Eqn. 4.10) and the *modelled standardized internal temperature* (T_{mod}) (Section 4.8, Eqn. 4.11) followed by their sensitivity to different energy efficiency measures in Section 8.4. In Section 8.5 the *monitored* and the *modelled standardized internal temperatures* are compared in relation to the *heat loss parameter* to determine any evidence of the *comfort taking* (□Q_{CT}). The discussion is presented in Section 8.6. All dwellings owning non-metered heating appliance(s) are excluded from the analysis.

8.1. External Temperature

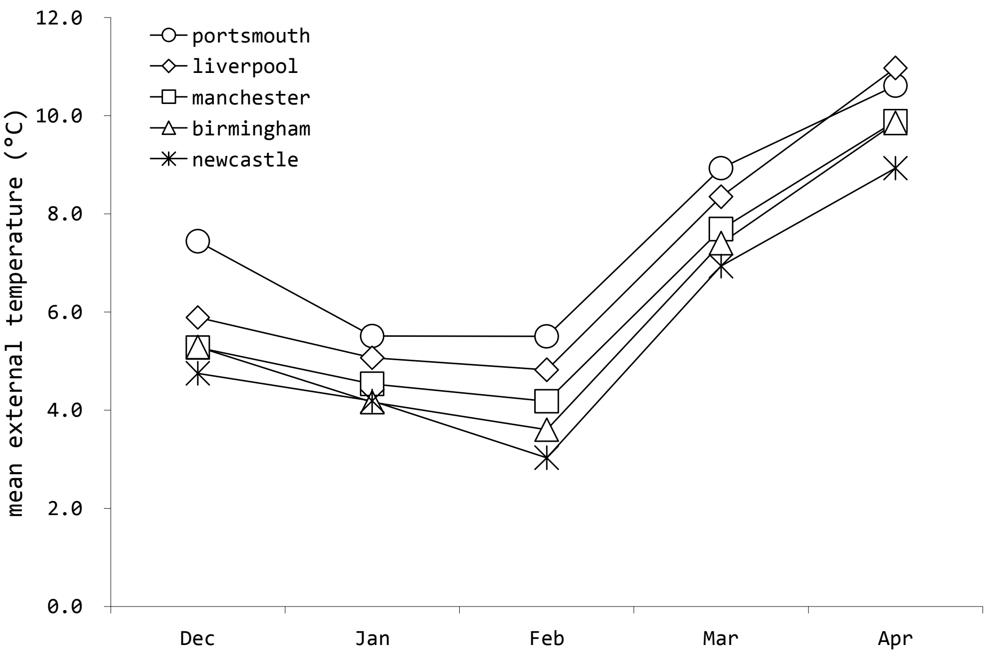
This section compares the monitored external temperature of the two surveyed winters for the five geographical areas. The mean external temperatures monitored over the two surveyed winters were found to be the same at 6.9 °C (winter 1: SD 3.9 °C, winter 2: SD 4.1 °C). However, a comparison of the mean monthly temperatures in Figure 8.1 shows different temperature profiles between the two surveyed winters with December recording the lowest temperature in winter 1 and in the case of winter 2 January and February. The monthly temperatures varied from 3.2 °C to 9.4 °C in winter 1 and from 4.1 °C to 9.8 °C in winter 2 indicating that the conditions were cold enough to require space heating when the dwellings were being monitored for temperature.

Figure 8.1: Monthly mean external temperatures of the two surveyed winters for the five surveyed urban clusters.

(A) Winter 1 (2001 – 2002)



(B) Winter 2 (2002 – 2003)



8.2. Internal Temperature

The *pre*- and *post-WF monitored living room temperature* ($\square T_{mon.lv}$), the *monitored bedroom temperature* ($\square T_{mon.bd}$) and the *monitored internal temperature* ($\square T_{mon.int}$) (Section 4.7.2) are examined. No separate comparisons are made between the longitudinal and the cross-sectional case studies and the temperatures have deliberately not been corrected for the external condition. Detailed analysis on the internal temperature has been already been carried out in a separate a *Warm Front Study* [45].

Table 8.1 shows that the *post-WF* mean living room temperature is 1.0 °C (95%CI: 0.7, 1.3) higher than the *pre-WF* mean living room temperature and the *post-WF* mean bedroom temperature is greater by 1.8 °C (95%CI: 1.5, 2.2). The mean *monitored internal temperature*, which is determined by taking into account the zone 2 room temperature difference (Section 4.7.2), is 1.5 °C higher (95%CI: 1.2, 1.9) *post-WF*. These comparisons which depend heavily on the cross-sectional sample may not provide an accurate assessment of the impact of the *Warm Front scheme*. This issue is explored in Section 8.3 when examining the *standardized internal temperature*.

Table 8.1: A comparison of *pre*- and *post-WF* mean *monitored living room temperature* ($\square T_{mon.lv}$), mean *monitored bedroom temperature* ($\square T_{mon.bd}$) and mean *monitored internal temperature* ($\square T_{mon.int}$).

category	intervention status	mean (95%CI), °C	difference to *pre-WF* group		
			%	□T (95% C), °C	*p*-value
$T_{mon.lv}$	*pre-WF* (n = 514)	18.60 (18.39, 18.80)	5.4	1.05 (0.73, 1.37)	<0.001
	post-WF (n = 386)	19.65 (19.41, 19.99)			
$T_{mon.bd}$	*pre-WF* (n = 514)	16.77 (16.53, 17.00)	10.9	1.82 (1.46, 2.18)	<0.001
	post-WF (n = 386)	18.58 (18.31, 18.86)			
$T_{mon.int}$	*pre-WF* (n = 514)	17.13 (16.92, 17.34)	9.0	1.54 (1.22, 1.86)	<0.001
	post-WF (n =386)	18.67 (18.43, 18.91)			

Figure 8.2 compares the distribution of the living room temperature *pre*- and *post-WF*.

Although there is a clear shift in the distribution towards a higher temperature range *post-WF*, 22 % of the *post-WF* dwellings were still found to maintain the living room temperature below 18 °C compared to 38 % *pre-WF*. A greater shift in the distribution of the bedroom temperature is observed *post-WF* as evidenced by the higher rise in the mean bedroom temperature in Table 8.1. However, the bedrooms are maintained at a lower temperature than the living room with 65 % below 18 °C *pre-WF* and 39 % *post-WF*. The temperature of the *monitored internal temperature* in Figure 8.6 shows a much lower distribution range than the bedroom clearly indicating the potential overestimation of the internal temperature had the bedroom temperature been assumed to represent the entire zone 2 condition.

The impact of different energy efficiency measures on the monitored living room, monitored bedroom and the *monitored internal temperature* are examined in Figure 8.3, Figure 8.5 and Figure 8.7. The temperatures represent means determined from multi-variable analysis where the impact of other energy efficiency measures is taken into account as covariates (Section 4.1). Temperatures associated with measures of draught proofing, insulation and central heating were all found to be higher. The highest mean temperature was found with the combination of insulation and central heating with the living room higher by 1.9 °C (95%CI: 1.1, 2.8), the bedroom by 3.8 °C (95%CI: 2.9, 4.7) and the *monitored internal temperature* by 3.1 °C (95%CI: 2.3, 3.9). This is followed by central heating with a 1.3 °C (95%CI: 0.9, 1.7) higher mean living room temperature, 2.7 °C (95%CU: 2.3, 3.2) higher bedroom temperature and 2.1 °C (95%CI: 1.7, 2.5) higher *monitored internal temperature*. Insulation resulted in a 0.7 °C (95%CI: 0.3, 1.1) higher mean living room, 1.1 °C (95%CI: 0.7, 1.6) higher bedroom temperature and 1.1 °C (95%CI: 0.7, 1.5) higher *monitored mean internal temperature*. Draught proofing was found to be associated with a higher mean bedroom temperature of 0.6 °C (95%CI: 0.2, 1.0) and the *monitored internal temperature* by 0.5 °C (95%CI:

0.1, 0.8).

Figure 8.2: Distribution of the *pre*- and the *post-WF monitored living room temperature* ($T_{mon.lv}$).

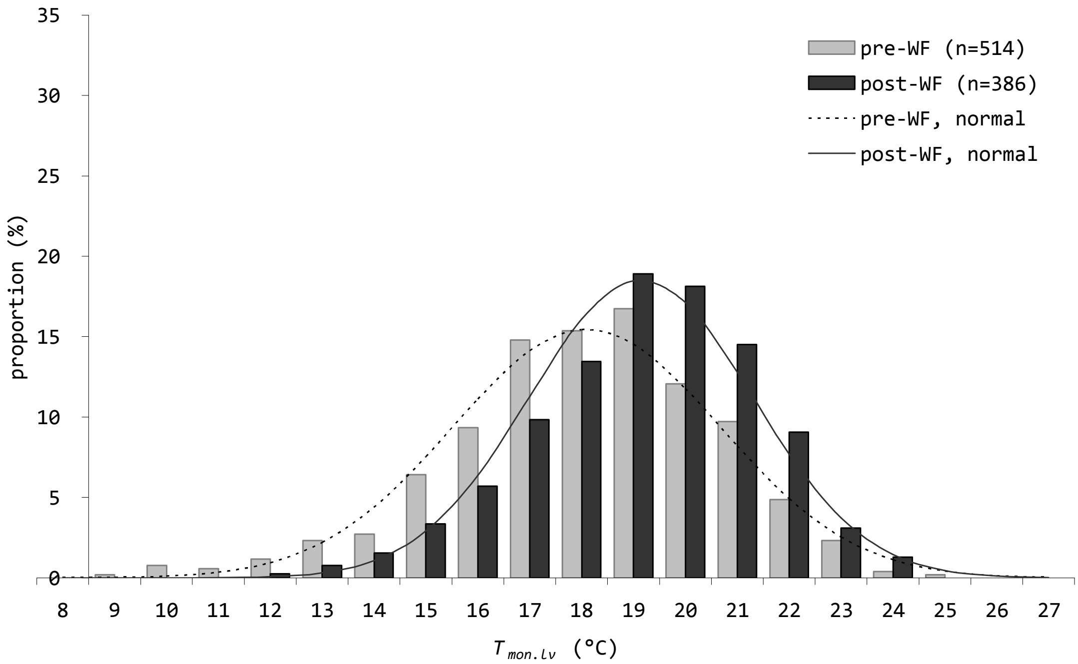


Figure 8.3: A comparison of pre- and post-intervention mean *monitored living room temperature* ($T_{mon.lv}$) ([a] adjusted for insulation and heating, [b] adjusted for draught proofing and heating, [c] adjusted for draught proofing and insulation, *NDP*: no draught proofing, *FDP*: full draught proofing, *NI*: no insulation, *PI*: partial insulation, *FI*: full insulation, *nonCH*: non-central heating, *CH+nonCH*: combination of central and non-central heating, *CHonly*: central heating only, *CH*: *CH+nonCH* & *CHonly*, statistically significant relationship ($p < 0.05$) indicated in solid).

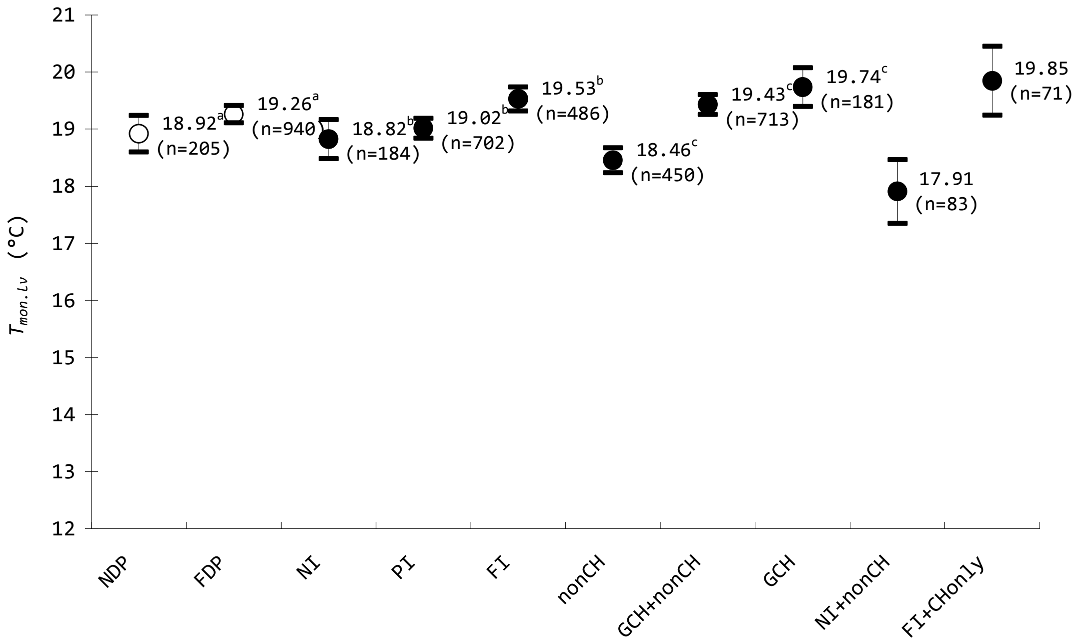


Figure 8.4: Distribution of the *pre-* and the *post-WF monitored bedroom temperature* ($T_{mon.bd}$).

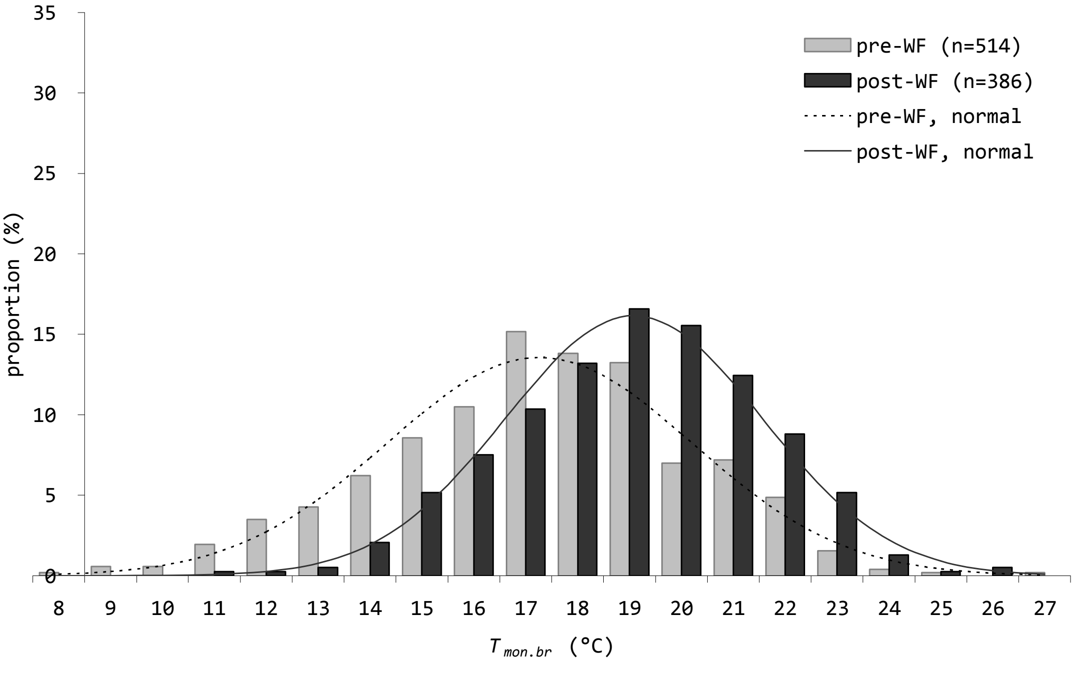


Figure 8.5: A comparison of pre- and post-intervention mean *monitored bedroom temperature* ($T_{mon.bd}$) ([a] adjusted for insulation and heating, [b] adjusted for draught proofing and heating, [c] adjusted for draught proofing and insulation, *NDP*: no draught proofing, *FDP*: full draught proofing, *NI*: no insulation, *PI*: partial insulation, *FI*: full insulation, *nonCH*: non-central heating, *CH+nonCH*: combination of central and non-central heating, *CHonly*: central heating only, *CH*: *CH+nonCH* & *CHonly*, statistically significant relationship ($p < 0.05$) indicated in solid).

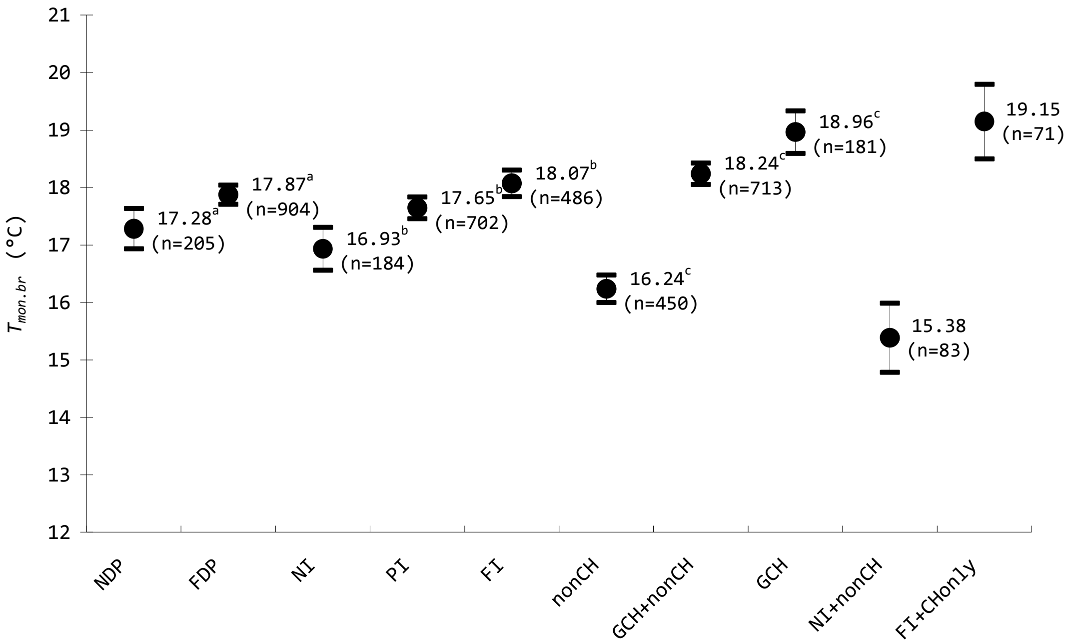


Figure 8.6: Distribution of the *pre*- and the *post-WF monitored internal temperature* ($T_{mon.int}$).

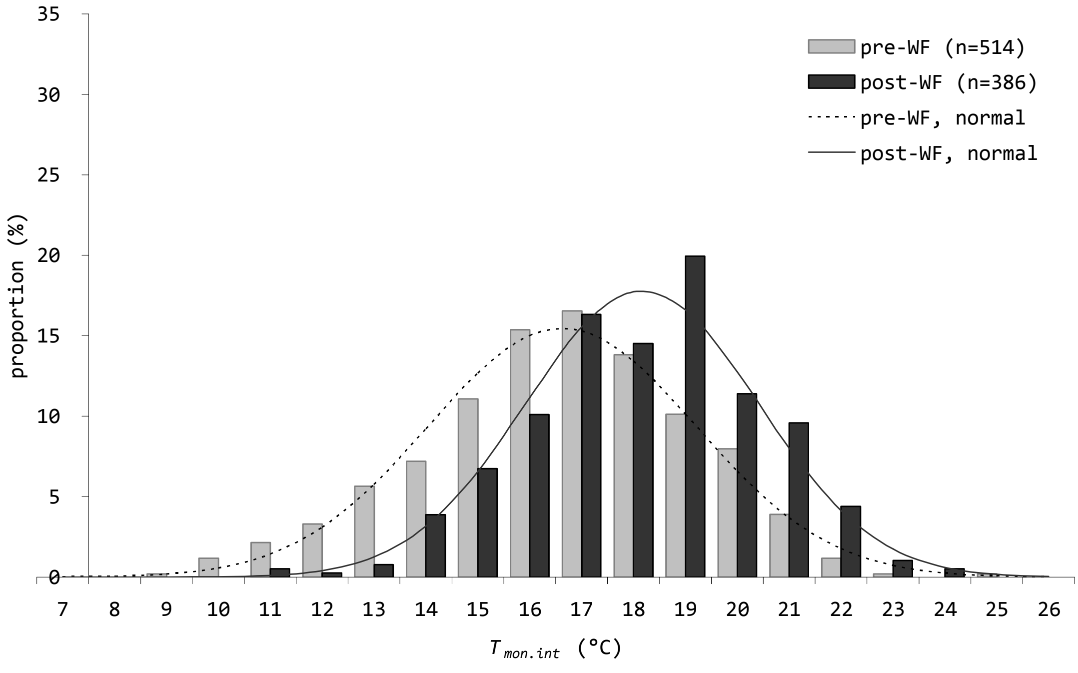
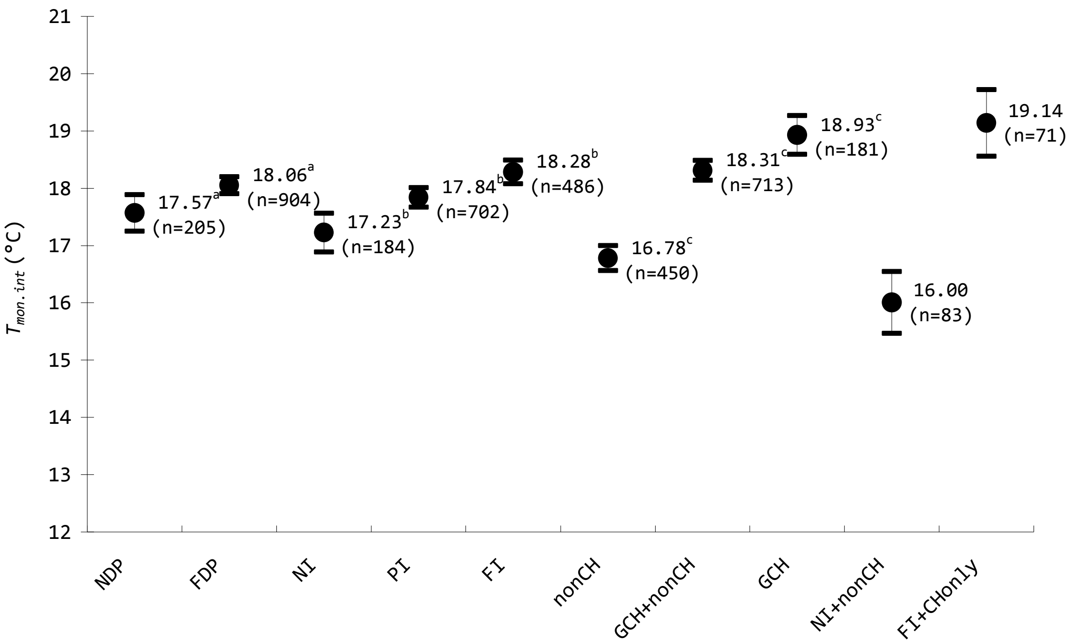


Figure 8.7: A comparison of pre- and post-intervention mean *monitored internal temperature* ($T_{mon.int}$) ([a] adjusted for insulation and heating, [b] adjusted for draught proofing and heating, [c] adjusted for draught proofing and insulation, *NDP*: no draught proofing, *FDP*: full draught proofing, *NI*: no insulation, *PI*: partial insulation, *FI*: full insulation, *nonCH*: non-central heating,

CH+nonCH: combination of central and non-central heating, *CHonly*: central heating only, *CH*: *CH+nonCH* & *CHonly*, statistically significant relationship ($p < 0.05$) indicated in solid).



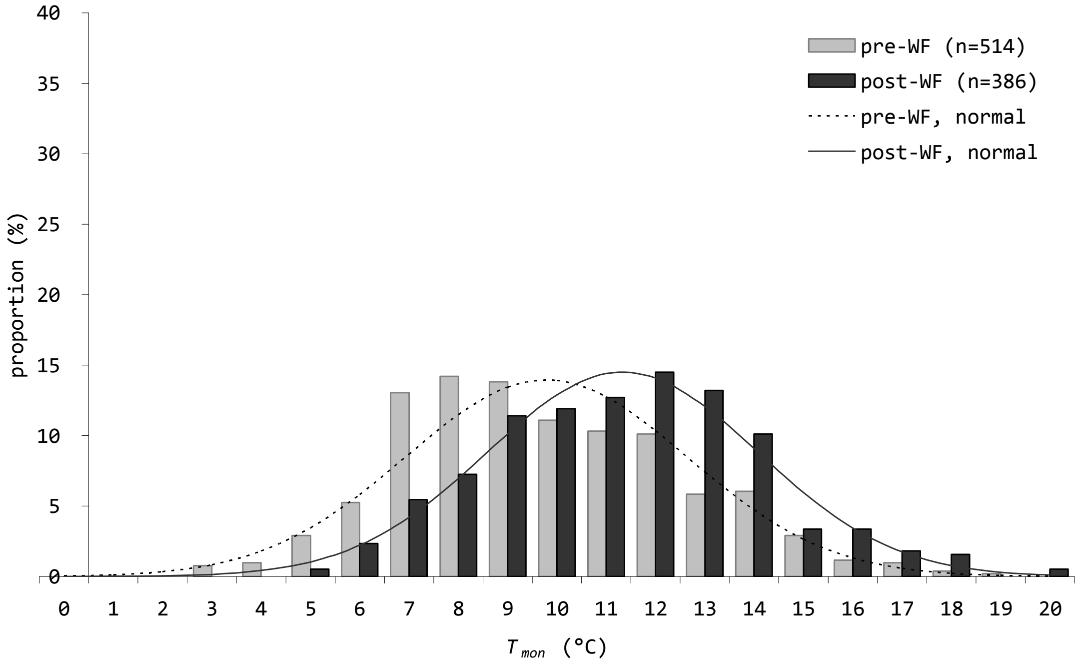
8.3. ***Warm Front Scheme* and *Standardized Internal Temperature***

The distributions of the pre- and the *post-WF monitored* (T_{mon}) and *modelled standardized internal temperatures* (T_{mod}) are compared in Figure 8.8. Both temperatures represent the mean internal temperatures that have been adjusted to the external condition with the former determined from actual monitored temperature and the latter based on BREDEM prediction under a standard heating regime (Sections 4.7 and 4.8). The longitudinal and the cross-sectional case studies are combined in the comparison.

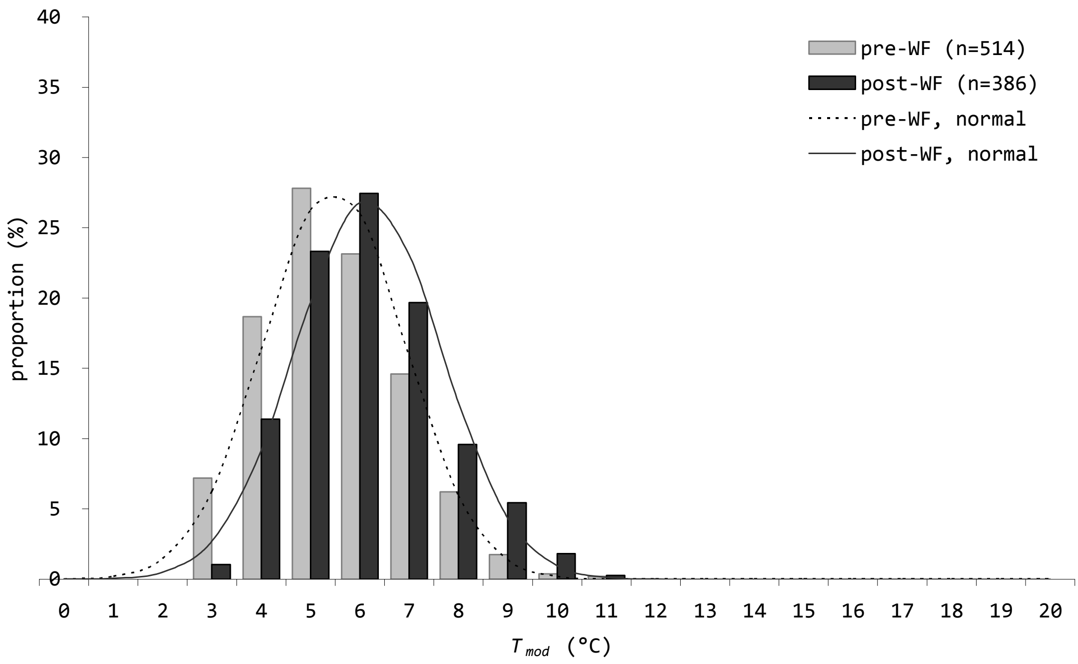
A comparison of the temperature distribution between the monitored and the modelled temperatures shows that the monitored result has a wider range which is reflecting the more varied heating pattern observed in the real dwellings. In contrast the clustering observed in the modelled temperature shows the standard heating regime assumed in the model. The comparison also shows that the modelled result is clustered in a much lower temperature range indicating that the standard heating regime assumed in the model is underestimating the actual heating practice. The underestimation is thought to be less the result of the modelled demand temperature (zone 1: 21 °C; zone 2: 18 °C) but more the result of the lower modelled heating hours (zone 1, weekdays: 9 hrs, weekend: 16 hrs) (zone 2, weekdays: 7 hrs, weekend: 11 hrs) which might not reflect the actual occupancy pattern of the case study households many of whom are likely to spend longer hours inside the house.

Figure 8.8: Distribution of the *pre*- and the *post-WF standardized internal temperature*.

(A) *Monitored standardized internal temperature* (T_{mon}).



(B) *Modelled standardized internal temperature* (T_{mod}).



The mean values of the *monitored* and the *modelled standardized internal temperatures* are *temperatures* are compared in

Table 8.2 disaggregated into the longitudinal and the cross-sectional groups. The monitored result in table 8.2A shows that the post-WF mean temperature is greater by 1.55 °C (95%CI: 1.18, 1.92) and when disaggregated into longitudinal and cross-sectional groups, the longitudinal difference is greater at 2.65 °C (95%CI: 1.17, 4.12) compared to 1.50 °C (95%CI: 1.12, 1.88) in the cross-sectional group although this difference is statistically not significant. Similarly, the difference between the longitudinal and the cross-sectional modelled temperatures are also statistically not significant.

When the changes to the *mean standardized internal temperature* are compared between the *pre*- and *post-WF* following a multi-variable adjustment on the variables of region, dwelling age, dwelling type, household size and income, the longitudinal resulted in 2.01 °C (95%CI: -0.07, 4.10) (not shown) and the cross-sectional 2.09 °C (95%CI: 1.64, 2.53) (not shown) respectively both of which showed similar mean values. On the other hand, the post multi-variable adjusted figures are not found to be statistically significant from the pre-adjusted figures. Similarly, although the multi-variable adjustment changed the modelled result to 1.41 °C (95%CI: 0.66, 2.16) (not shown) in the longitudinal and 0.81 °C (95%CI: 0.58, 1.04) (not shown) in the cross-sectional (not shown), these changes are statistically not significant.

Table 8.2: A comparison of *pre-* and *post-WF* mean *standardized internal temperatures*.

(A) *Monitored standardized internal temperature* (T_{mon}).

category	intervention status	mean (95%CI), °C	difference to *pre-WF* group		
			%	□T (95% C), °C	*p*-value
all sample	*pre-WF* (n = 514)	10.29 (10.04, 10.53)	15.1	1.55 (1.18, 1.92)	<0.001
	post-WF (n = 386)	11.8 (11.6, 12.1)			
longitudinal	*pre-WF* (n = 22)	9.13 (8.09, 10.17)	29.0	2.65 (1.17, 4.12)	<0.001
	post-WF (n = 22)	11.8 (10.7, 12.8)			
cross-sectional	*pre-WF* (n = 492)	10.34 (10.09, 10.59)	14.5	1.50 (1.12, 1.88)	<0.001
	post-WF (n = 364)	11.84 (11.55, 12.13)			

(B) *Modelled standardized internal temperature* (T_{mod}).

category	intervention status	mean (95%CI), °C	difference to *pre-WF* group		
			%	□T (95% C), °C	*p*-value
all sample	*pre-WF* (n = 514)	5.98 (5.86, 6.10)	11.5	0.69 (0.51, 0.88)	<0.001
	post-WF (n = 386)	6.67 (6.53, 6.82)			
longitudinal	*pre-WF* (n = 28)	5.24 (4.77, 5.72)	26.1	1.37 (0.70, 2.03)	<0.001
	post-WF (n = 28)	6.6 (6.1, 7.1)			
cross-sectional	*pre-WF* (n = 486)	6.02 (5.89, 6.15)	11.0	0.66 (0.46, 0.85)	<0.001
	post-WF (n = 358)	6.68 (6.53, 6.83)			

8.4. Energy Efficiency Measures and *Standardized Internal Temperature*

Figure 8.9 examines the impact of draught proofing, insulation and central heating on the mean *monitored* and *modelled standardized internal temperature*. The two centrally heated groups *CHonly* (central heating only) and *CH+nonCH* (central heating and room heaters) are combined as *CH* (central heating) in the modelled analysis since central heating is assumed the only source of space heating in the model. Dwellings using storage heaters as central heating (2 %) are excluded from the analysis.

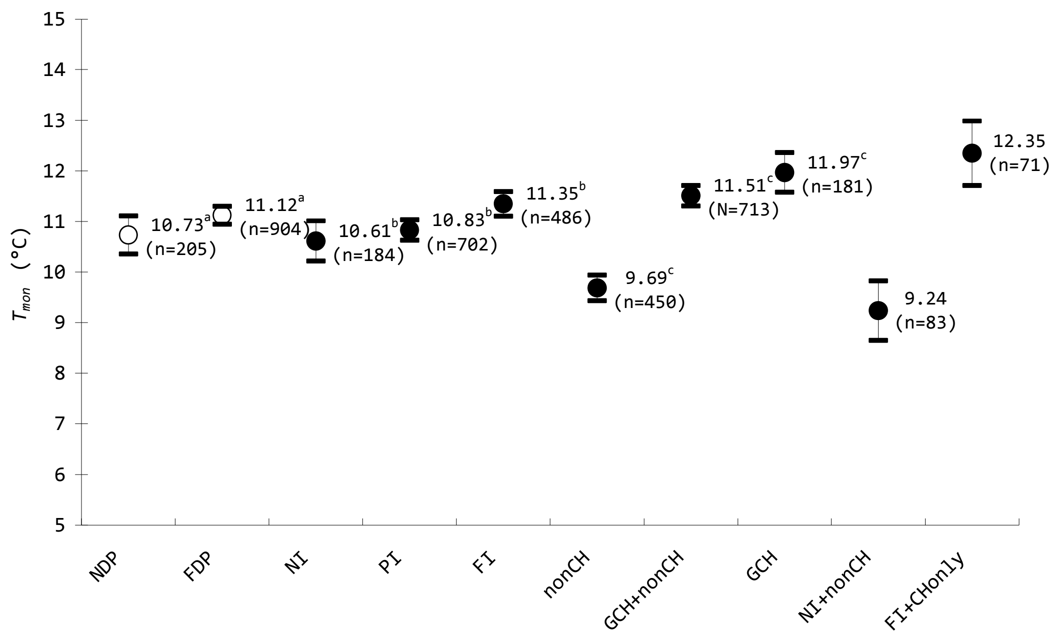
The monitored result in Figure 8.9A shows that draught proofing is associated with a mean 0.39 °C (95%CI: -0.03, 0.81) rise in temperature although statistically not significant. Full insulation resulted in a 0.73 °C (95%CI: 0.26, 1.20) rise and the gas central heating 2.28 °C (95CI: 1.81, 2.75). As expected the highest increase is observed from the combination of insulation and central heating resulting in an increase of 3.11 °C (95CI: 2.25, 3.98).

The modelled result in Figure 8.9B shows draught proofing increased the internal temperature by a mean of 0.26 °C (95CI: 0.04, 0.47) although this is also statistically not significant. Full insulation resulted in a mean increase of 1.06 °C (95CI: 0.83, 1.29) which is higher than the monitored observation. Central heating, on the other hand, resulted in only a 0.24 °C (95CI: 0.08, 0.40) rise and the combination of full insulation and central heating a 1.71 °C (95CI: 1.26, 2.15) increase both of which are lower than the monitored result.

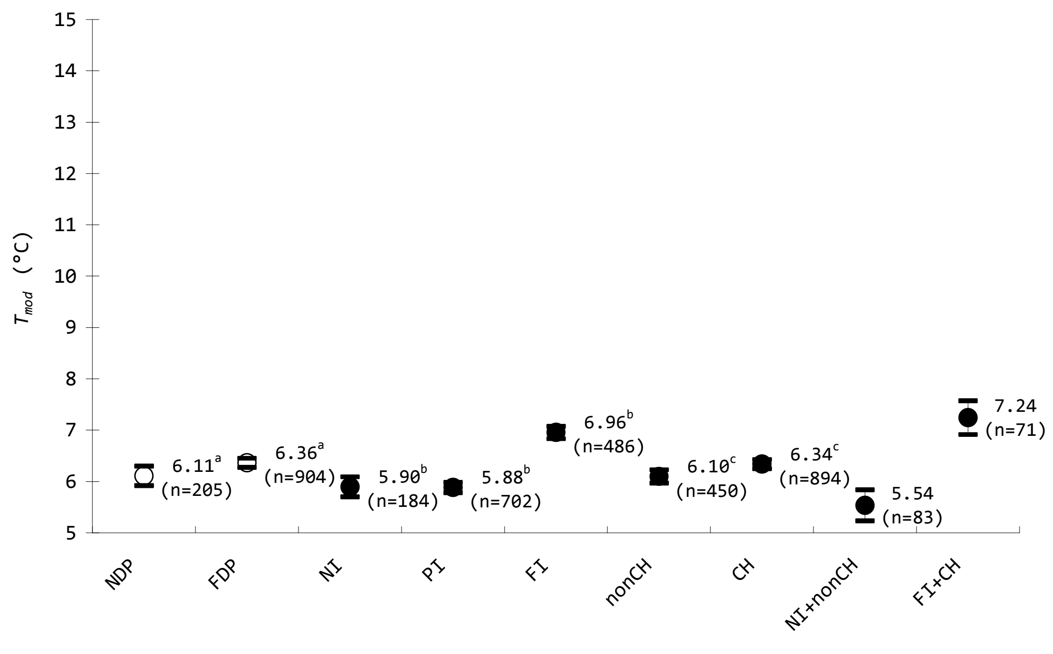
The same analyses carried out with multi-variable adjustment of region, dwelling age, dwelling type, household size and income (Table 8.3) showed statistically no significant changes in both the monitored and the modelled results (not shown) despite smaller sample sizes resulting from disaggregation.

Figure 8.9: Impact energy efficiency measures on the mean *monitored* and *modelled standardized internal temperature* ([a] adjusted for insulation and heating, [b] adjusted for draught proofing and heating, [c] adjusted for draught proofing and insulation, *NDP*: no draught proofing, *FDP*: full draught proofing, *NI*: no insulation, *PI*: partial insulation, *FI*: full insulation, *nonCH*: non-central heating, *CH+nonCH*: combination of central and non-central heating, *CHonly*: central heating only, *CH*: *CH+nonCH* & *CHonly*, statistically significant relationship ($p<0.05$) indicated in solid).

(A) *Monitored standardized internal temperature* (T_{mon}).



(B) *Modelled standardized internal temperature* (T_{mod}).



8.5. Heat Loss Parameter and *Standardized Internal Temperature*

Two principle mechanisms explain the rise in internal temperature following energy efficiency improvement: one through the physical process of reduced heat loss through the building fabric and the other is through the occupancy behavior of increased demand temperature known as the *comfort taking* (Section 2.11). Correctly identifying the change in the internal temperature by these two different mechanisms is important when quantifying the associated change in the energy consumption as will be examined in Chapter 9.

What follows is a series of 4 figures relating the *monitored* and the *modelled standardized internal temperatures* to the *heat loss parameter* (*HLP*) which is a measure of the building fabric *heat loss performance*, i.e. how well a building is insulated and sealed (Section 4.4). These comparisons explore how much of the rise in internal temperature is attributable to improved *heat loss performance* of the building fabric.

Two linear regression lines are shown in Figure 8.10, one, the monitored relationship between the *monitored standardized internal temperature* (T_{mon}) and the *ventilation and insulation adjusted modelled heat loss parameter* ($HLP_{mod(vi)}$) and two, the modelled relationship between the *modelled standardized internal temperatures* (T_{mod}) and the *modelled heat loss parameter* (HLP_{mod}). The three different insulation levels of NI (no insulation), PI (partial insulation) and FI (full insulation) are included in the figure to qualitatively measure the *heat loss parameter* range. The *ventilation and insulation adjusted modelled heat loss parameter* is considered to be a closer representation of the actual building heat loss performance since it is adjusted for the *monitored air leakage rate* (Section 6.1) and the *monitored U-values* (Section 6.2).

The significance of the modelled relationship is that its slope describes the rise in the internal temperature that can be expected from the physical process alone. This is because the change in the *modelled standardized internal temperatures* is not affected by the *comfort taking* (Section 4.7.1). Compared to the modelled relationship if the slope of the monitored relationship is greater, then the difference between the two slopes could be interpreted as the effect of the *comfort taking*.

In Figure 8.10, the slope of the modelled relationship shows a 0.60 °C (st. error: ± 0.04 °C) rise in temperature in relation to a unit decrease – improved performance – in the *modelled heat loss parameter*. In comparison, the monitored relationship shows a lower slope of 0.41 °C (st. error: ± 0.09 °C) which is statistically significant indicating not only no evidence of *comfort taking* but draught proofing and insulation having lesser impact on the internal temperature than the level theoretically expected.

Figure 8.10: The *monitored standardized internal temperature* (T_{mon}) related to the *ventilation and insulation adjusted modelled heat loss parameters* ($HLP_{mod(vi)}$) and the *modelled standardized internal temperature* (T_{mod}) related to the *modelled heat loss parameter* (HLP_{mod}).

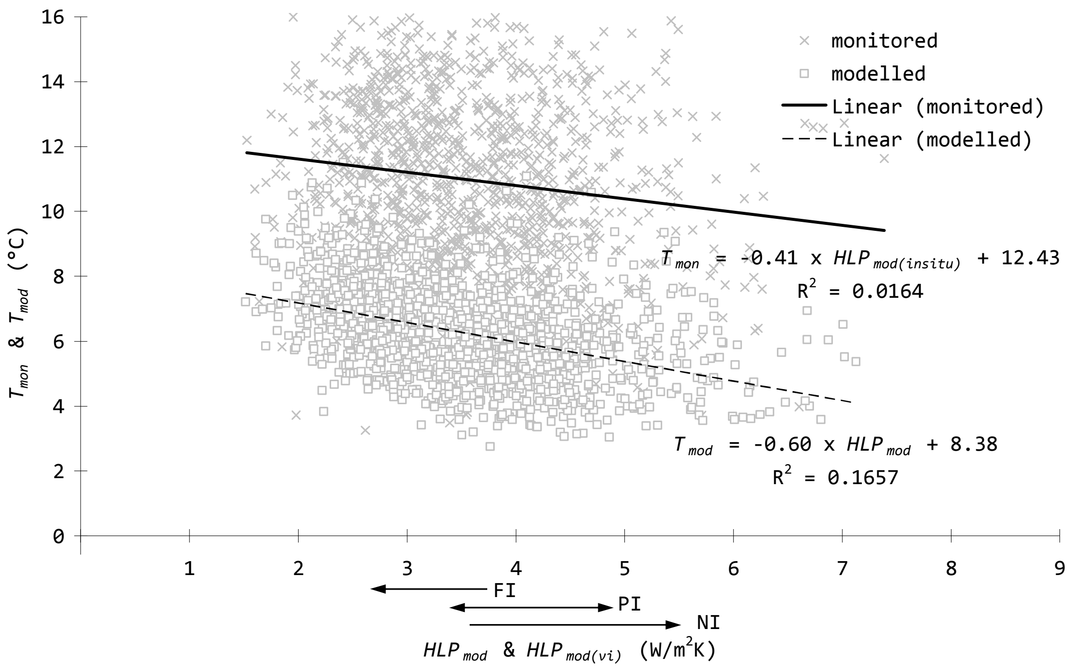
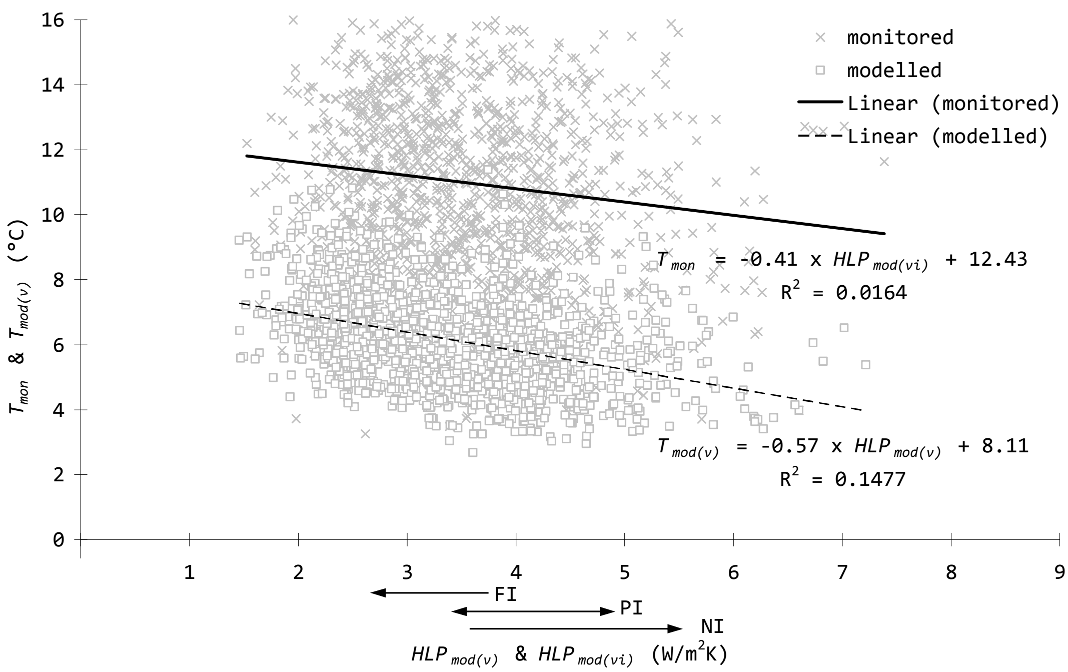


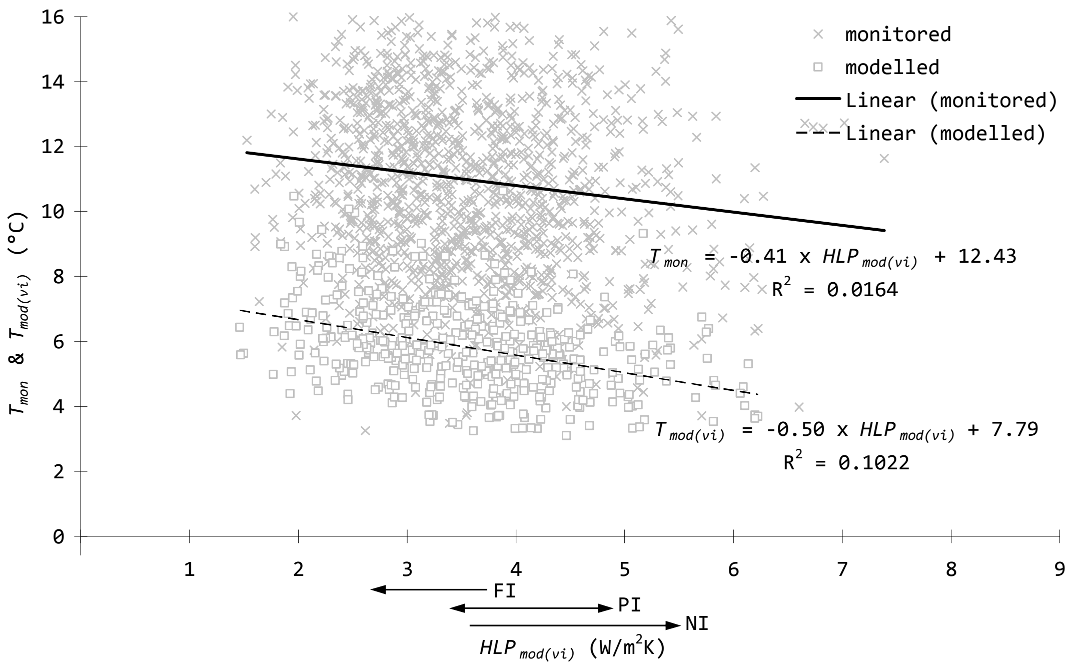
Figure 8.11 shows the same comparison but the monitored relationship is adjusted by the *monitored air leakage rate* intended to bring the slope of the modelled relationship closer to that of the monitored condition by introducing a monitored performance variable which could partly explain the difference in the slope. This adjustment was effective in reducing the absolute value of the modelled slope from 0.60 °C to 0.57 °C (st. error: ± 0.04 °C) but the slope is still greater than the monitored slope and the difference statistically significant.

Figure 8.11: The *monitored standardized internal temperature* (T_{mon}) related to the *ventilation and insulation adjusted modelled heat loss parameter* ($HLP_{mod(vi)}$) and the *ventilation adjusted modelled standardized internal temperature* ($T_{mod(v)}$) related to the *ventilation adjusted modelled heat loss parameter* ($HLP_{mod(v)}$).



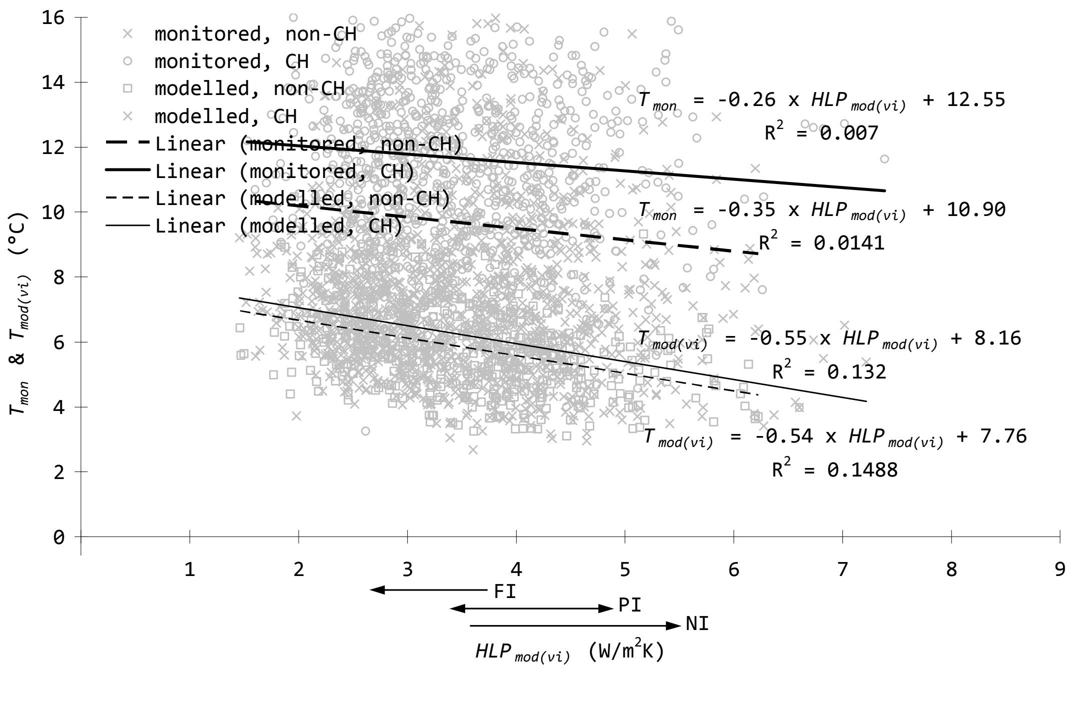
In Figure 8.12, the ventilation adjusted modelled relationship is further adjusted by the *monitored U-values*. This resulted in a further reduction in the absolute value of the modelled slope from 0.57 °C to 0.50 °C (st. error: ± 0.06 °C) bordering a statistically significant difference between the two slopes and thereby indicating no evidence of the *comfort taking* associated with draught proofing and insulation.

Figure 8.12: The *monitored standardized internal temperature* (T_{mon}) related to the *ventilation and insulation adjusted heat loss parameter* ($HLP_{mod(vi)}$) and the *ventilation and insulation adjusted modelled standardized internal temperature* ($T_{mod(vi)}$) related to the *ventilation and insulation adjusted heat loss parameter* ($HLP_{mod(vi)}$).



In Figure 8.13, the monitored and the modelled relationships from Figure 8.12 are disaggregated into non-centrally heated (*nonCH*) and centrally heated (*CH*) dwellings. In both the monitored and the modelled relationships, the *CH* regression lines are shifted in parallel to a higher temperature range in relation to their *nonCH* counterparts by about 1.5 °C and by about 0.4 °C in the modelled group. The greater temperature difference in the monitored group reflects the effect of the *comfort taking*. The figure also shows that there is little difference in the slopes between the *nonCH* and the *CH* dwellings within each respective group indicating that isolating the effect of the heating system resulted in very little change in the monitored and the modelled relationships between the temperature and the heat loss parameter.

Figure 8.13: The *monitored standardized internal temperature* (T_{mon}) and the *ventilation and insulation adjusted modelled standardized internal temperature* ($T_{mod(vi)}$) – disaggregated by the heating system – related to *the ventilation and insulation adjusted modelled heat loss parameter* ($HLP_{mod(vi)}$).



8.6. Discussion

This chapter examined the impact of energy efficiency measures on the indoor temperature. The internal temperatures examined were the *monitored living room temperature* ($T_{mon.lv}$), the *monitored bedroom temperature* ($T_{mon.bd}$) and the *monitored internal temperature* ($T_{mon.int}$), the *monitored standardized internal temperature* (T_{mon}) and the *modelled standardized internal temperature* (T_{mod}).

The impact of energy efficiency measure on the different internal temperatures examined in this chapter is summarized in Table 8.3. Although not specifically examined, the last column also shows the changes to the *ventilation and insulation adjusted modelled standardized internal temperature* ($\triangle T_{mod(vi)}$) where the *modelled standardized internal temperature* is adjusted for the *monitored air leakage rate* (Section 6.1) and the *monitored U-values* (Section 6.2).

The examination of the monitored room temperatures showed that the scheme resulted in the highest mean increase in the bedroom temperature by 1.8 °C (95%CI: 1.5, 2.2) from 16.8 °C to 18.6 °C followed by the living room temperature by 1.0 °C (95%CI: 0.7, 1.3) from 18.6 °C to 19.6 °C.

Compared to the average English dwelling condition [25], the *post-WF* mean living temperature of 19.6 °C is higher than the English average of 19.1 °C while a similarity in the bedroom temperature is found in to the English average of 18.5 °C. These *post-WF* temperatures were also found to be well within the thermally comfortable range determined from a previous *Warm Front Thermal Comfort Paper* (Appendix 4) [38] indicating that the scheme was effective in delivering the desired living room and bedroom temperatures.

Table 8.3: A comparison of mean *monitored living room temperature* ($\Delta T_{mon.lv}$), mean *monitored bedroom temperature* ($\Delta T_{mon.bd}$), mean *monitored internal temperature* ($\Delta T_{mon.int}$), mean *monitored standardized internal temperature* (ΔT_{mon}), mean *modelled standardized internal temperature* (ΔT_{mod}) and the mean *ventilation and insulation adjusted modelled standardized internal temperature* ($\Delta T_{mod(vi)}$).

intervention (baseline group)		change relative to baseline group (95%CI), °C					
		$\Delta T_{mon.lv}$	$\Delta T_{mon.bd}$	$\Delta T_{mon.int}$	ΔT_{mon}	ΔT_{mod}	$\Delta T_{mod(vi)}$
FDP (NDP)	*unadj*	0.34 (-0.01, 0.70)	**0.59 (0.20, 0.98)**	0.48 (0.13, 0.84)	0.39 (-0.03, 0.81)	**0.26 (0.04, 0.47)**	**0.16 (-0.05, 0.36)**
	*adj**	-	-	-	0.44 (-0.08, 0.96)	0.15 (-0.09, 0.39)	-
FI (NI)	*unadj*	**0.71 (0.31, 1.11)**	**1.14 (0.70, 1.58)**	**1.06 (0.66, 1.46)**	**0.73 (0.26, 1.20)**	**1.06 (0.83, 1.29)**	**0.65 (0.41, 0.88)**
	*adj**	-	-	-	**1.14 (0.55, 1.73)**	**1.16 (0.90, 1.43)**	-
CH (nonCH)	*unadj*	**1.28 (0.88, 1.69)**	**2.73 (2.29, 3.17)**	**2.15 (1.75, 2.55)**	**2.28 (1.81, 2.75)**	**0.24 (0.08, 0.40)**	**0.37 (0.21, 0.52)**
	*adj**	-	-	-	**2.05 (1.41, 2.68)**	-0.01 (-0.18, 0.63)	-
FI+CH (NI+nonCH)	*unadj*	**1.94 (1.12, 2.76)**	**3.80 (2.88, 4.65)**	**3.13 (2.34, 3.93)**	**3.11 (2.25, 3.98)**	**1.48 (1.17, 1.79)**	**1.14 (0.82, 1.45)**
	*adj**	-	-	-	3.58 (2.16, 5.01)	**1.25 (-0.90, 1.61)**	-
Post-WF (Pre-WF)	*unadj*	**1.05 (0.73, 1.37)**	**1.82 (1.46, 2.18)**	**1.54 (1.22, 1.86)**	**1.55 (1.18, 1.92)**	**0.69 (0.51, 0.88)**	**0.5 (0.4, 0.7)**
	*adj**	-	-	-	**2.08 (1.65, 2.51)**	**0.84 (0.63, 1.06)**	-

positive figures indicate increase in temperature.
statistically significant changes ($p < 0.05$) are highlighted in bold.
NDP: no draught proofing, FDP: full draught proofing, NI: no insulation, FI: full insulation, nonCH: no central heating, CHonly: central heating only, CH: central heating with or without local heating.
**adjusted for region, dwelling age, dwelling type, household size and income.*

The combination of insulation and central heating resulted in the greatest rise across all monitored temperatures followed by central heating followed by insulation followed by draught proofing. On the other hand, the modelled temperatures show insulation resulting in a greater temperature rise than central heating due to constant heating regime assumed in the model. The temperature rise observed with the combination of full insulation and central heating (*FI+CHonly*) is not observed in *Warm Front* since many of the *pre-WF* cases already owned insulation or central heating or both measures while many of the *post-WF* cases were still missing the full measures due to solid walled dwellings and households with young children not qualifying for central heating.

Table 8.3 shows that the multi-variable adjustment of the mean temperatures based on a representative property and household characteristics showed statistically no significant differences in the results indicating that the distribution of the *pre*- and *post-WF* cross-sectional samples, which are predominantly compared in the analyses, is fairly similar providing robust results even when the sample was disaggregated into smaller numbers.

The mean values and the confidence intervals indicate that there is no difference in the temperature rise associated with insulation between the *monitored standardized internal temperature* (ΔT_{mon}) and the *ventilation and insulation adjusted modelled standardized internal temperature* ($\Delta T_{mod(vi)}$). Since the effect of the *comfort taking* is not taken into account in the model, the similarity between the monitored and the modelled results suggests no *comfort taking* associated with insulation.

In all comparisons between the *monitored standardized internal temperature* and the *modelled standardized internal temperature*, the monitored values were found to be on average about 4 °C higher than the modelled. The external temperature does not explain the difference because they are both standardized to the same *monitored external temperature*. While the greater monitored temperature in the *post-WF* group may partially be explained as the effect of the *comfort taking*, the difference in the *pre-WF* group indicates the likely combination of over-estimation in the *monitored internal temperature* (Section 4.7.2) and under-estimation in the *modelled internal temperature* (Section 4.7.1) assumed to arise from lower heating hours assumed in the model, i.e. the standard heating regime may not reflect the possibly longer heating hours experienced in the case study dwellings.

However, the temperature difference is expected to have little impact on the outcome of this study because the analyses focus on the temperature change. The changes in the *monitored* and the *modelled standardized internal temperatures* determined from this chapter will be used in Chapter 9 when determining the change in the energy consumption associated with the *comfort taking*.

CHAPTER 9 COMFORT TAKING

The aim of this chapter is to estimate the *comfort taking* (□Q_{CT}) associated with the *Warm Front Scheme* and energy efficiency measures (Section 4.11.2). The process requires relating the *monitored space heating energy consumption* (Q_{mon}) and its associated cost and carbon emissions to the *monitored standardized internal temperature* (T_{mon}) – the two parameters which so far have been examined separately in Chapters 7 and 8 respectively – using the graphical approach illustrated in Figure 4.4. Although no evidence of the *comfort taking* was found with the installation of draught proofing and insulation in Section 8.5, their effects on the energy consumption and the temperature are also included for comparison. The figures describing the relationships between the energy cost ($Q_{mon(cost)}$) and the carbon emissions ($Q_{mon(co2)}$) to the temperature are also presented but the descriptions mainly focus on the *monitored space heating energy consumption* (Q_{mon}) due to the similarity in the methodology.

Sections 9.1 and 9.2 examine the effect of the draught proofing and the insulation on the *monitored space heating energy consumption* (associated cost and carbon emissions) and the *monitored standardized internal temperature*; Section 9.3 estimates the *comfort taking* associate with central heating; Section 9,4 estimated the *comfort taking* in relation to the combination of full insulation and central heating and Section 9.5 in relation to the *Warm Front Scheme*. Section 9.6 summarizes the findings.

9.1. Impact of Draught Proofing on Temperature and Energy Usage

The impact of draught proofing on the *monitored standardized internal temperature* (T_{mon}) and the *monitored space heating energy consumption* (Q_{mon}) is examined by comparing their differences between the no draught proofing (*NDP*) and the full draught proofing (*FDP*) case study dwellings in Figure 9.1 (Table 4.5).

The geometric figures represent the estimated marginal means, i.e. taking into account the effect of insulation and heating (Section 4.1), of the *monitored standardized internal temperature* and the *monitored space heating energy consumption* for the *NDP* (○: 10.7 °C, 0.8 kWh/m^2/day) and the *FDP* (□: 11.1 °C, 0.8 kWh/m^2/day) dwellings. The figure also includes two linear equations describing the relationship between the temperature and the energy consumption generated from the scatter plots of *NDP* and the *FDP* with their origins forced to the respective internal temperature gains of 2.4 °C and 2.5 °C (Table 4.25).

The geometric figures describing the estimated marginal means are indicated as non-solids to represent the lack of statistical significance in the difference between the two groups (Table 7.4, Table 8.3). Although not shown in the figure, the overlap in the 95%CI of the two regression lines also provides inconclusive evidence on the impact of draught proofing on the temperature and the energy consumption. The results are found to be similar when examined based on the energy cost ($Q_{mon(cost)}$) and carbon emissions ($Q_{mon(co2)}$) in Figure 9.2 and Figure 9.3 respectively.

Figure 9.1: The m*onitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* (Q_{mon}) by draught proofing status (*NDP*: no draught proofing, *FI*: full draught proofing, regression lines do not show 95%CI).

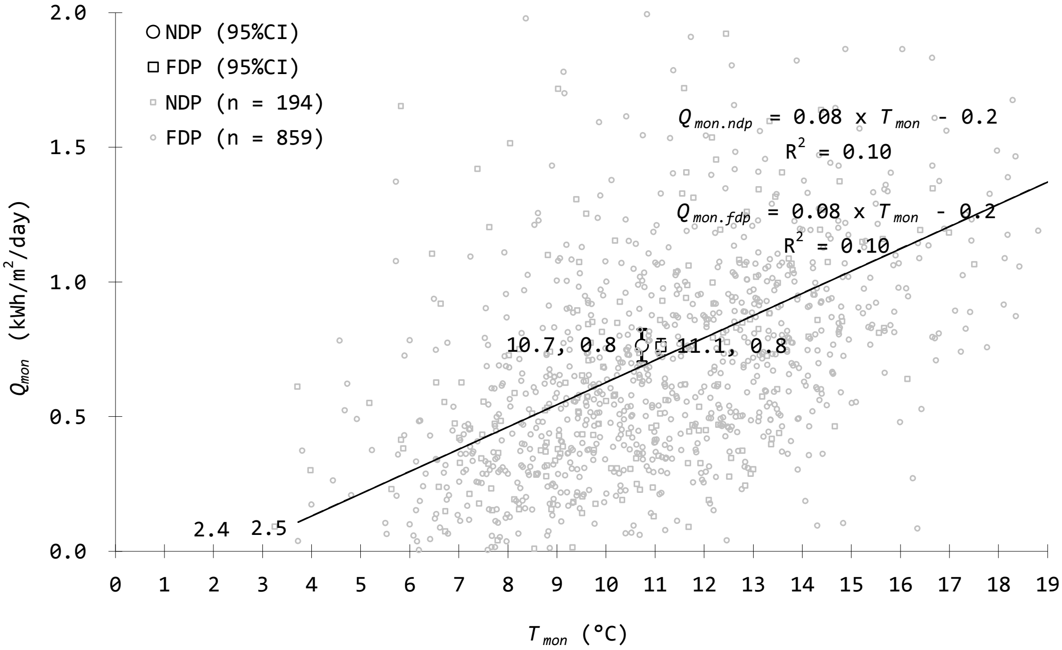


Figure 9.2: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* associated cost ($Q_{mon(cost)}$) by draught proofing status (*NDP*: no draught proofing, *FI*: full draught proofing, regression lines do not show 95%CI).

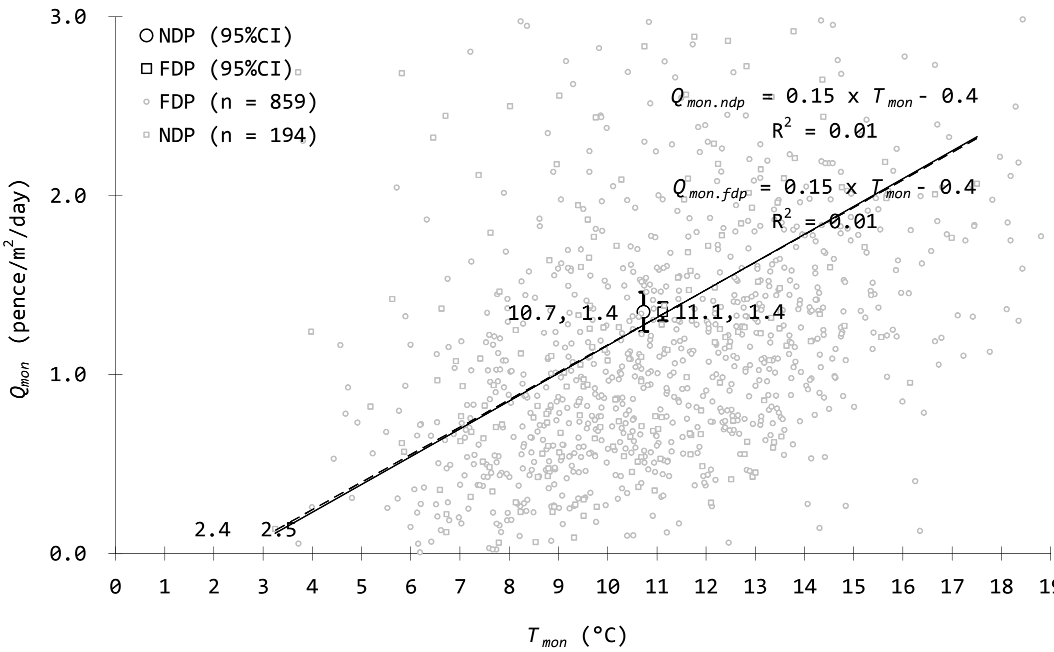
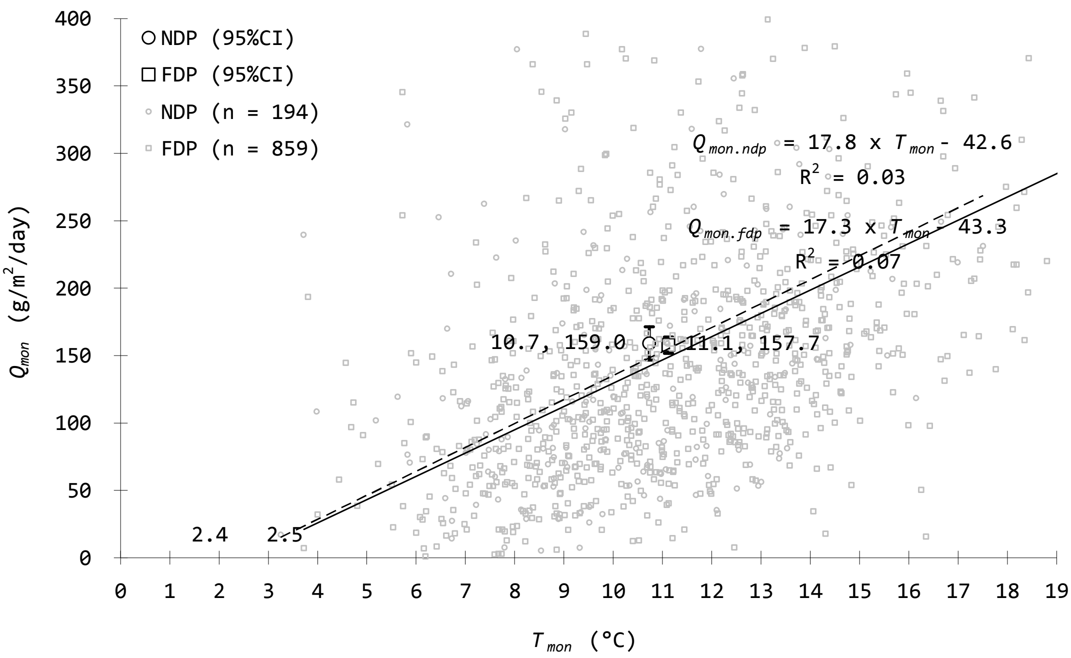


Figure 9.3: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* associated carbon emissions ($Q_{mon(co2)}$) by draught proofing status (*NDP*: no draught proofing, *FI*: full draught proofing, regression lines do not show 95%CI).



9.2. Impact of Insulation on Temperature and Energy Usage

The impact of insulation on the *monitored standardized internal temperature* (T_{mon}) and the *monitored space heating energy consumption* (Q_{mon}) is examined by comparing their differences between the no insulation (NI) and the full insulation (FI) case study dwellings in Figure 9.4 (Table 4.6).

The figure shows the estimated marginal means of the *monitored standardized internal temperature* and the *monitored space heating energy consumption* for the NI (○: 10.6 °C, 0.8 kWh/m^2/day) and the FI (□: 11.3 °C, 0.7 kWh/m^2/day) dwellings (Section 4.1). Scatter plots describing the relationship between the temperature and the energy consumption of the two groups are also included along with their best-fit regression lines with origins forced to the internal temperature gains of 2.1 °C and 3.0 °C for the NI and the FI respectively (Table 4.25).

Although the estimated marginal mean in Table 8.3 indicated a statistically significant improvement in the internal temperature by 0.7 °C, the 0.1 kWh/m^2/day decrease in the mean energy consumption was found to be statistically weak in Table 7.4 as can be seen by the overlap in the 95%CI in Figure 9.4. On the other hand, the decrease in the slope of the regression line from NI to FI indicates improved energy performance from insulation while the lower y-intercept in the FI regression line indicates the FI dwellings are requiring on average 0.05 kWh/m^2/day less energy to maintain the same internal temperature compared to the NI dwellings. When examined in relation to the energy cost ($Q_{mon(cost)}$) and carbon emissions ($Q_{mon(co2)}$), clear evidence of their reduction is found associated with insulation accompanied by an increase in the temperature. No *comfort taking* is estimated in relation to insulation based on the evidence from Section 8.5.

Figure 9.4: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* (Q_{mon}) by insulation status (NI: no insulation, FI: full insulation).

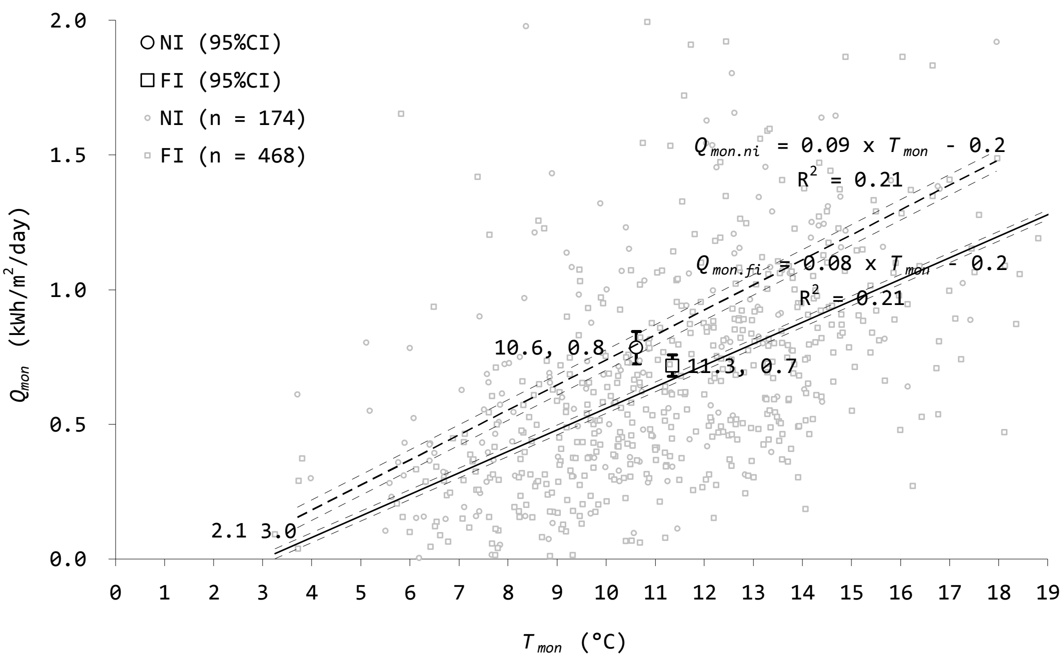


Figure 9.5: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* associated cost ($Q_{mon(cost)}$) by insulation status (NI: no insulation, FI: full insulation).

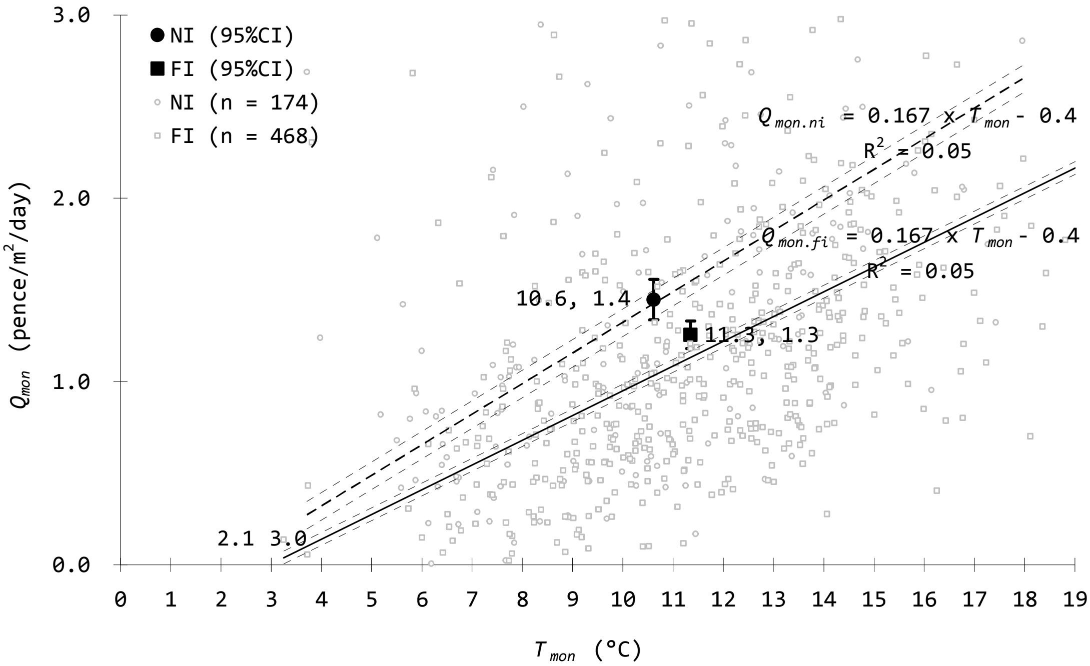
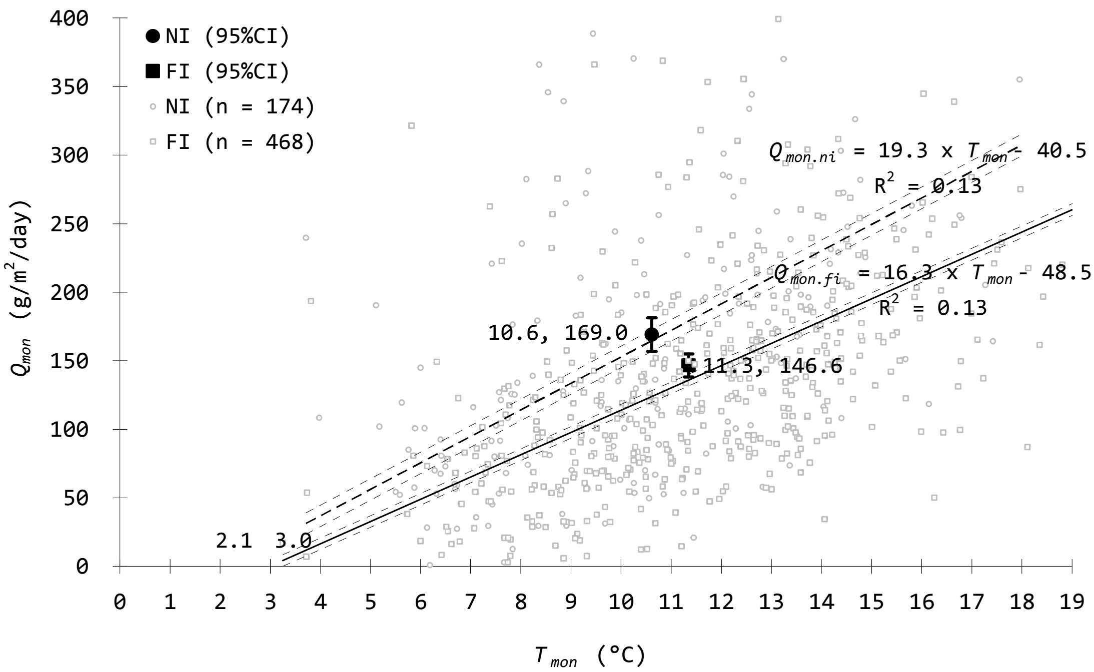


Figure 9.6: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* associated carbon emissions ($Q_{mon(co2)}$) by insulation status (NI: no insulation, FI: full insulation).



9.3. Impact of Central Heating on the *Comfort Taking*

The impact of central heating on the *monitored standardized internal temperature* (T_{mon}) and the (T_{mon}) and the *monitored space heating energy consumption* (Q_{mon}) is examined by comparing comparing the performances between the case study dwellings grouped into non-central central heating (*nonCH*) and central heating only (*CHonly*) case study dwellings in

Figure 9.7 (Table 4.7)

The figure shows the estimated marginal means of the *monitored standardized internal temperature* and the *monitored space heating energy consumption* for the *nonCH* (●: 9.7 °C, 0.6 kWh/m^2/day) and the *CHonly* (■: 12.0 °C, 0.8 kWh/m^2/day) dwellings (Section 4.1). The temperature difference of 2.3 °C (Table 8.3) and the energy consumption difference of 0.2 kWh/m^2/day (Table 7.4) were both found to be statistically different and therefore indicated in solid.

Scatter plots describing the relationship between the temperature and the energy consumption of the two groups are included along with their best-fit regression lines with origins forced to the internal temperature gains of 2.4 °C and 2.7 °C for the *nonCH* and the *CHonly* respectively (Table 4.25). The overlap in the 95% confidence intervals between the two regression lines suggests no improvement in the energy performance associated with central heating.

$Q_{mon.chonly}$ equation is solved for the pre-*comfort taking* temperature of 9.7 °C to determine the post-intervention hypothetical point *CHonly'* (△: 9.7 °C, 0.6 kWh/m^2/day)

The temperature and energy consumption rise associated with the *comfort taking* is determined as the difference between *CHonly* (■: 12.0 °C, 0.8 kWh/m^2/day) and *CHonly'* resulting in 2.3 °C and 0.2 kWh/m^2/day.

Figure 9.7: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* (Q_{mon}) by heating system (*nonCH*: non-central heating, *CHonly*: central heating only).

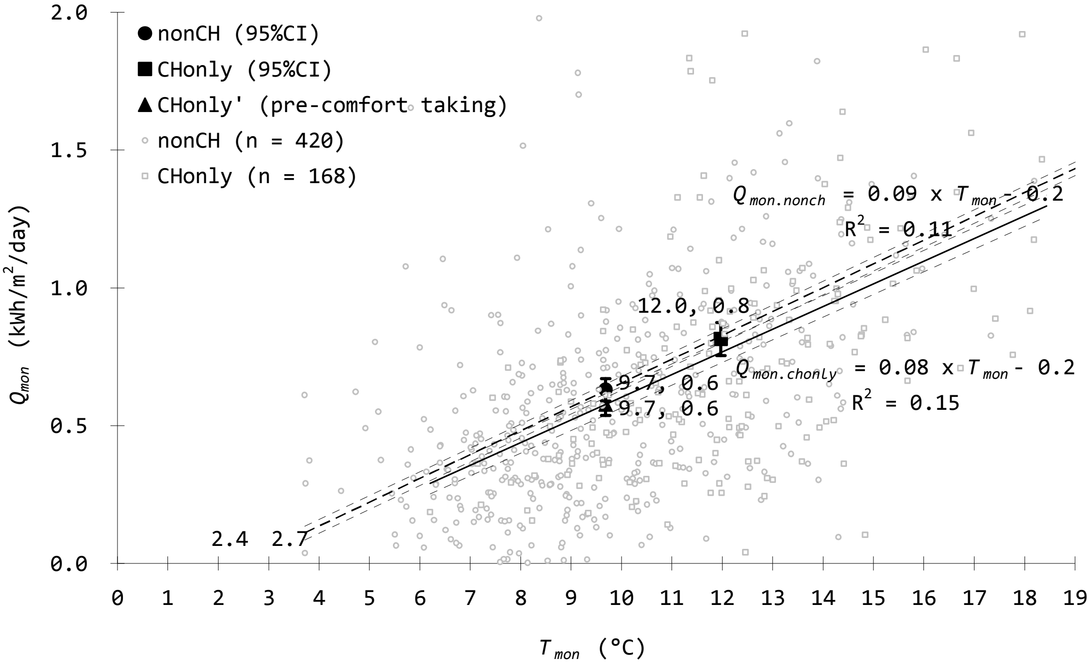


Figure 9.8: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* associated cost ($Q_{mon(cost)}$) by heating system (*nonCH*: non-central heating, *CHonly*: central heating only).

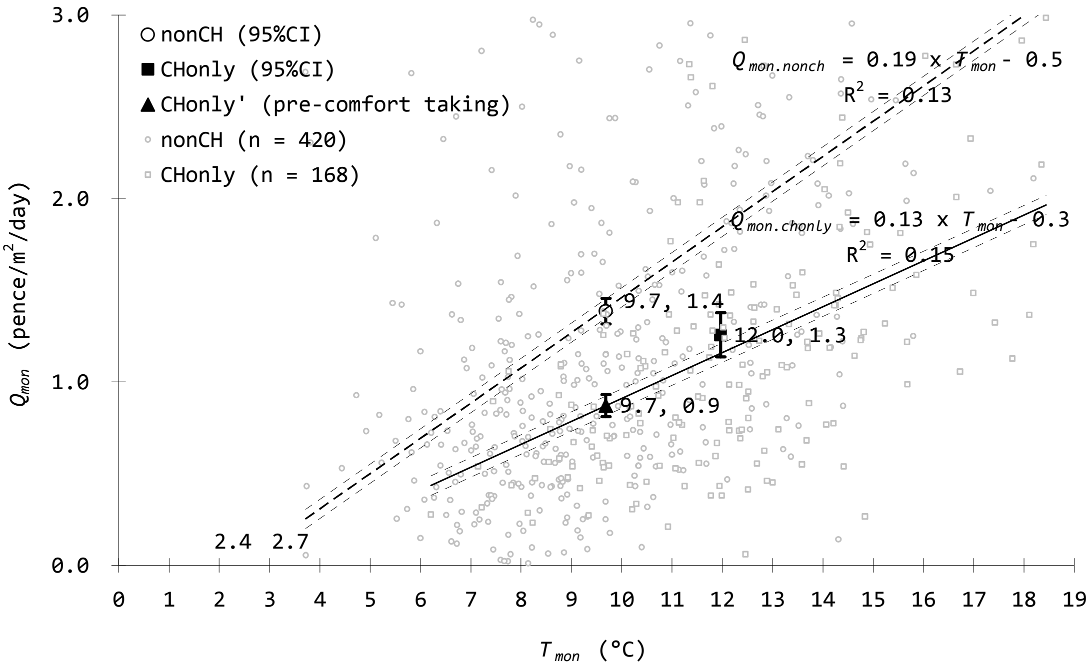
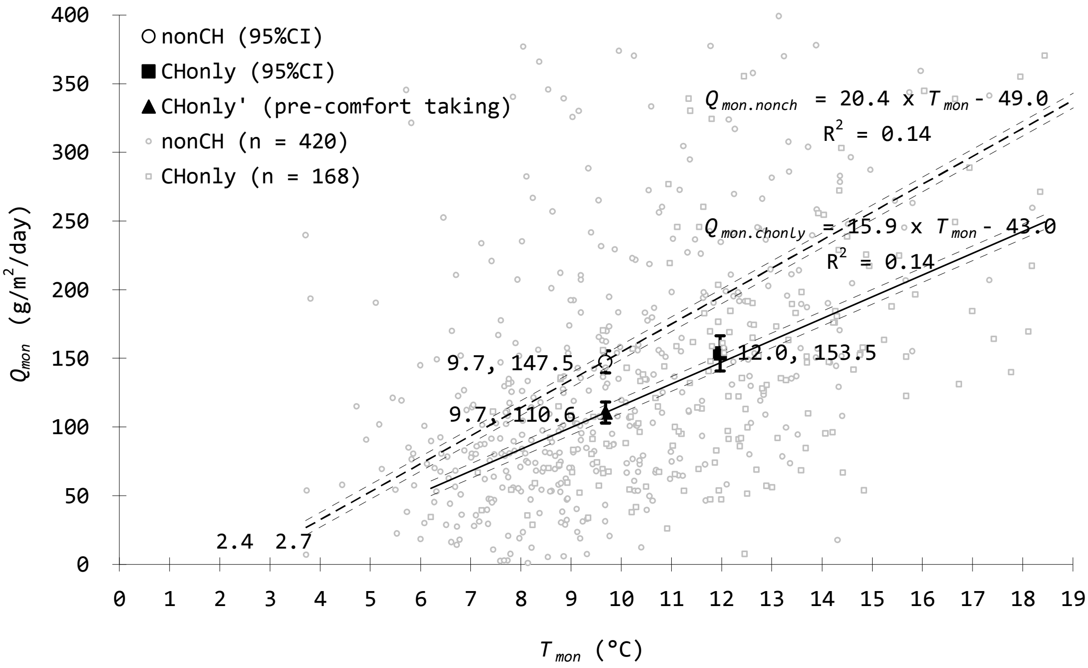


Figure 9.9: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* associated carbon emissions ($Q_{mon(co2)}$) by heating system (*nonCH*: non-central heating, *CHonly*: central heating only).



9.4. Impact of Insulation and Central Heating on the *Comfort Taking*

The combined impact of full insulation and central heating on the *monitored standardized internal temperature* (T_{mon}) and the *monitored space heating energy consumption* (Q_{mon}) is examined by comparing the performances between the case study dwellings grouped into no insulation + non-central heating (*NI+nonCH*) and full insulation + central heating only (*FI+CHonly*) in Figure 9.10 (Table 4.8).

The figure shows the estimated marginal means of the *monitored standardized internal temperature* and the *monitored space heating energy consumption* for the *NI+nonCH* (○: 9.2 °C, 0.7 kWh/m^2/day) and the *FI+CHonly* (□: 12.3 °C, 0.8 kWh/m^2/day) dwellings (Section 4.1). These geometric figures are indicated as non-solid since the difference in the energy usage of 0.1 kWh/m^2/day (Table 7.4) is not found to be statistically significant.

Scatter plots describing the relationship between the temperature and the energy consumption of the two groups are included along with their best-fit regression lines with origins forced to the internal temperature gains of 1.9 °C and 3.3 °C for the *NI+nonCH* and the *FI+CHonly* respectively (Table 4.25). Although there is little difference in the slopes, the shift in the *NI+CHonly* regression line to a lower energy consumption range indicates increased energy performance from the combination of full insulation and central heating.

When determining the hypothetical, i.e. prior to the *comfort taking*, post-intervention condition of *FI+CHonly*' (□: 9.9 °C, 0.6 kWh/m^2/day), the *NI+nonCH* temperature that has been adjusted for the effect of full insulation is used. This temperature is determined by adjusting the *NI+nonCH* temperature by the temperature change determined from the relationship between the heat loss parameter and the temperature in Figure 8.12. The $Q_{mon.fi+chonly}$ equation is solved for the insulation adjusted pre-*comfort taking* temperature of 9.9 °C to determine the counterfactual point *FI+CHonly*'. The temperature and energy consumption rise associated with the *comfort taking* is determined as the difference between *FI+CHonly* (▫) and *FI+CHonly*' (□) resulting in 2.4 °C and 0.2 kWh/m^2/day.

Figure 9.10: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* (Q_{mon}) by the combination of insulation and heating status (*NI+nonCH*: no insulation and non-central heating, *FI+CHonly*: full insulation and central heating only).

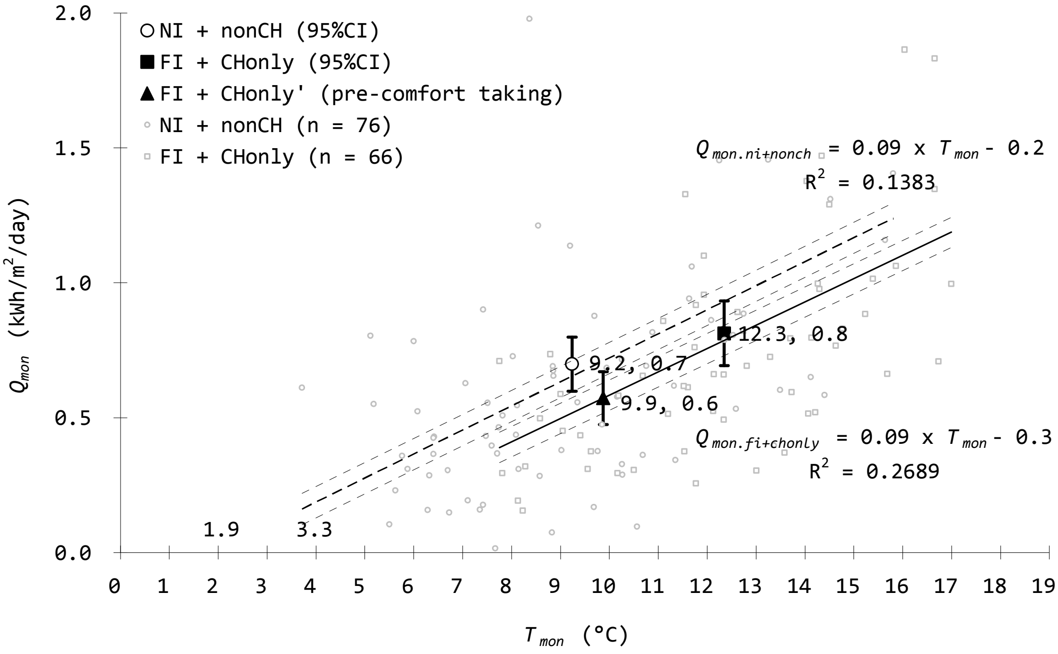


Figure 9.11: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* assocaited cost ($Q_{mon(cost)}$) by the combination of insulation and heating status (*NI+nonCH*: no insulation and non-central heating, *FI+CHonly*: full insulation and central heating only).

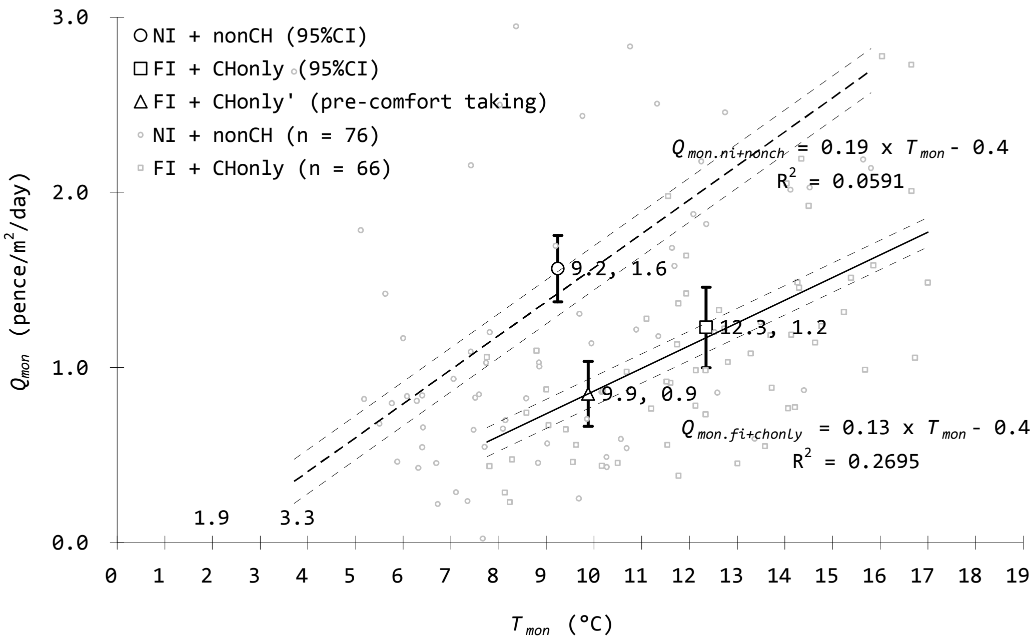
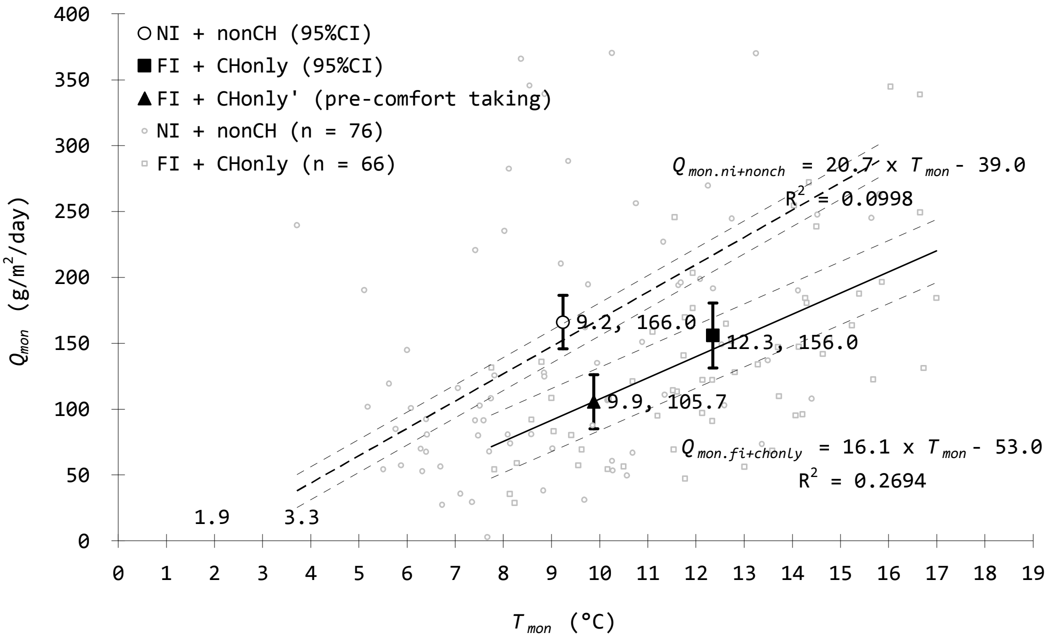


Figure 9.12: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* assocaited carbon emissions ($Q_{mon(co2)}$) by the combination of insulation and heating status (*NI+nonCH*: no insulation and non-central heating, *FI+CHonly*: full insulation and central heating only).



9.5. Impact of the *Warm Front Scheme* on the *Comfort Taking*

The impact of the *Warm Front Scheme* on the *monitored standardized internal temperature* (T_{mon}) and the *monitored space heating energy consumption* (Q_{mon}) is examined by comparing the performances between the case study dwellings grouped into pre-*Warm Front* (*pre-WF*) and post-*Warm Front* (*post-WF*) in Figure 9.13 (Table 4.4).

The figure shows the estimated marginal means of the *monitored standardized internal temperature* and the *monitored space heating energy consumption* for the *pre-WF* (●: 10.3 °C, 0.7 kWh/m^2/day) and the *post-WF* (■: 11.8 °C, 0.8 kWh/m^2/day) dwellings (Section 4.1). These geometric figures are shown in solid because the temperature difference of 1.5 °C (Table 8.3) and the energy consumption difference of 0.1 kWh/m^2/day (Table 7.4) were both found to be statistically significant.

Linear regression lines generated from the temperature and energy consumption scatter plots for the *pre-WF* and the *post-WF* groups are also shown in the figure. The lower slope and the shift in the post-WF regression line indicate the *Warm Front Scheme* resulting in an improvement in the energy performance.

As in the Section 9.4, the post-intervention hypothetical condition *post-WF'* (□: 10.6 °C, 0.6 kWh/m^2/day) is determined by substituting the *pre-WF* temperature which has been adjusted for the effect of insulation based on the relationship between the heat loss parameter and the temperature in Figure 8.12. The $Q_{mon.post\text{-}wf}$ equation is solved for the insulation adjusted pre-*comfort taking* temperature of 10.6 °C to determine the counterfactual point *post-WF'* (□: 10.6 °C, 0.6 kWh/m^2/day). The temperature and energy consumption rise associated with the *comfort taking* is determined as the difference between *post-WF* (■) and *post-WF'* (□) resulting in 1.2 °C and 0.2 kWh/m^2/day.

Figure 9.13: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* (Q_{mon}) by *Warm Front* status.

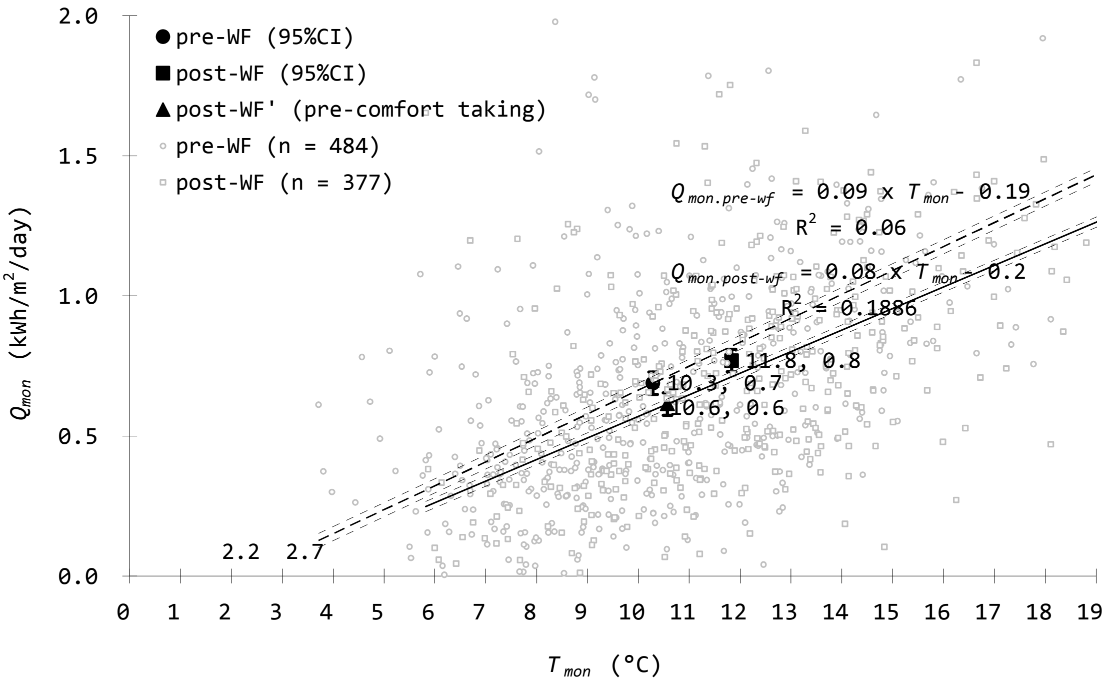


Figure 9.14: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* associated cost ($Q_{mon(cost)}$) by *Warm Front* status.

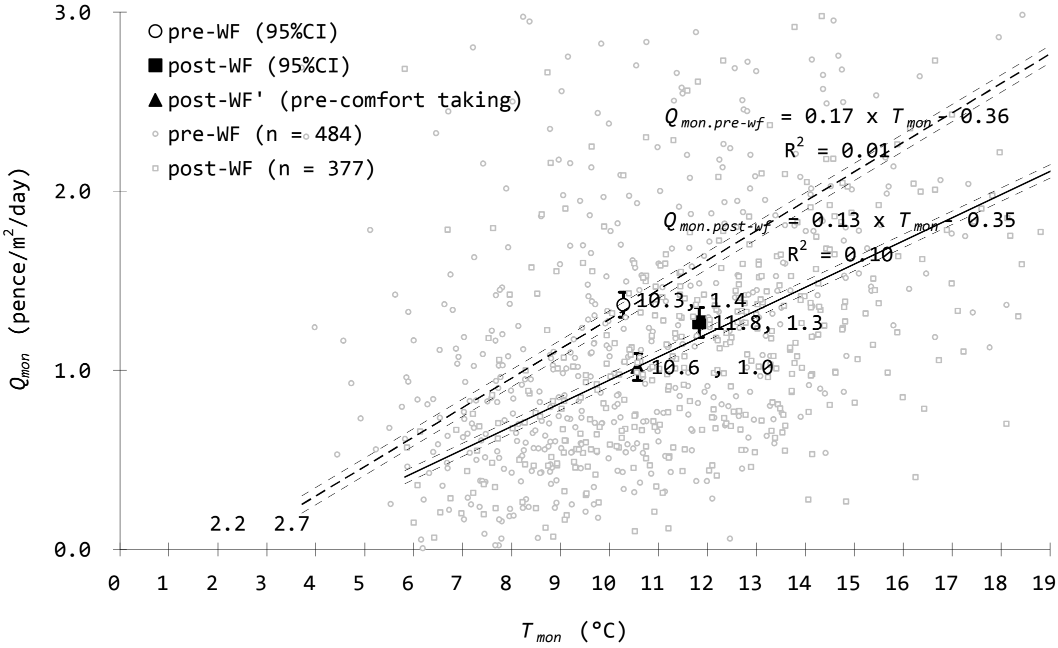
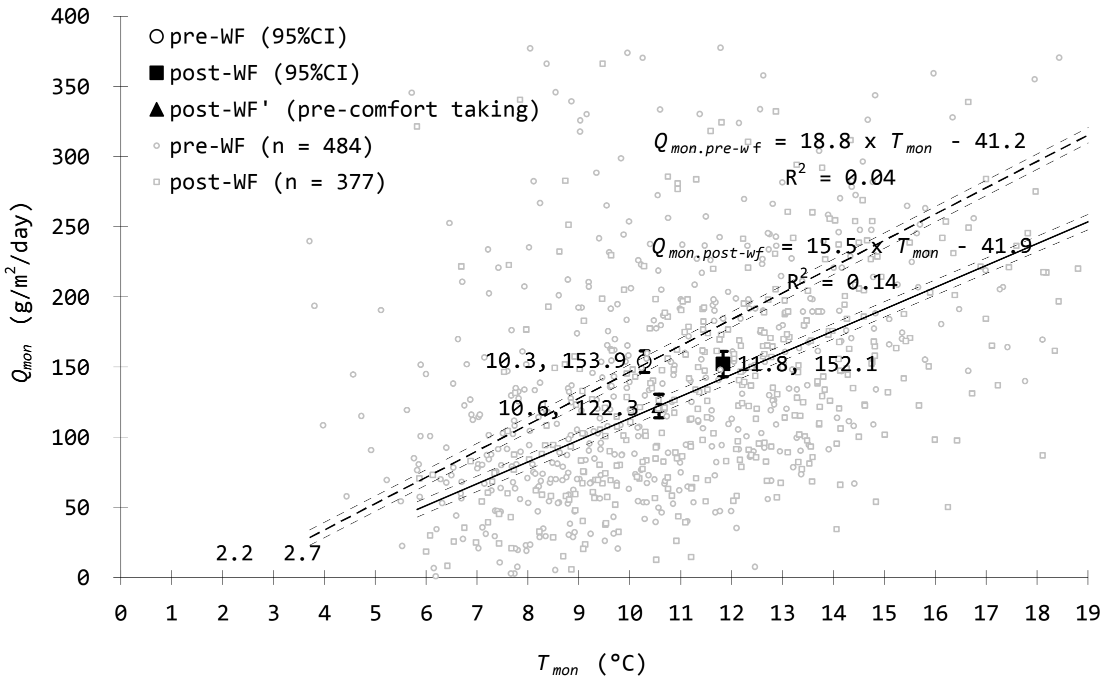


Figure 9.15: The *monitored standardized internal temperature* (T_{mon}) related to the *monitored space heating energy consumption* associated carbon emissions ($Q_{mon(co2)}$) by *Warm Front* status.



9.6. Discussion

This chapter estimated the *comfort taking* (□Q_{CT}) associated with the *Warm Front Scheme* and energy efficiency measures. The findings are summarized in Table 9.1 in which the *comfort taking* is quantified based on changes observed in indoor temperature, energy consumption, energy cost and carbon emissions. The *comfort taking* associated with draught proofing and insulation was assumed to be zero based on the findings from Section 8.5.

Table 9.1: Impact of energy efficiency measures on the *comfort taking* (□Q_{CT}).

intervention (baseline group)	□Q_{CT} (95%CI)			
	monitored standardized internal temperature (°C)	delivered energy (kWh/m^2/day)	energy cost (pence/m^2/day)	carbon emissions (g/m^2/day)
FDP *(NDP)*	0.00	0.00	0.00	0.00
FI *(NI)*	0.00	0.00	0.00	0.00
CH *(nonCH)*	**2.28** (**2.05**, **2.50**)	**0.24** (**0.18**, **0.29**)	**0.39** (**0.30**, **0.47**)	**43.97** (**32.2**, **53.7**)
FI+CHonly *(NI+nonCH)*	**2.47** (**2.03**, **2.91**)	**0.24** (**0.13**, **0.35**)	0.38 (0.17, 0.59)	**50.38** (**26.92**, **73.83)**
Post-WF *(Pre-WF)*	**1.26** (**1.07**, **1.45**)	**0.16** (**0.11**, **0.20**)	**0.22** (**0.16**, **0.33**)	**29.79** (**20.31**, **39.28**)
positive figures indicate comfort taking				

The introduction of insulation in centrally heated dwellings does not seem to reduce the *comfort taking* as observed in the *FI+CHonly* group suggesting that insulation is not taking up some of the increased temperature demand from central heating. In fact, the slightly greater *comfort taking* observed in the *FI+CHonly* when compared to the *CH* is suggesting insulation resulting in some *comfort taking*. The *comfort taking* associated with the *Warm Front Scheme* is comparatively less than the *CH* and the *FI+CHonly* groups which can be explained as the result of not all *post-WF* dwellings owning a central heating system.

The accuracy of the *comfort taking* estimated in this chapter is considered to be poor. One reason is that the method relied on estimating a hypothetical energy consumption level determined from a relationship of low statistical power. The second reason is that the errors associated with the temperature were omitted from all the analyses to simplify the process but if included would have resulted in a wider *comfort taking* range.

CHAPTER 10 LOSS

This chapter aims to estimate the *loss* ($\square Q_{LS}$) (Eqn. 4.20) associated with the *Warm Front Scheme* and energy efficiency measures (Section 4.11.3). The *loss* describes the unrealized saving in BREDEM predicted energy consumption (cost or carbon emissions) due to factors other than the *comfort taking* ($\square Q_{CT}$). The *loss* is measured in this study by determining the difference between the *monitored saving* ($\square Q_{SVmon}$) (Eqn. 4.12) and the saving in the *modelled space heating energy consumption with monitored temperature* ($Q_{mod(mt)}$) determined using BREDEM by substituting monitored zones 1 and 2 temperatures (Section 4.5.1). Since the temperature condition between the monitored and the modelled saving are equal, any difference in the energy saving is explainable by factors other than the *comfort taking*.

The *loss* is determined for the *Warm Front Scheme* and for the energy efficiency measures of draught proofing, insulation, central heating and the combination of insulation and central heating and the results are presented based on the delivered energy and its associated energy cost and carbon emissions in Table 10.1. The effects of adjusting for the *monitored air leakage rate* ($\square Q_{LS(v)}$) (Table 4.17, Section 6.1) and the *monitored U-values* ($\square Q_{LS(vi)}$) (Table 4.11, Section 6.2) and the *monitored central heating performance* ($\square Q_{LS(insitu)}$) (Section 6.3, Section 7.4) on the *loss* are also included in the table.

The table shows that adjusting for the *monitored air leakage rate* resulted in only a small change in the *loss*. In comparison, the additional adjustment with the *monitored U-values* greatly improved the modelled prediction in all groups with the *loss* (in terms of delivered energy) reducing by 17 % in the *FI* group, 15 % in the *FI+CHonly* group and 12 % in *Warm Front* and negligible change in the *CH* group. Further adjustment for the *monitored central heating performance* resulted in the greatest reduction in the *loss* in the CH group by 19 % followed by 10 % in the *Warm Front* group and a negligible impact in the FI group.

The introduction of all three adjustments ($\Delta Q_{LS(insitu)}$) resulted in an average of 26 % reduction in the *loss* although the figure varies greatly depending on the type of measurement and the intervention group. In theory, further reduction in the *loss* is achievable if other elements contributing to the *loss* can be identified and the accuracy of the input parameters into BREDEM increased. The changes in the *loss* observed in the *FDP* group in response to all three monitored adjustments are found to have had negligible impact.

Table 10.1: Comparison of the *loss* (ΔQ_{LS}) adjusted for the *monitored air leakage rate* ($\Delta Q_{LS(v)}$), the *monitored U-values* ($\Delta Q_{LS(vi)}$) and the *monitored central heating performance* ($\Delta Q_{LS(insitu)}$) in relation to the *Warm Front Scheme* and different energy efficiency measures (95%CI).

measurement	intervention	ΔQ_{LS}	$\Delta Q_{LS(v)}$	$\Delta Q_{LS(vi)}$	$\Delta Q_{LS(insitu)}$
delivered energy (kWh/m^2/day)	*FDP*	-0.02 (-0.07, 0.04)	0.00 (-0.05, 0.06)	0.00 (-0.05, 0.05)	-0.01 (-0.07, 0.04)
	FI	0.36 (0.30, 0.42)	0.37 (0.31, 0.43)	0.30 (0.24, 0.36)	0.29 (0.23, 0.35)
	CH	0.25 (0.21, 0.30)	0.22 (0.17, 0.26)	0.21 (0.16, 0.25)	0.17 (0.12, 0.21)
	FI+CHonly	0.53 (0.40, 0.66)	0.52 (0.40, 0.65)	0.45 (0.32, 0.57)	0.45 (0.33, 0.57)
	Warm Front	0.34 (0.30, 0.39)	0.34 (0.29, 0.38)	0.30 (0.26, 0.35)	0.27 (0.22, 0.31)
energy cost (pence/m^2/day)	*FDP*	0.00 (-0.10, 0.09)	0.03 (-0.06, 0.13)	0.03 (-0.07, 0.13)	0.01 (-0.08, 0.11)
	FI	0.48 (0.38, 0.59)	0.50 (0.40, 0.60)	0.40 (0.29, 0.50)	0.39 (0.29, 0.49)
	CH	0.19 (0.10, 0.28)	0.12 (0.04, 0.21)	0.11 (0.03, 0.20)	0.11 (0.02, 0.19)
	FI+CHonly	0.52 (0.28, 0.76)	0.49 (0.26, 0.72)	0.37 (0.14, 0.61)	0.46 (0.23, 0.70)
	Warm Front	0.43 (0.35, 0.51)	0.41 (0.33, 0.49)	0.36 (0.28, 0.44)	0.36 (0.28, 0.44)
carbon emissions (g/m^2/day)	*FDP*	-2.96 (-13.88, 7.97)	1.12 (-9.70, 11.94)	0.84 (-10.01, 11.69)	-1.38 (-12.21, 9.44)
	FI	60.61 (48.87, 72.36)	62.88 (51.21, 74.55)	50.09 (38.33, 61.85)	48.75 (37.01, 60.50)
	CH	36.92 (27.63, 46.20)	29.91 (20.72, 39.09)	28.57 (19.36, 37.81)	24.58 (15.36, 33.81)
	FI+CHonly	81.51 (56.01, 107.02)	81.51 (56.30, 106.73)	64.51 (39.19, 89.82)	71.46 (46.37, 96.54)
	Warm Front	58.42 (48.80, 68.05)	56.87 (47.31, 66.42)	50.40 (40.81, 60.00)	47.54 (37.97, 57.11)
positive figures indicate loss					

CHAPTER 11 SHORTFALL

The aim of this chapter is to estimate the *shortfall* associated with *Warm Front* and energy efficiency measures (Section 4.11.4). The *shortfall* quantifies the unrealized potential saving in the predicted energy consumption (cost or carbon emissions) due to the *comfort taking* and the *loss*. Two types of *shortfall* are presented: the *modelled shortfall* (ΔQ_{SFmod}) (Eqn. 4.22) which is determined as the difference between the *modelled* (ΔQ_{SVmod}) (Eqn. 4.13) *and the monitored saving* (ΔQ_{SVmon}) (Eqn. 4.12) and the *theoretical shortfall* (ΔQ_{SFthry}) (Eqn. 4.23) which is determined as the sum of the *comfort taking* and the *loss*, the two elements which explain the difference between the actual and theoretical saving. The results are summarized in Tables Table 11.1 and Table 11.2. The *modelled* ($\Delta Q_{SFmod(insitu)}$) and the *theoretical shortfalls* ($\Delta Q_{SFthry(insitu)}$) presented in Table 11.2 have been adjusted with the *monitored air leakage rate* (Table 4.17, Section 6.1), the *monitored U-values* (Table 4.11, Section 6.2) and the *monitored central heating performance* (Section 6.3).

Although in theory the *modelled saving* (ΔQ_{SVmod}) and the *theoretical saving* (ΔQ_{SVthry}) should equal (Figure 4.4), the tables show the latter to be much greater, by a factor of two, which in turn is also reflected in the difference between the *theoretical shortfall* and the *modelled shortfall*. The large difference is thought to be the result of overestimation in the *comfort taking* as a result of uncertainties associated in determining the *comfort taking*. Nevertheless, the difference in the *shortfall* figures clearly illustrates the dependency of the *shortfall* on the theoretical prediction against which the unrealized saving is measured.

The introduction of in situ adjustment in Table 11.2 resulted in a reduction in both the *modelled* ($\Delta Q_{SVmod(insitu)}$) and the *theoretical saving* ($\Delta Q_{SVthry(insitu)}$) resulting in reduced *modelled* ($\Delta Q_{SFmod(insitu)}$) and *theoretical shortfalls* ($\Delta Q_{SFthry(insitu)}$) demonstrating the benefit of adjusting the BREDEM input variables with monitored performances of energy efficiency measures. Although the degree of change varies depending on the parameters examined, the *shortfalls* were found reduce by an average of about 15 % as a result of the in situ adjustment.

Table 11.1: Impact of the *Warm Front Scheme* and energy efficiency measures on the *modelled* (□Q_{SFmod}) and the *theoretical shortfall* (□Q_{SFthry}) (□Q_{SVmon}: *monitored saving* (Table 7.4), □Q_{SVmod}: *modelled saving* (Table 7.4), □Q_{CT}: *comfort taking* (Table 9.1), □Q_{LS}: *loss* (Table 10.5), □Q_{SVthry}: *theoretical saving*) (95%CI).

measurement	intervention (baseline group)	□Q_{SVmon} ①	□Q_{SVmod} ②	□Q_{CT} ③	□Q_{LS} ④	□Q_{SVthry} ⑤ (① + ③ + ④)	□Q_{SFmod} (② - ①)	□Q_{SFthry} (③ + ④)
delivered energy (kWh/m²/day)	*FDP (NDP)*	0.00 (-0.07, 0.06)	-0.01 (-0.05, 0.03)	0.00	-0.02 (-0.07, 0.04)	-0.01 (-0.08, 0.05)	-0.01 (-0.06, 0.04)	-0.02 (-0.07, 0.04)
	FI (NI)	0.07 (-0.02, 0.14)	**0.26 (0.22, 0.31)**	0.00	0.36 (0.30, 0.42)	0.43 (0.35, 0.50)	0.19 (0.14, 0.25)	0.36 (0.30, 0.42)
	CH (nonCH)	**-0.18 (-0.26, -0.11)**	**0.09 (0.06, 0.12)**	**0.24** (**0.18**, **0.29**)	0.25 (0.21, 0.30)	0.30 (0.23, 0.38)	0.77 (0.24, 0.32)	0.49 (0.42, 0.56)
	FI+CHonly (NI+nonCH)	-0.11 (-0.27, 0.03)	**0.31 (0.21, 0.42)**	**0.24** (**0.13**, **0.35**)	0.53 (0.40, 0.66)	0.66 (0.48, 0.84)	0.43 (0.31, 0.54)	0.77 (0.61, 0.94)
	Post-WF (pre-WF)	**-0.08 (-0.14, -0.03)**	**0.20 (0.16, 0.24)**	**0.16** (**0.11**, **0.20**)	0.34 (0.30, 0.39)	0.42 (0.35, 0.49)	0.28 (0.24, 0.32)	0.50 (0.41, 0.58)
energy cost (pence/m²/day)	*FDP (NDP)*	0.00 (-0.12, 0.12)	-0.02 (-0.09, 0.06)	0.00	0.00 (-0.10, 0.09)	-0.01 (-0.12, 0.11)	-0.02 (-0.11, 0.08)	-0.01 (-0.10, 0.09)
	FI (NI)	**0.19 (0.06, 0.33)**	**0.42 (0.34, 0.50)**	0.00	0.48 (0.38, 0.59)	0.68 (0.55, 0.80)	0.23 (0.13, 0.33)	0.48 (0.38, 0.59)
	CH (nonCH)	0.13 (-0.01, 0.27)	**0.30 (0.24, 0.35)**	**0.39** (**0.30**, **0.47**)	0.19 (0.10, 0.28)	0.71 (0.55, 0.86)	0.17 (0.09, 0.25)	0.58 (0.45, 0.70)
	FI+CHonly (NI+nonCH)	**0.34 (0.04, 0.64)**	**0.66 (0.46, 0.86)**	0.38 (0.17, 0.59)	0.52 (0.28, 0.76)	1.24 (0.90, 1.57)	0.32 (0.10, 0.54)	0.90 (0.59, 1.21)
	Post-WF (pre-WF)	0.10 (-0.01, 0.21)	**0.39 (0.33, 0.46)**	**0.22** (**0.16**, **0.33**)	0.43 (0.35, 0.51)	0.78 (0.64, 0.91)	0.30 (0.22, 0.37)	0.68 (0.56, 0.80)
carbon emissions (g/m²/day)	*FDP (NDP)*	1.31 (-12.48, 15.11)	-1.47 (-9.20, 6.26)	0.00	-2.96 (-13.88, 7.97)	-1.65 (-14.74, 11.45)	-2.78 (-12.90, 7.33)	-2.96 (-13.88, 7.97)
	FI (NI)	**22.46 (7.49, 37.44)**	**51.28 (42.58, 59.97)**	0.00	60.61 (48.87, 72.36)	83.07 (68.82, 97.33)	28.81 (17.76, 39.87)	60.61 (48.87, 72.36)
	CH (nonCH)	-6.08 (-21.18, 9.03)	**30.43 (24.73, 36.14)**	**43.97** (**32.2**, **53.7**)	36.92 (27.63, 46.20)	73.81 (57.56, 90.07)	36.51 (28.38, 44.63)	79.89 (65.97, 93.81)
	FI+CHonly (NI+nonCH)	10.01 (-21.97, 41.98)	**70.57 (50.30, 90.84)**	**50.38** (**26.92**, **73.83**)	81.51 (56.01, 107.02)	141.90 (104.46, 179.34)	60.56 (35.23, 85.89)	131.89 (97.82, 165.96)
	Post-WF (pre-WF)	1.73 (-10.22, 13.69)	**44.63 (37.24, 52.02)**	**29.79** (**20.31**, **39.28**)	58.42 (48.80, 68.05)	89.95 (75.04, 104.85)	42.90 (34.03, 51.77)	88.22 (74.68, 101.75)

Table 11.2: Impact of the *Warm Front Scheme* and energy efficiency measures on the *in situ modelled shortfall* (□$Q_{SFmod(insitu)}$) and the *in situ theoretical shortfall* (□$Q_{SFthry(insitu)}$) (□Q_{SVmon}: *monitored saving* (Table 7.4), □$Q_{SVmod(insitu)}$: *in situ modelled saving* (Table 7.4), □Q_{CT}: *comfort taking* (Table 9.1), □$Q_{LS(insitu)}$: *in situ loss* (Table 10.5), □$Q_{SVthry(insitu)}$: *in situ theoretical saving*) (95%CI).

measurement	intervention (baseline group)	□Q_{SVmon} ①	□$Q_{SVmod(insitu)}$ ②	□Q_{CT} ③	□$Q_{LS(insitu)}$ ④	□$Q_{SVthry(insitu)}$ ⑤ (① + ③ + ④)	□$Q_{SFmod(insitu)}$ (② - ①)	□$Q_{SFthry(insitu)}$ (③ + ④)
delivered energy (kWh/m^2/day)	*FDP (NDP)*	0.00	0.00	0.00	-0.01 (-0.07, 0.04)	-0.01 (-0.07, 0.05)	0.00 (-0.05, 0.05)	-0.01 (-0.06, 0.04)
	FI (NI)	0.07 (-0.02, 0.14)	**0.23 (0.18, 0.27)**	0.00	0.29 (0.23, 0.35)	0.36 (0.29, 0.43)	0.16 (0.11, 0.22)	0.29 (0.24, 0.35)
	CH (nonCH)	**-0.18 (-0.26, -0.11)**	**0.05 (0.02, 0.07)**	**0.24 (0.18, 0.29)**	0.17 (0.12, 0.21)	0.22 (0.15, 0.29)	0.23 (0.19, 0.27)	0.40 (0.34, 0.46)
	FI+CHonly (NI+nonCH)	-0.11 (-0.27, 0.03)	**0.26 (0.17, 0.36)**	**0.24 (0.13, 0.35)**	0.45 (0.33, 0.57)	0.58 (0.40, 0.76)	0.38 (0.26, 0.49)	0.69 (0.53, 0.85)
	Post-WF (pre-WF)	**-0.08 (-0.14, -0.03)**	**0.16 (0.12, 0.19)**	**0.16 (0.11, 0.20)**	0.27 (0.22, 0.31)	0.34 (0.27, 0.41)	0.24 (0.20, 0.28)	0.42 (0.36, 0.49)
energy cost (pence/m^2/day)	*FDP (NDP)*	0.00 (-0.12, 0.12)	0.01 (-0.06, 0.07)	0.00	0.01 (-0.08, 0.11)	0.01 (-0.10, 0.12)	0.01 (-0.05, 0.06)	0.01 (-0.08, 0.10)
	FI (NI)	**0.19 (0.06, 0.33)**	**0.36 (0.30, 0.43)**	0.00	0.39 (0.29, 0.49)	0.58 (0.46, 0.70)	0.19 (0.09, 0.28)	0.39 (0.30, 0.49)
	CH (nonCH)	0.13 (-0.01, 0.27)	**0.26 (0.21, 0.31)**	**0.39 (0.30, 0.47)**	0.11 (0.02, 0.19)	0.62 (0.48, 0.77)	0.13 (0.05, 0.21)	0.49 (0.38, 0.61)
	FI+CHonly (NI+nonCH)	**0.34 (0.04, 0.64)**	**0.64 (0.45, 0.82)**	0.38 (0.17, 0.59)	0.46 (0.23, 0.70)	1.18 (0.85, 1.51)	0.30 (0.08, 0.52)	0.84 (0.54, 1.15)
	Post-WF (pre-WF)	0.10 (-0.01, 0.21)	**0.36 (0.30, 0.43)**	**0.25 (0.16, 0.33)**	0.36 (0.28, 0.44)	0.71 (0.57, 0.84)	0.26 (0.19, 0.33)	0.61 (0.49, 0.72)
carbon emissions (g/m^2/day)	*FDP (NDP)*	1.31 (-12.48, 15.11)	0.89 (-6.60, 8.37)	0.00	-1.38 (-12.21, 9.44)	-0.07 (-12.60, 12.46)	-0.43 (-10.49, 9.64)	-1.38 (-11.45, 8.68)
	FI (NI)	**22.46 (7.49, 37.44)**	**45.43 (36.96, 53.90)**	0.00	48.75 (37.01, 60.50)	71.21 (57.41, 85.02)	22.97 (11.91, 34.02)	48.75 (37.70, 59.81)
	CH (nonCH)	-6.08 (-21.18, 9.03)	**23.78 (18.17, 29.39)**	**42.97 (32.21, 53.73)**	24.58 (15.36, 33.81)	61.48 (46.32, 76.64)	29.86 (21.77, 37.95)	67.55 (55.09, 80.02)
	FI+CHonly (NI+nonCH)	10.01 (-21.97, 41.98)	**65.05 (45.87, 84.23)**	**50.38 (26.92, 73.83)**	71.46 (46.37, 96.54)	131.84 (94.81, 168.87)	55.04 (31.75, 78.33)	121.83 (88.18, 155.49)
	Post-WF (pre-WF)	1.73 (-10.22, 13.69)	**38.91 (31.75, 46.08)**	**29.79 (20.31, 39.28)**	47.54 (37.97, 57.11)	79.07 (64.51, 93.63)	37.18 (28.34, 46.02)	77.33 (64.20, 90.46)

CHAPTER 12   SHORTFALL FACTOR

The *modelled* (SFF_{mod}) (Eqn. 4.24) and the *theoretical shortfall factors* (SFF_{thry}) (Eqn. 4.25) are determined in this chapter by expressing the *modelled* (□Q_{SFmod}) and the *theoretical shortfalls* (□Q_{SFthry}) determined in Chapter 11 as percentages relative to the *modelled* (□Q_{SVmod}) (Eqn. 4.13) and the *theoretical saving* (□Q_{SVthry}) (Eqn. 4.15). The *theoretical shortfall factor* is further disaggregated into the *theoretical saving factor* (SVF_{thry}) (Eqn. 4.17), the *comfort factor* (*CTF*) (Eqn. 4.19) and the *loss factor* (*LSF*) (Eqn. 4.21).

The results are shown in Table 12.1 and Table 12.2 where the results in the latter table is based on the *in situ modelled saving* (□$Q_{SVmod(insitu)}$) and the in situ *theoretical saving* (□$Q_{SVthry(insitu}$) which have been adjusted for the *monitored air leakage rate* (□$Q_{LS(v)}$) (Table 4.17, Section 6.1) and the *monitored U-values* (□$Q_{LS(vi)}$) (Table 4.11, Section 6.2) and the *monitored central heating performance* (□$Q_{LS(insitu)}$) (Section 6.3, Section 7.4). The effect of draught proofing, i.e. the *NDP* and the *FDP* groups, is excluded from the results since this measure was found to have little impact on the energy usage.

All the *shortfall* values in both tables are positive indicating that the *monitored saving* is not delivering the *theoretical saving* across all energy efficiency measures. Where there is monitored saving, i.e. positive *SVF* figures, such as observed with insulation and across energy cost based analysis, the *shortfall factors* rarely fall below 50 % indicating that only about half of the theoretically expected saving is being achieved even under the best performance. When analyzed in terms of the delivered energy, all the *shortfalls* are above 100 % with the exception of the FI group indicating that not only are the theoretically expected energy saving not being achieved but energy efficiency measures, particularly if involving central heating, are associated with increased energy consumption.

The result is somewhat encouraging when examined in terms of the energy cost which shows some saving across all the intervention groups indicating energy efficiency measures having a beneficial impact in reducing the fuel cost. In terms of carbon emissions, only full insulation was found to result in any reduction. In fact, full insulation resulted in the greatest saving and is the only measure with saving in the delivered energy, fuel cost and carbon emissions while gas central heating is associated with the least saving. The performance of the *FI+CHonly* and *Warm Front* are found to fall in between these two opposite performances.

Table 12.2 shows that the in situ adjustment is beneficial in reducing the *shortfall* in cases where the *shortfall* figures were below 100 % in Table 12.1. In contrast when the *shortfalls* were above 100 %, the in situ adjustment resulted in a further increase in their values. Both instances can be explained by the adjustment resulting in reduced *in situ modelled* and *theoretical saving* ($\Delta Q_{SVmod(insitu)}$, $\Delta Q_{SVthry(insitu)}$) against which the *shortfall factors* are measured.

The findings in Table 12.1 are summarized in Figure 12.1 to Figure 12.2 and the findings from Table 12.2 in Figure 12.3 to Figure 12.4. The distribution of the *comfort taking factor*, the *loss factor* and the *theoretical saving factor* (SVF_{thry}) is shown in Figure 12.1 and the distribution of the *shortfall factor* and the *modelled saving factor* (SVF_{mod}) is shown in Figure 12.2. The same comparisons are repeated in Figure 12.3 to Figure 12.4 but in relation to the *in situ theoretical saving* ($SVF_{thry(insitu)}$) and the *in situ modelled saving* ($SVF_{mod(insitu)}$) respectively.

In all figures, the *comfort taking factor* and the *loss factor* in Figure 12.1 and Figure 12.3 and the *shortfall factor* in Figure 12.2 and Figure 12.4 are measured from the

100 % level representing a hypothetical condition where the *monitored saving* is equal to the *theoretical saving* or the *modelled saving*. The remaining portion is the *saving factor* which if positive, i.e. above 0 %, represents actual saving and if negative represents 'back-fire' where the energy consumption (cost, carbon emissions) is greater following the intervention. The *modelled shortfall factor* (SFF_{mod}) in Figure 12.2 and Figure 12.4 is not disaggregated into the *comfort taking factor* and the *loss factor* because this would result in either of these two taking up a proportion greater than the *modelled shortfall factor* in many instances due to the *comfort taking* or the *loss* or both being greater than the *modelled shortfall* as shown in Table 11.1.

Table 12.1: Impact of the *Warm Front Scheme* and energy efficiency measures on the *saving factor* (*SVF*), the *comfort taking factor* (*CTF*), the *loss factor* (*LSF*) and the *shortfall factor* (*SFF*) measured in relation to the *modelled saving* (□Q_{SVmod}) (Table 7.4) and the *theoretical saving* (□Q_{SVthry}) (Table 11.1)) (95%CI).

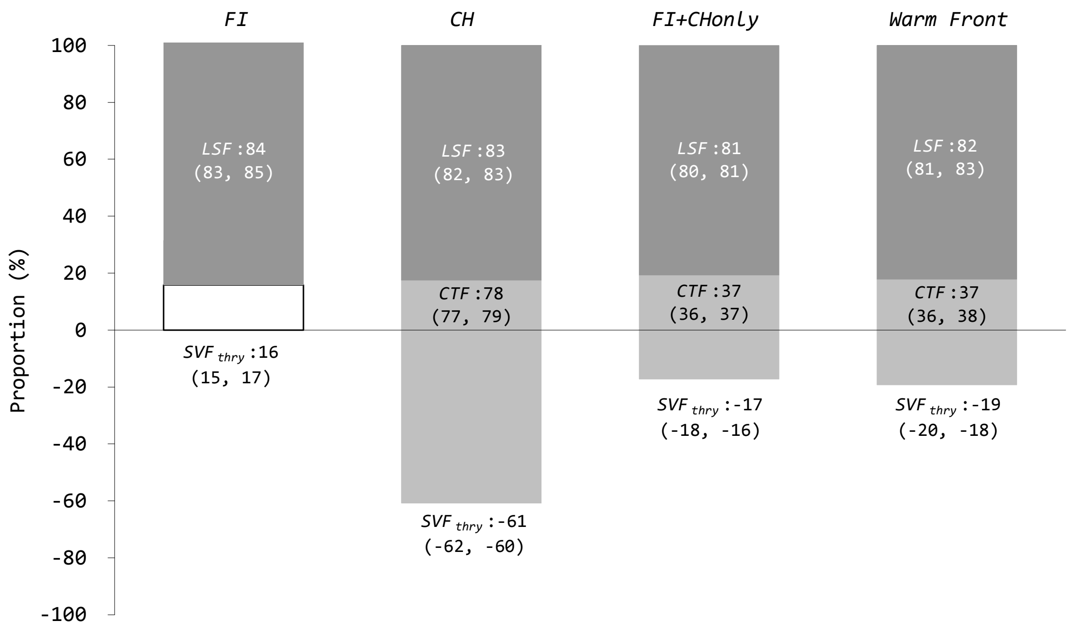
measurement	intervention (baseline group)	SVF_{mod} (Eqn. 4.16)	SVF_{thry} (Eqn. 4.17)	*CTF* (Eqn. 4.19)	*LSF* (Eqn. 4.21)	SFF_{mod} (Eqn. 4.24)	SFF_{thry} (Eqn. 4.25)
delivered energy (kWh/m^2/day)	*FI (NI)*	25.7 (23.6, 27.8)	15.8 (14.6, 17.0)	0.0	84.2 (83.4, 85.1)	74.3 (73.0, 75.7)	84.2 (83.4, 85.1)
	CH (nonCH)	-197.1 (-199.4, -194.9)	-60.7 (-61.7, -59.8)	78.2 (77.5, 78.9)	82.5 (81.9, 83.1)	297.1 (296.0, 298.3)	160.7 (159.8, 161.6)
	FI+CHonly (NI+nonCH)	-36.1 (-37.6, -34.6)	-17.2 (-18.0, -16.3)	36.5 (35.9, 37.1)	80.7 (80.0, 81.4)	136.1 (135.0, 137.2)	117.2 (116.3, 118.1)
	Warm Front (pre-WF)	-40.8 (-42.4, -39.2)	-19.3 (-20.1, -18.4)	37.2 (36.5, 37.8)	82.1 (81.4, 82.7)	140.8 (139.7, 141.9)	119.3 (118.1, 120.5)
energy cost (pence/m^2/day)	*FI (NI)*	45.5 (43.9, 47.1)	28.4 (27.3, 29.5)	0.0	71.6 (70.8, 72.4)	54.5 (53.3, 55.7)	71.6 (70.8, 72.4)
	CH (nonCH)	43.4 (41.1, 45.8)	18.4 (17.5, 19.3)	54.5 (54.0, 55.1)	27.1 (26.5, 27.6)	56.6 (55.2, 57.9)	81.6 (80.7, 82.4)
	FI+CHonly (NI+nonCH)	50.9 (49.5, 52.4)	27.2 (26.3, 28.1)	30.7 (30.1, 31.3)	42.1 (41.4, 42.8)	49.1 (48.0, 50.2)	72.8 (71.9, 73.7)
	Warm Front (pre-WF)	25.2 (23.5, 26.9)	12.8 (12.0, 13.6)	31.9 (31.2, 32.5)	55.4 (54.8, 56.0)	74.8 (73.7, 75.9)	87.2 (86.3, 88.1)
carbon emissions (g/m^2/day)	*FI (NI)*	43.8 (42.1, 45.5)	27.0 (26.0, 28.1)	0.0	73.0 (72.1, 73.8)	56.2 (54.9, 57.5)	73.0 (72.1, 73.8)
	CH (nonCH)	-20.0 (-22.6, -17.3)	-8.2 (-9.2, -7.3)	58.2 (57.6, 58.9)	50.0 (49.4, 50.6)	120.0 (118.5, 121.4)	108.2 (107.4, 109.1)
	FI+CHonly (NI+nonCH)	14.2 (12.6, 15.8)	7.1 (6.2, 7.9)	35.5 (34.9, 36.1)	57.4 (56.8, 58.1)	85.8 (84.6, 87.1)	92.9 (92.0, 93.9)
	Warm Front (pre-WF)	3.9 (2.3, 5,5)	1.9 (1.1, 2.7)	33.1 (32.5, 33.8)	65.0 (64.3, 65.6)	96.1 (94.9, 97.3)	98.1 (97.2, 99.0)

Table 12.2: Impact of the *Warm Front Scheme* and energy efficiency measures on the *saving factor* (*SVF*), the *comfort taking factor* (*CTF*), the *loss factor* (*LSF*) and the *shortfall factor* (*SFF*) measured in relation to the *in situ modelled saving* ($\Delta Q_{SVmod(insitu)}$) (Table 7.4) and the *in situ theoretical saving* ($\Delta Q_{SVthry(insitu)}$) (Table 11.1) (95%CI).

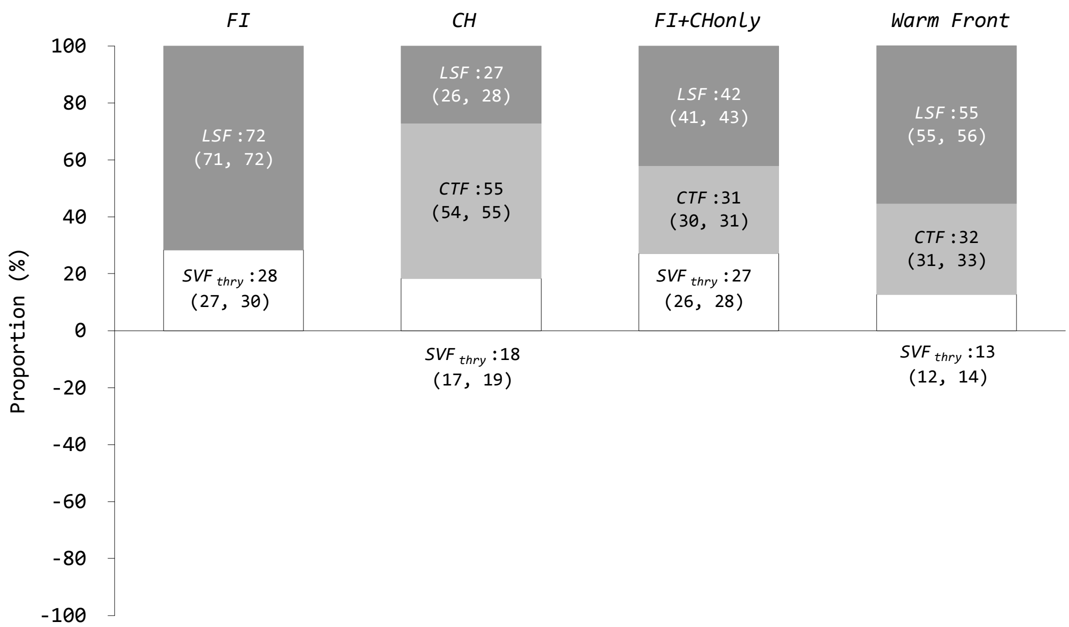
measurement	intervention (baseline group)	$SVF_{mod(insitu)}$ (Eqn. 4.16)	$SVF_{thry(insitu)}$ (Eqn. 4.17)	$CTF_{(insitu)}$ (Eqn. 4.19)	$LSF_{(insitu)}$ (Eqn. 4.21)	$SFF_{mod(insitu)}$ (Eqn. 4.24)	$SFF_{thry(insitu)}$ (Eqn. 4.25)
delivered energy (kWh/m^2/day)	*FI (NI)*	29.4 (27.6, 31.3)	18.6 (17.4, 19.9)	0.0	81.4 (80.5, 82.2)	70.6 (69.4, 71.7)	81.4 (80.6, 82.2)
	CH (nonCH)	-401.6 (-404.5, -398.7)	-84.0 (-85.1, -83.0)	108.2 (107.4, 109.0)	75.8 (75.2, 76.4)	501.6 (500.1, 503.1)	184.0 (183.2, 184.9)
	FI+CHonly (NI+nonCH)	-42.6 (-44.3, -41.0)	-19.6 (-20.4, -18.7)	41.6 (41.0, 42.2)	78.0 (77.3, 78.7)	142.6 (141.4, 143.8	119.6 (118.7, 120.5)
	Warm Front (pre-WF)	-51.4 (-53.1, -49.8)	-23.4 (-24.3, -22.6)	45.2 (44.5, 45.9)	78.2 (77.6, 78.9)	151.4 (150.3, 152.6)	123.4 (122.5, 124.3)
energy cost (pence/m^2/day)	*FI (NI)*	50.8 (49.1, 52.5)	32.9 (31.8, 34.0)	0.0	67.1 (66.2, 67.9)	49.2 (48.0, 50.4)	67.1 (66.3, 67.9)
	CH (nonCH)	49.9 (47.1, 52.7)	20.9 (19.9, 21.9)	61.9 (61.3, 62.5)	17.2 (16.6, 17.8)	50.1 (48.5, 51.6)	79.1 (78.3, 79.9)
	FI+CHonly (NI+nonCH)	52.8 (51.2, 54.3)	28.5 (27.6, 29.4)	32.1 (31.5, 32.8)	39.4 (38.7, 40.1)	47.2 (46.1, 48.4)	71.5 (70.6, 72.4)
	Warm Front (pre-WF)	27.5 (25.7, 29.3)	14.1 (13.3, 14.9)	35.2 (34.5, 35.8)	50.7 (50.1, 51.3)	72.5 (71.3, 73.6)	85.9 (85.0, 86.8)
carbon emissions (g/m^2/day)	*FI (NI)*	49.4 (47.7, 51.2)	31.5 (30.5, 32.6)	0.0	68.5 (67.6, 69.3)	50.6 (49.3, 51.9)	68.5 (67.7, 69.3)
	CH (nonCH)	-25.5 (-28.2, -22.9)	-9.9 (-10.9, -8.9)	69.9 (69.2, 70.6)	40.0 (39.4, 40.6)	125.5 (124.1, 127.0)	109.9 (109.1, 110.7)
	FI+CHonly (NI+nonCH)	15.4 (13.7, 17.1)	7.6 (6.7, 8.5)	38.2 (37.6, 38.8)	54.2 (53.5, 54.9)	84.6 (83.4, 85.8)	92.4 (91.5, 93.3)
	Warm Front (pre-WF)	4.5 (2.8, 6.1)	2.2 (1.4, 3.0)	37.7 (37.0, 38.3)	60.1 (59.5, 60.8)	95.5 (94.3, 96.8)	97.8 (96.9, 98.7)

Figure 12.1: The *loss factor* (*LSF*), the *comfort taking factor* (*CTF*) and the *theoretical saving factor* (SVF_{thry}) determined based on the (A) delivered energy, (B) energy cost and (C) carbon emissions in relation to energy efficiency measures of central heating (*CH*), full insulation (*FI*), full insulation and central heating only (*FI+CHonly*) (95%CI).

(A) Delivered energy



(B) Energy cost



(C) Carbon Emissions

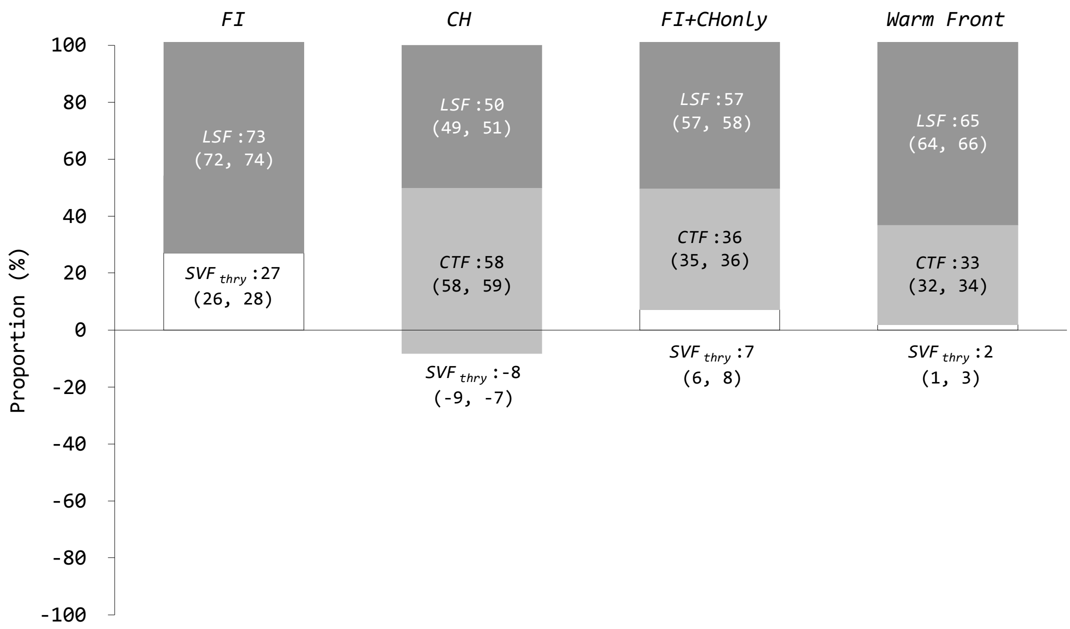
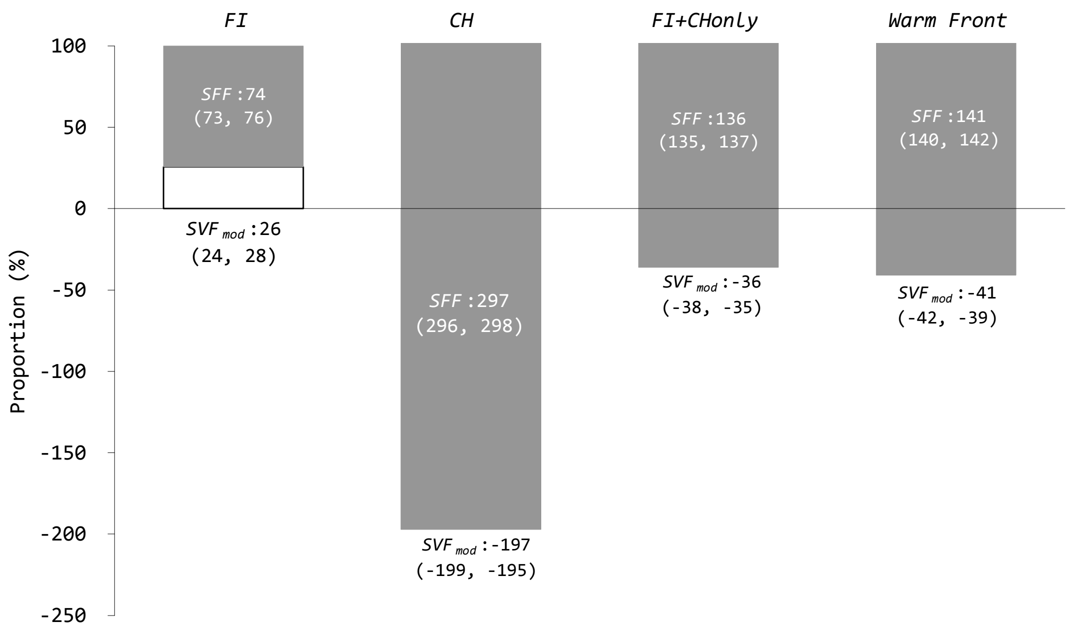
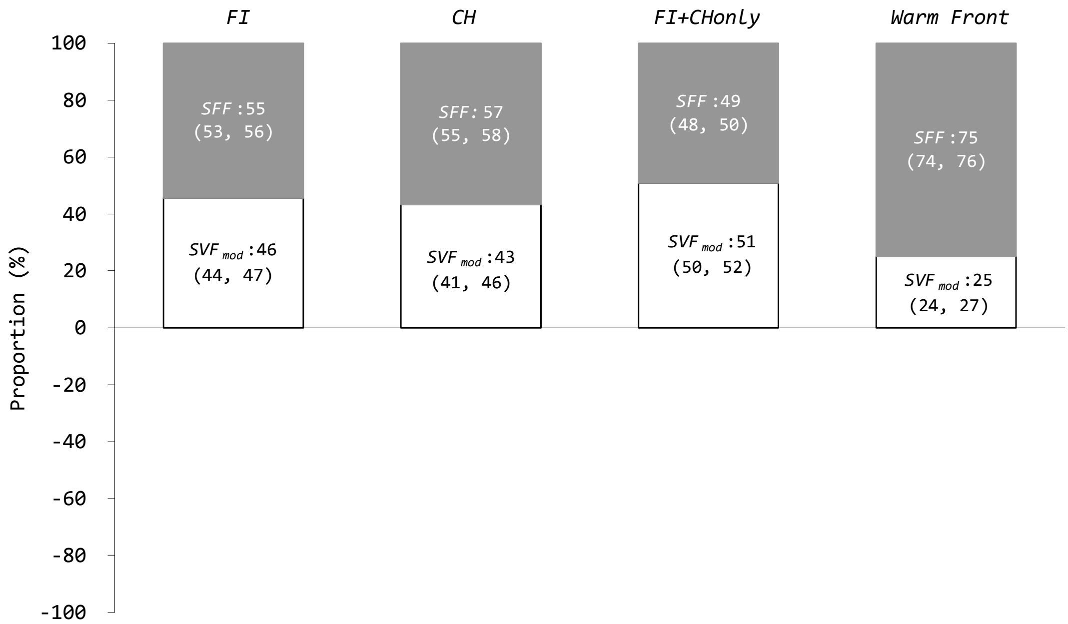


Figure 12.2: The *shortfall factor* (*SFF*) and the *modelled saving factor* (*SVF_{mod}*) determined based on the (A) delivered energy, (B) energy cost and (C) carbon emissions in relation to energy efficiency measures of central heating (*CH*), full insulation (*FI*), full insulation and central heating only (*FI+CHonly*) (95%CI).

(A) Delivered Energy



(B) Energy Cost



(C) Carbon Emissions

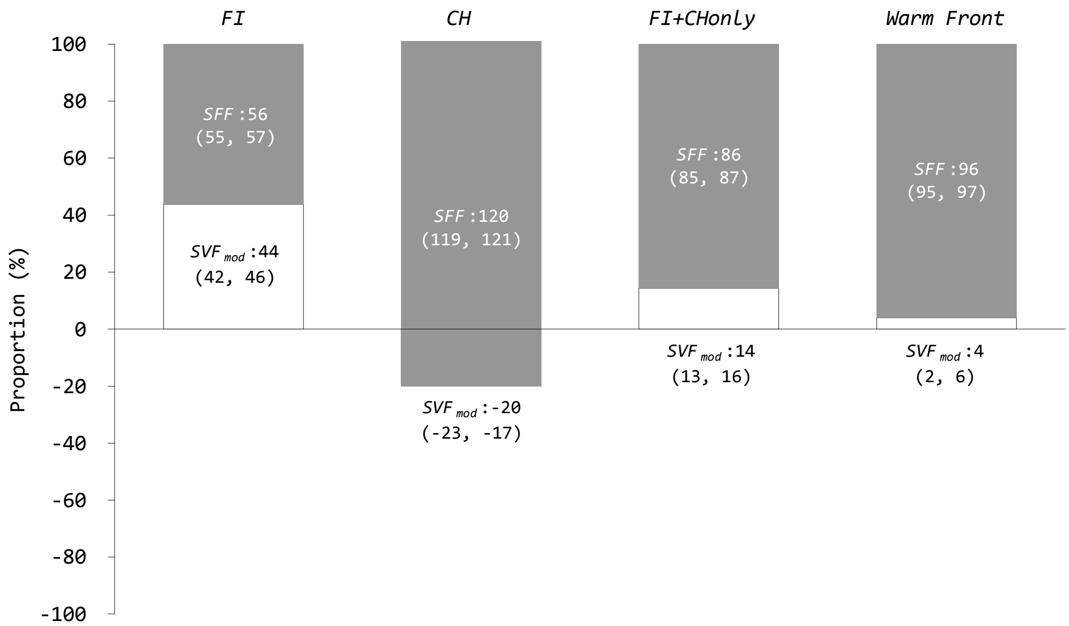
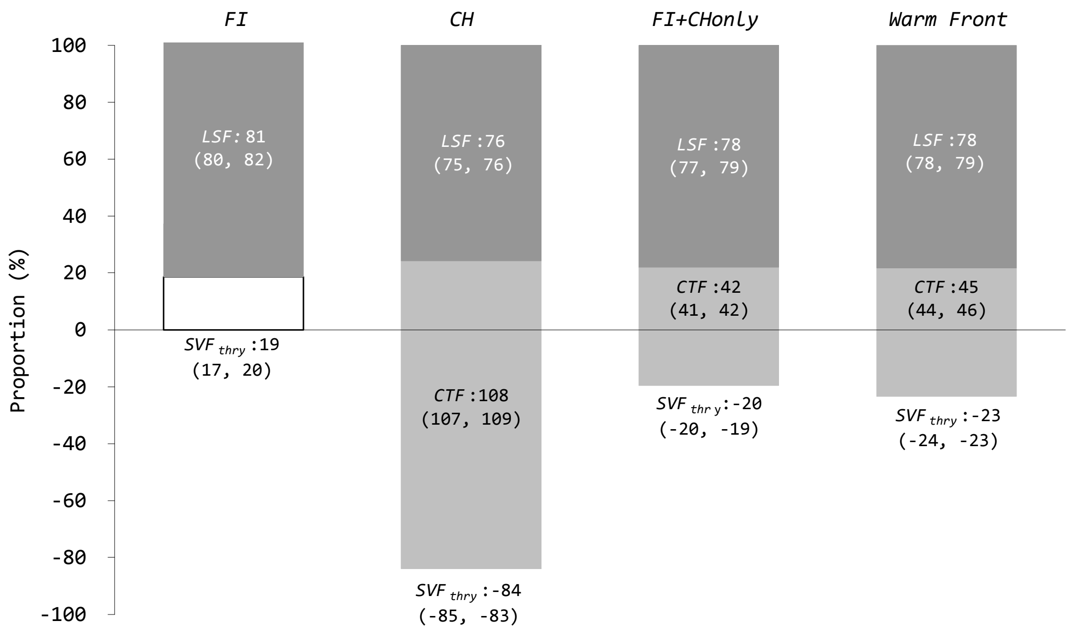
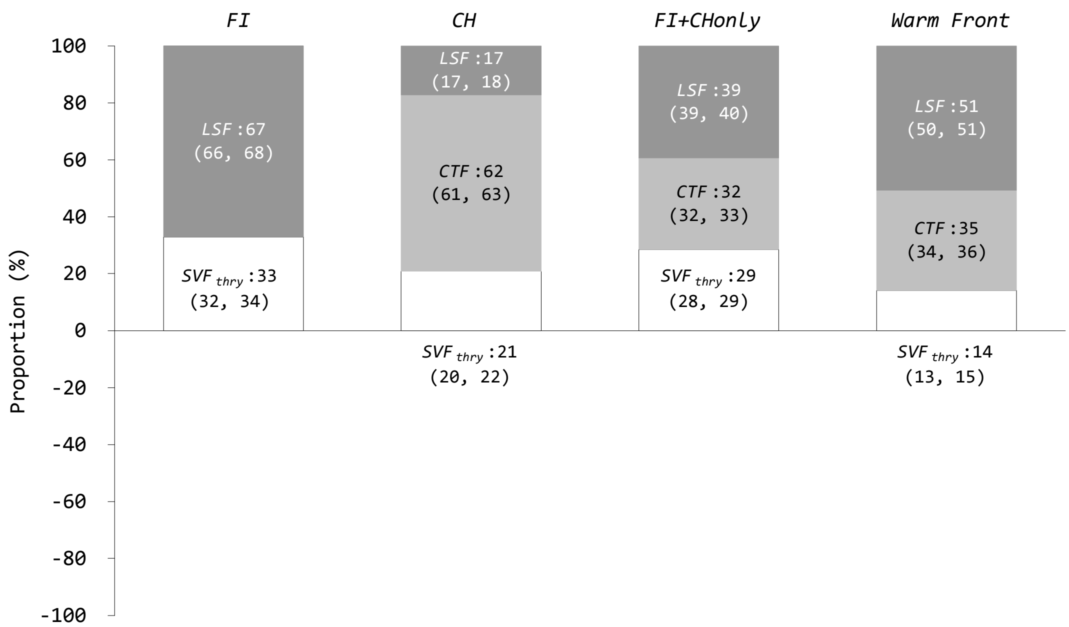


Figure 12.3: The *in situ loss factor* ($LSF_{(insitu)}$), the *comfort taking factor* ($CTF_{(insitu)}$) and the *theoretical saving factor* ($SVF_{thry(insitu)}$) determined based on the (A) delivered energy, (B) energy cost and (C) carbon emissions in relation to energy efficiency measures of central heating (*CH*), full insulation (*FI*), full insulation and central heating only (*FI+CHonly*) (95%CI).

(A) Delivered Energy



(B) Energy Cost



(C) Carbon Emissions

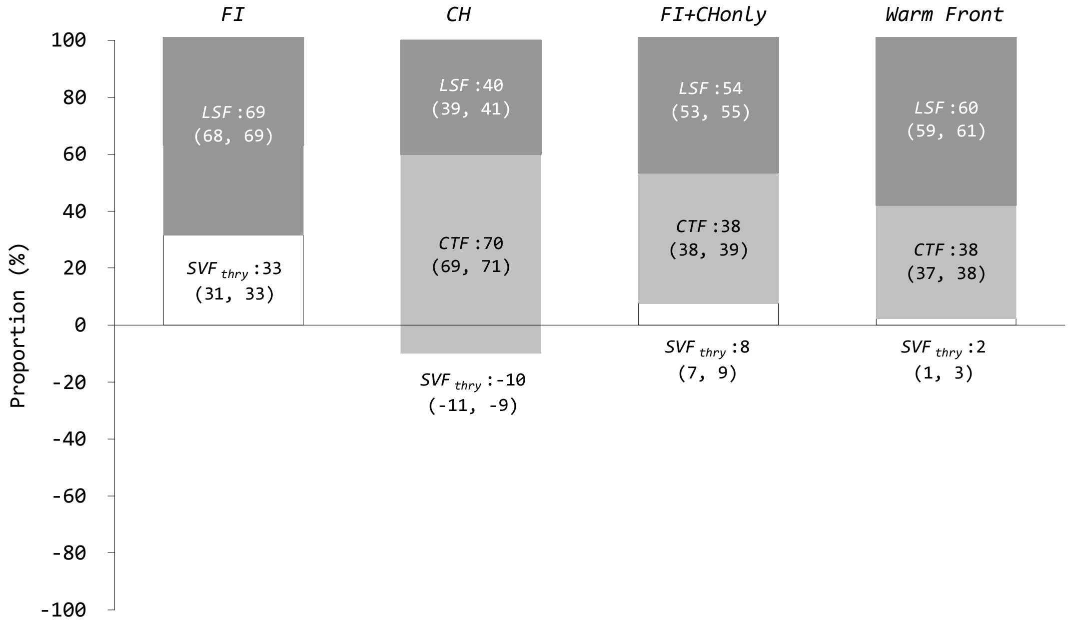
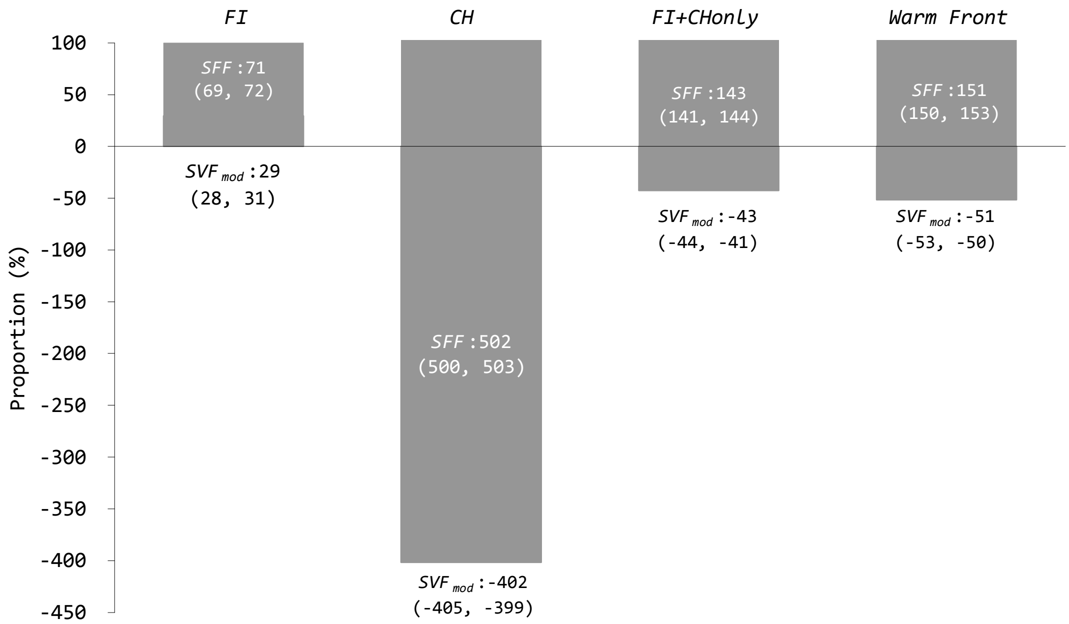
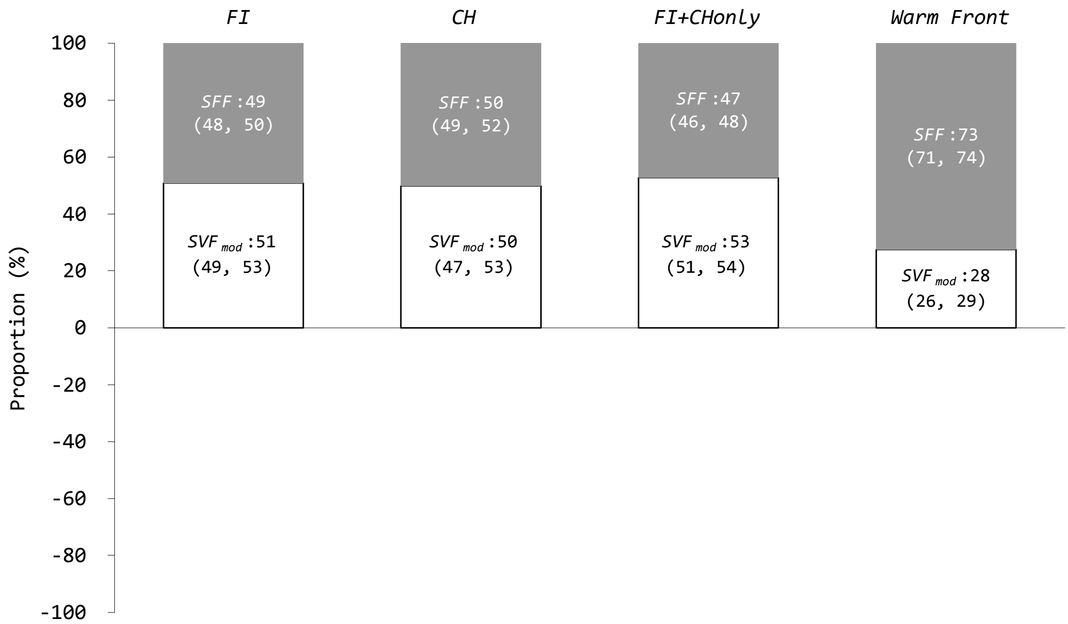


Figure 12.4: The *in situ modelled shortfall factor* ($SFF_{mod(insitu)}$) and the *in situ modelled saving factor* ($SVF_{mod(inisitu)}$) determined based on the (A) delivered energy, (B) energy cost and (C) carbon emissions in relation to energy efficiency measures of central heating (*CH*), full insulation (*FI*), full insulation and central heating only (*FI+CHonly*) (95%CI).

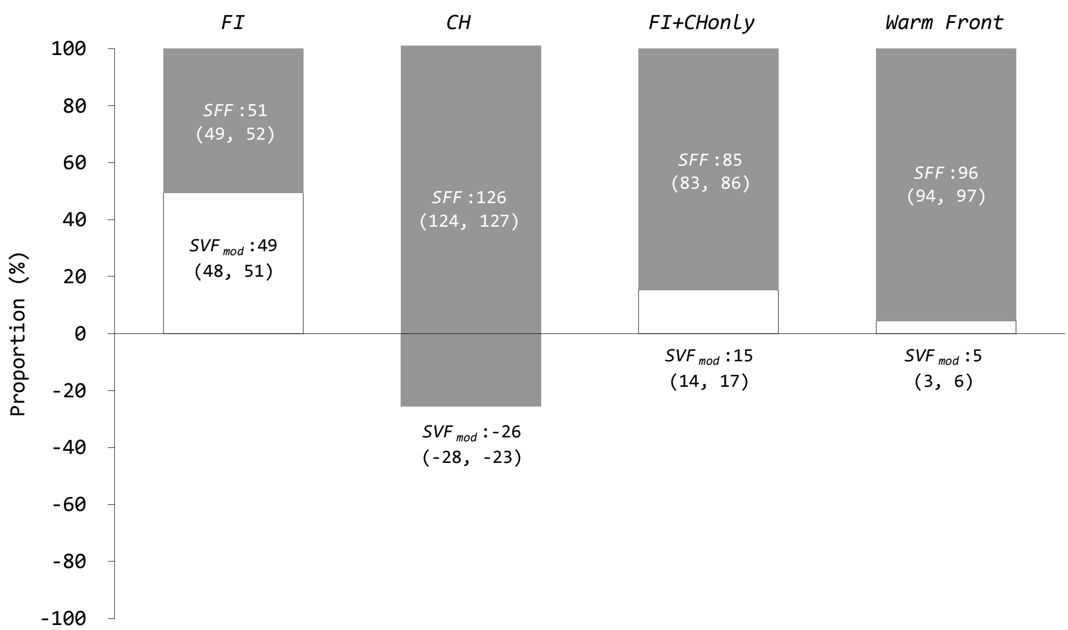
(A) Delivered Energy



(B) Energy Cost



(C) Carbon Emissions



CHAPTER 13 DISCUSSION

This study was based on an extensive data set (property, household, temperature and fuel consumption) collected from some 3000 dwelling making it one of the largest single study exploring the relationship between energy efficiency upgrade and energy consumption in UK housing.

This thesis sets out to explore why no saving in energy consumption was observed following England's *Warm Front Scheme* (Appendix 1) [1] by exploring different factors that contribute to the rise in the energy use. It also answers the 'conundrum' of households reporting reduced difficulty in paying fuel bills despite increased energy use following the upgrade [2].

13.1. Different Method of Analysis, Same Result

The *Warm Front Energy Paper* (Appendix 1) [1] found no saving in space heating energy use despite taking into account the effect of temperature. This was found to be the result of little improvement in the energy performance in spite of introducing energy improving measures with insulation delivering only minor saving and falling short by as much as 80 % from the theoretically expected level of saving and central heating resulting in no saving. Despite having used a different method to normalize the energy consumption to temperature (Chapter 10) in this thesis, the findings reconfirm the previous results with the *loss factor* (in terms of delivered energy) associated with insulation found to be 84 % and with central heating 83 %. The improvement in the central heating performance is thought to be the effect of overestimation in the *comfort taking*.

13.2. Impact of the *Warm Front Scheme*

The *post-WF* mean indoor temperature was found to be on average 1.6 °C (95%CI: 1.2, 1.9) higher – living room: 1.1 °C (95%CI: 0.7, 1.4); bedroom: 1.8 °C (95%CI: 1.5, 2.2) – and the *post-WF* space heating related fuel consumption higher by an average of 12 %. When compared to the potential energy saving which assumes no change in the demand temperature, the rise in the *post-WF* mean energy use represents a *shortfall* of 119 %. When taking into account the change in the demand temperature there is a reduction in the *shortfall* down to 82 %, i.e. the *loss*, indicating that in spite of eliminating the effect of temperature, the scheme still falls far short in delivering the expected level of energy saving.

However, when examined in relation to the energy cost, the result is more encouraging in that the scheme resulted in an average cost saving of 7 %. The combination of increased indoor temperature and reduced fuel cost confirms that the *Warm Front Scheme* is achieving its objectives by reducing exposure to cold and the fuel cost associated with fuel poverty. These results also explain why households were reporting reduced difficulty in paying fuel bills [2] despite monitored increase in the fuel consumption. On the other hand, the 7 % fuel cost saving represents a *shortfall* as high as 75 % to 87 % (Table 12.1), and this marginal benefit is likely be lost if the gas price continues to increase by relatively greater proportion compared to the electricity price into the future [64]. When examined in terms of carbon emissions, the scheme was found to have a negligible impact.

The findings from this study are not unique in that similar results were also observed in English House Condition Survey 1991 [72] which examined the energy consumption of 172 dwellings pre- and post-energy efficiency upgrade and found a mean 1.1 °C rise in indoor temperature accompanied by a 14% increase in fuel consumption following the improvement. However, since many households switched to cheaper fuel, the average fuel expenditure reduced by 11 %.

Characteristic differences were observed with individual energy efficiency measures. Central heating resulted in the greatest mean temperature rise by 2.3 °C (95%CI: 1.8, 2.8) followed by insulation by 0.7 °C (95%CI: 0.3, 1.2) with a negligible impact from draught proofing (Table 8.3). However, in terms of space heating energy, insulation was the only measure that resulted in a mean saving of 9 % whereas central heating resulted in a mean increase of 29 %. On the other hand, when examined in terms of energy cost, insulation and central heating both resulted in mean cost savings of 13 % and 9 % respectively and in the case of carbon emissions, insulation resulted in a 13 % mean saving and central heating in a 4 % mean increase. Draught proofing again was found to have negligible impact on the energy use, cost and carbon emissions.

Thus by analyzing for individual energy efficiency measures and for different measures of performance, a clearer picture emerged as to the reason behind the reported reduction in the fuel cost in spite of the increase in the energy use. The explanation can be found with central heating in that its introduction explains a large part of the increase in the energy use while the switch in the primary space heating fuel type from electricity to gas explains the reduced fuel cost.

The 29 % increase in the space heating energy consumption observed with central heating is largely the effect of the *comfort taking* which was found to be associated with central heating only in this study. Assuming that there was no *comfort taking*, i.e. no mean increase in internal temperature by 2.3 °C (95%CI: 1.8, 2.8) (Table 8.3) from central heating, the *shortfall* would have reduced to 83 % (the *loss*) (Table 12.1) indicating some saving from central heating.

The lack of evidence found in this study between the *comfort taking* and insulation contrasts in particular to the BRE study which estimated a *comfort factor* of 14 % from insulation [42]. This difference is particularly notable since the same method of analysis was used in finding an evidence of the *comfort taking* by relating the heat loss parameter to the internal temperature as undertaken in Section 8.5. Although a likely explanation behind the BRE finding could be linked to the difference in the heating system found in the case study dwellings – gas heating, conventional boilers, storage heaters and condensing boilers – the BRE study does not elaborate on how the effect of the heating system has been isolated from insulation.

13.3. The *Comfort Taking*

The low *monitored mean internal temperature* of 17.1 °C (95%CI: 16.9, 17.3) (Table 8.1) observed in the *pre-WF* dwellings is thought to explain the high *comfort taking factor* observed following the installation of a central heating system. Accordingly, if central heating were to be introduced in dwellings with higher initial temperature, the *comfort taking* is expected to reduce and energy saving achieved.

On the other hand, in the case of the our sample, the benefit of temperature rise from insulation was not found to contribute to any decrease in the *comfort taking* as shown in Table 9.1 which shows the *comfort taking* from the combination of insulation and central heating no less than from central heating measure alone. This is also reflected in the temperature change from the combination of insulation and central heating resulting in a mean rise of 2.5 °C (95%CI: 2.0, 2.9) compared to 2.3 °C (95%CI: 2.1, 2.5) from central heating alone indicating that insulation is not taking up some *comfort taking* associated temperature rise.

The likely explanation seems to be that central heating alone is unable to deliver the desired indoor temperature in the case study dwellings. This is suggested from the results of the *Warm Front Thermal Comfort Paper* (Appendix 4) [38] which showed that the households felt ‘comfortably warm’ (Comfort Vote = 0) from the combination of insulation and central heating whereas the thermal comfort sensation was slightly on the cooler side (Comfort Vote = -0.5) with central heating alone.

On the other hand, the increase in the energy consumption from the combined measures of insulation and central heating was found to be lower by about 16 % compared to 29 % found with central heating alone, and the *shortfall* in the energy cost from the combination of insulation and central heating found to be less by 49 % to 73 % (Table 12.1) compared to 57 % to 82 % (Table 12.1) observed with central heating alone. These benefits along with the highest mean temperature gain of 3.1 °C indicate the importance of combining these two measures for the maximum gain in thermal comfort while minimizing energy penalty. However, the high proportion of the solid-walled *Warm Front* dwellings (37 %, Section 5.5) mean that the benefit to be gained from insulation i.e. wall insulation, is partially lost and underlines the importance of extending the *Warm Front* grant to provide for solid wall insulation if the increase in the energy consumption from central heating is to be lessened [65].

The relationship between the lower initial temperature and a greater *comfort taking* was indicated in a study by Milne & Boardman [39] although the relationship does not always appear to be evident as shown in a study by Martin & Watson [41]. Unfortunately, the initial temperature and the *comfort taking* relationship was not explored in this study because only 37 pairs of longitudinal case study dwellings were available with both the monitored temperature and fuel data likely giving results with low statistical significance.

13.4. The *Loss* and the *Loss factor*

Three sources contributing to the *loss* were identified in this study: one is due to the difference in the variables that determine the *modelled air leakage rate* (Section 4.3.2) compared to those that determine the *monitored air leakage rate* (Section 4.3.3); two is due to retrofit insulation measures not delivering the theoretically expected level of performance (Section 6.2) and three is due to central heating system not delivering the expected level of performance as a result of occupancy behavior (Section 6.3).

By updating the BREDEM input parameters with these known variables, the *loss* was found to reduce by as much as 26 % – although this figure can vary greatly depending on the type of measurement and the intervention group – showing the sensitivity of the *loss* in response to the accuracy of the input data. In theory, if all the factors contributing to the *loss* can be identified, the theoretical model could be calibrated to the point where only the *comfort taking* remains to explain the *shortfall*.

Identifying all the factors contributing to the *loss* is however very difficult and one of the more obvious contributors to the *loss* which have not been identified in this study is occupant controlled ventilation by window opening which may increase with increased air tightness and increased indoor temperature [66]. Although one aspect of reduced heating system performance was investigated (Section 6.3) other contributing factors resulting from poor design, commissioning and setting of controls known to decrease boiler performance were not [4]. The thermal imaging method was also limited in detecting areas of missing insulation but not in assessing the actual thickness of insulation and as a result, the difference between the actual and the estimated U-values in this study are expected to be present and have an impact on the *loss* as well [5].

13.5. The *Modelled Saving* and the *Theoretical Saving*

Two types of *saving*, the *modelled saving* (□Q_{SVmod}) (Eqn. 4.13) and the *theoretical saving* (□Q_{SVthry}) (Eqn. 4.15), were determined in this study. The reason for determining the two savings was to examine how these two, which in theory ought to be the same as illustrated in the idealized diagram in Figure 4.4, actually compare. The result in Table 11.1 shows that there is in fact a large difference between the two savings with the *theoretical saving* being much greater often by a factor of two.

Overestimation in the *comfort taking* (□Q_{CT}) is assumed to be one of the likely causes which can result from under-estimation in the pre-intervention mean internal temperature or over-estimation in the post-intervention mean internal temperature or both. These are possibilities since the method used in determining the mean internal temperature, described in Section 4.7.2, relied on estimating the room-to-room temperature difference based on profiles obtained from other studies whose case study dwellings may not be representative of our case study dwellings [60, 62]. Overestimation in the *comfort taking* (□Q_{CT}) can also result from the inaccuracy associated in the method used in its estimation, described in Chapter 9, relying on temperature and energy relationships of low statistical power.

13.6. The *Shortfall* and the *Shortfall Factor*

Two types of *shortfalls*, the *modelled shortfall* (□Q_{SFmod}) and the *theoretical shortfall* (□Q_{SFthry}), were determined depending on whether the unrealized saving is calculated in relation to the *modelled saving* (□Q_{SVmod}) (Table 7.4) or the *theoretical saving* (□Q_{SVthry}). The purpose was to examine how the *shortfall* and the *shortfall factors* can also vary depending on the choice of the theoretical prediction.

Differences were clearly found between the *modelled shortfall factor* (SFF_{mod}) and the *theoretical shortfall factor* (SFF_{thry}) associated with insulation at 74 % and 84 % respectively. In the case of central heating, the difference was more pronounced with the *modelled shortfall factor* of 297 % compared to the *theoretical shortfall factor* of 161 %. The greater theoretical *shortfall factors* is explained by the greater *theoretical saving* – than the *modelled saving* – against which the *shortfall* is calculated.

The two *shortfall factors* of 74 % and 84 % associated with insulation estimated from this study are greater than the 40 % to 53 % *shortfalls* estimated from other UK based studies [41, 43]. The difference is particularly noticeable since the 74 % *shortfall* was determined by comparing the monitored saving to the BREDEM predicted saving under standard heating regime. This is the same method used in the study by Martin & Watson [41] whose study is also based on a sample of *Warm Front* dwellings and who estimated a lower *shortfall* of 40 %.

The reason for the difference could be the high pre-intervention mean internal temperature of 19.2 °C observed in Martin & Watson's study in contrast to the lower *pre-WF* mean internal temperature of 17.1 °C observed in this study. 19.2 °C is already above the thermal comfort neutral temperature, i.e. the temperature at which most residents feel thermal neutrality, of 18.9 °C to 19.1 °C observed from the *Warm Front Thermal Comfort Study* [38]. This means that the introduction of insulation in that study could have led to decreased thermostat setting resulting in lower *post-WF* energy consumption compared to the condition observed in this study where the thermal comfort could not be achieved with insulation alone (Section 13.1) [38].

Among the different case study groups included in the study undertaken by Milne and Boardman [39], there were two groups that included a central heating system as a part of the energy efficiency upgrade package and the *shortfalls* presented for these two groups were between 35 % and 50 % when determined in terms of the energy cost.

These figures are lower than the value of 57 % (*modelled shortfall factor*) (Table 12.1) determined in this thesis, a different which might be explained by the effect of other energy efficiency measures in the other study.

13.7. Limitations of the Study

The impact of energy efficiency upgrade on changes in ventilation such as increased stack driven ventilation and occupant window opening behavior have received little attention in this thesis. These if quantified into ventilation rate would have provided additional explanation to the *shortfall*. Stack ventilation would draw more outdoor air into the house while collecting warm air upstairs which some householders may consider stuffy. A comparison of the average window opening days from the *Warm Front* household survey in fact showed that those with central heating are more likely to open windows on an average of 3.3 days per week compared to 2.9 days in non-centrally heated dwellings perhaps due to increased temperature or increased pollutant level or both. Although this change in the window opening behavior clearly contributes to the *shortfall*, its effect was not taken into account because estimating the change in the ventilation rate would have required additional detailed analysis which was outside the scope of this study.

Although three to four week gas and electricity consumption data was obtained from the *Warm Front Study*, no information was collected on how much of this was actually consumed for space heating. This entailed a complex data analysis, described in Section 4.5.2, in estimating the space heating energy consumption from the total monitored energy use, a method, despite the best effort, would have limitations in accurately matching the space heating energy use. On the other hand, the similar correlation found in the change between the total delivered energy use (Section 7.1) and the change in the space heating energy use (Section 7.2) form pre- to *post-WF* indicates that the space heating energy use is correctly estimating the change from the upgrade.

Similarly although the monitored internal temperatures were available in this study, these were collected from the living room and the bedroom only none of which are good representation of the mean dwelling temperature. The mean dwelling temperature was therefore determined, as described in Section 4.7.2, by estimating the non-monitored zone 2 room temperatures from the monitored bedroom temperature using room-to-room temperature measurements obtained from other studies [60, 61, 62]. The accuracy of this method unfortunately could not be verified since none of the case study dwellings were monitored for all the rooms.

On the other hand, the impact of this method is evident in the difference it makes to the mean internal temperatures as shown in Table 4.23. In the case of the non-insulated and non-centrally heated dwellings, the mean internal temperature derived using this methods was found 2.3 °C lower when compared to the mean internal temperature derived without zone 2 room-to-room temperature condition and in the case of the insulated and centrally heated dwellings, the mean internal temperature was found to be lower by as much as 3.2 °C. Had the study been carried out without introducing the room-to-room temperature adjustment to the mean internal temperature, the *comfort taking* would have been overestimated.

The applicability of the evidence from this study to a wider context in England is likely to be limited due to the specific characteristic of our case study dwellings focused on the low-income households. Furthermore, the applicability of the findings to the fuel poor in England also requires caution because one, a crude approximation was used to determine the level of fuel poverty in the case of the Warm Front dwelling and two, based on this crude approximation, only about 32 % of the case study dwellings was found to be in fuel poverty and three, only two specific age groups were targeted in the *Warm Front Study* although the proportion of the elderly group in our sample was found to be similar to its representation among the national fuel poor. Finally, the sample also represents a special group in that they have successively applied for the *Warm Front Scheme* and consented to participate in the *Warm Front Study* introducing a potential 'self-selection' bias in our result.

Finally, the findings in this dissertation were predominantly based on cross-sectional comparisons due to the small number of longitudinal cases. This raises questions about the validity of the results particularly since the findings between the longitudinal and the cross-sectional comparisons differed significantly (Chapters 7 & 8). Further investigation using multi-variable analysis based on a set of representative property and household characteristics however showed statistically no significant changes to the cross-sectional results indicating that the sample distribution between the cross-sectional *pre*- and *post-WF* groups are similar and sufficiently robust to accurately capture the impact of energy efficiency improvement even where the cross-sectional sample was disaggregated into smaller groups. The comparison of a selection of property and household characteristics between the *pre*- and the *post-WF* dwellings in Chapter 5 supports the evidence of similarity between the two sets.

CHAPTER 14 CONCLUSION

The findings from this thesis can be summarized as follows:

1. The *Warm Front Scheme* resulted in a 1.6 °C mean increase in indoor temperature and a 12 % mean increase in fuel consumption. Nevertheless, the switch from electricity to gas for space heating following the introduction of gas boilers resulted in a mean heating cost reduction by 7 %. The scheme was found to have a negligible impact on carbon emissions.

2. Insulation resulted in a 0.7 °C mean increase in indoor temperature with a 9 % mean energy saving, a 13 % mean cost saving and a 13 % mean carbon emissions saving. No evidence was found in householders increasing the demand temperature following the introduction of insulation.

3. Central heating resulted in a 2.3 °C mean increase in indoor temperature with a 29 % mean increase in energy consumption. On the other hand, a 9 % mean cost saving was observed as a result of the switch in the primary space heating fuel type from electricity to gas following the installation of gas boilers. Clear evidence was found in householders increasing the demand temperature following the introduction of a central heating system. Central heating was found to have had no impact on carbon emissions.

4. Combining insulation with central heating was found to be beneficial in attaining the greatest indoor temperature rise by a mean of 3.1 °C while mitigating the mean increase in energy consumption associated with central heating from 29 % down to 16 %. However, if these measures were to have been installed in dwellings with higher mean initial dwelling temperature (>17.3 °C) a lesser temperature rise might have been observed and a greater energy and carbon emissions saving achieved.

5. Retrofit insulation was found to be partially effective in insulating the exposed wall and loft areas. About 20 % of the cavity wall and 13 % of the loft area were found to be still missing in insulation following the *Warm Front* insulation upgrade.

6. The *Warm Front Scheme* was beneficial in increasing the proportion of dwellings owning a gas central heating system from 38% to 95%. Despite the presence of a gas central heating system, 77 % still owned some type of local heating appliance(s) increasing the likelihood of their continued use.

7. Rather than providing a definitive figure for the *shortfall*, as originally set out in this thesis, the *shortfall* was found to vary considerably depending on the unit selected to measure the change, i.e. delivered energy, cost or carbon emissions, the energy efficiency measure examined, i.e. insulation and central heating and the method used in determining the theoretically predicted saving.

8. When determining the *shortfall*, the unit selected to measure the change, i.e. delivered energy, cost or carbon emissions, is important depending on whether it is to examine the effectiveness of policies that are directed at tackling fuel poverty or at tackling carbon emissions.

9. Despite the reduction in the fuel cost observed with the *Warm Front Scheme*, the effectiveness of the scheme in improving the housing energy performance must be improved such as by including solid wall insulation if the scheme is to tackle fuel poverty in response to the rising fuel price and if the scheme is to have an impact in reducing the carbon emissions from the housing stock.

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