Brunel University

Reducing Domestic Energy Consumption Through Inclusive Interface Design

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A thesis submitted in partial fulfillment of the requirements for the degree of Engineering Doctorate in Environmental Technology.

School of Engineering and Design, September 2012.

Declaration of Authorship

I, **Nicola Combe**, declare that this thesis titled **Reducing Domestic Heat Energy Consumption Through Inclusive Interface Design** and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given.
- With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: 

Date: 20th August 2012

Abstract

Reducing Domestic Heat Energy Consumption Through Inclusive Interface Design

With housing in the UK responsible for over a quarter of all building related carbon dioxide (CO_2) emissions, it is becoming increasingly difficult to ignore the impact of occupant behaviour on such emissions. One area where occupant behaviour contributes largely towards emissions is space heating within domestic buildings. Despite technological improvements in the efficiency of heating systems, controls have become increasingly complex. Hence, there is a need to enable people to use their heating controls effectively in order to help reduce the associated CO_2 emissions.

This research found that significant numbers of people were excluded from using digital programmable thermostats, in particular people over 50 years old. The first study examined the scale of exclusion relating to digital programmable thermostats installed at a specific housing development. A second study explored in detail the reasons for exclusion from successfully programming a range of digital programmable thermostats. This was an in-depth usability study of heating controls that focused on the usability issues experienced by older people and was published in the Journal of Engineering Design.

Based upon the outcomes of the first two studies a more inclusive heating control interface prototype was developed. The prototype demonstrated a reduction in both cognitive demands and associated user exclusion. Task success rates increased by 56.3% amongst older participants, and detailed energy modelling indicated that energy savings of 14.5-15.6% annually could be achievable. This work suggests that a more inclusive heating control interface could enable energy savings in the region of 15% through reducing the cognitive demands. Furthermore, this research challenges the existing paradigm and shows that inclusive design research may contribute to sustainable development in an environmental, as well as social, capacity.

Acknowledgements

Standing on the shoulders of giants…

Back in 2009, I remember discussing my initial attempt at a literature review with Sal Craig when he asked me, 'Who are your giants? Whose shoulders are you going to stand on?'. To paraphrase Newton if I have seen any further, it is by standing on the shoulders of my giants, of whom there are several. To them all, I am extremely grateful to for your help, support and encouragement over the last four years.

To my industrial giants Buro Happold, thank you for the generous sponsorship. Thank you to all those I worked with over the last four years throughout my engineering doctorate (EngD). To Lindsey, Christine and Celia for having the patience to read my work. Special thanks have to go Sal and Neil for their advice in the earlier years of the research. Thanks to Zack for all he taught me while completing his own EngD. Mark, thank you for helping me through all the EngD modules and accompanying me on this journey. And to Jonathan, a huge thank you for all the proof reading, cups of tea and the friendship extended to me since the day I started back in 2008.

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I would like to dedicate this thesis to the memory of my mother, Jenny Combe (1948-1994), who is a constant source of inspiration. I hope she would have been proud.

Reader's Guide

This research work consists of two volumes. The first volume is the thesis, made up of the abstract, executive summary and nine subsequent chapters. The thesis reports findings of the Engineering Doctorate (EngD) research, which has been structured in the manner of a PhD thesis, for ease of reading. One requirement of the EngD is the provision of an Executive Summary, which is provided prior to the introduction in Chapter 1.

The thesis is designed to be read in order as each chapter builds upon the knowledge accumulated in the previous chapter(s). Following the introduction in Chapter 1 is the Literature Review, Chapter 2. The Research Methodology is discussed and an appropriate methodology is proposed in Chapter 3. Chapters 4, 5, 6 and 7 containing the body of the research work and may be read as independent studies, however it is recommended to read them sequentially. The thesis finishes with the Discussion in Chapter 8 and the Conclusions in Chapter 9.

The second volume consists of the appendices. This includes the journal papers published as part of this research project, to support the contributions to knowledge proposed. The seven six-monthly progress reports produced throughout the EngD process can be made available to the examiners on request.

List of Publications

Journal Papers

Combe, N., Harrison, D., Craig, S., & Young, M. S. (2012) "An investigation into usability and exclusivity issues of digital programmable thermostats" *Journal of Engineering Design*, 23 (5) pp. 401-417. doi:10.1080/09544828.2011.599027

Combe, N., Harrison, D., Dong, H., Craig, S., & Gill, Z. (2011) "Assessing the number of users who are excluded by domestic heating controls" *International Journal of Sustainable Engineering,* 4(1), pp. 84-92. doi:10.1080/19397038.2010.491563

Conference Papers

Combe, N., Harrison, D., & Way, C. (2011) "Enabling Sustainable User Interaction with Domestic Heating Controls" *Buildings Don't Use Energy, People Do? – Domestic Energy Use and CO_2 Emissions in Existing Dwellings,* pp. 89-96, University of Bath.

Combe, N., Harrison, D., & Way, C. (2011) "Modelling the impact of user behaviour on heat energy consumption" *2011 Conference Proceedings, Behavior, Energy and Climate Change Conference*, The Berkeley Institute of the Environment, UC Berkeley.

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Executive Summary

Background

People directly influence the heat energy consumption of their homes through the use of their heating controls. In the domestic sector, heat energy dominates consumption, accounting for 60% of energy consumption. Similarly, expected levels of thermal comfort have increased rapidly since 1970. Average internal temperatures have increased 5°C in three decades (Department of Trade and Industry, 2008). Encouraging users to reduce their indoor temperature and/or heating duration can prove difficult without compromising on perceived comfort. One approach to reducing domestic energy consumption is to improve the control inhabitants have over their consumption of heat. However, many existing heating controls are thought to be excessively complicated and not intuitive enough for users to engage with effectively.

Inclusive design is a people centred approach, which aims to enable a wider range of people to interact with a product, building or service. Currently, within the built environment, inclusive design focuses on ensuring equitable access and service provision. This research aims to utilise an inclusive design approach with the specific intention of reducing energy consumption in buildings. By enabling users to interact with buildings in an effective manner, it is anticipated that reductions in energy consumption may be possible. If the UK is to meet the Climate Change Bill target of an 80% reduction in carbon dioxide (CO_2) emissions by 2050 (DEFRA, 2009) then large-scale reductions in domestic energy consumption will be required.

Programming heating controls effectively has been established as an efficacious means of saving energy within the home (Gupta, Intille and Larson, 2009, Bordass, Leaman and Bunn, 2007, and Moon and Han, 2011). Despite this, usability problems of heating controls have been reported, firstly by Moore and Dartnall (1982) and more recently by Freundenthal and Mook (2003) and Peffer et al. (2011). Recent developments in the field of smart home interfaces have identified some aspects that are problematic for older people (Zhang, Rau and Salvendy, 2009, Sauer, Wastell and Schmeink, 2009). However, only one study has tried specifically to include older people in the control of their heating systems (Freundenthal and Mook, 2003). This research explores an opportunity for an inclusive design approach to enable people to save energy through effective interaction with heating controls in their homes.

This work is a collaboration between the School of Engineering and Design, Brunel University and the Inclusive Design and Sustainability groups of Buro Happold. Buro Happold, the sponsor organisation, is an international building engineering consultancy. The sponsor organisation wanted to understand where opportunities for collaboration between the inclusive design and sustainability groups might be feasible and appropriate. Both Brunel University and Buro Happold share an interest in user-centred design and the question of how it might contribute to more sustainable buildings. Although it is recognised that people influence the energy consumption of buildings significantly it is often difficult to account for this at the design stage. This research aims to contribute a greater understanding of the discrepancy between the designed and actual heat energy consumption of domestic buildings for the sponsor organisation.

Research Objectives

The intention of the research was to design, develop and test a product for use within the built environment, which is an example of both inclusive and sustainable design. Thus, a product outcome was expected from the research with the emphasis on enabling more users to reduce their energy consumption within domestic buildings. This was defined by the sponsor organisation, Buro Happold, at the beginning of the research project.

The novelty of the research lies in the overlap of inclusive and sustainable design fields. To make the research manageable the scope of the research was refined to heat energy consumption and enabling users to control their heating effectively and efficiently. As a consequence this may enable changes in user behaviour and reductions in energy consumption.

In order to achieve the research aims, the research objectives were defined as:

- To investigate the validity of existing tools for quantification of user exclusion in a real-world setting (Chapter 4)
- To understand the scale of and the reasons for user exclusion relating to heating controls products, especially amongst older users (Chapter 5)
- To design and develop an inclusive product or system which allows users to control their heating usage within the home (Chapter 6)
- To quantify the potential energy savings of any such system developed (Chapter 7)

Summary of Methods and Approach

To achieve the research objectives the Design Research Methodology (DRM) from Blessing and Chakrabarti (2009) was employed. The DRM provided a logical structure for the research to progress and involved the development of a design intervention. This methodology involved the following approach: research clarification, understanding issues with existing controls and the development and evaluation of the new system prototype.

Firstly, an extensive literature review was conducted to understand where users influence energy consumption within the domestic environment and opportunities for inclusive product development. To achieve this, a clear understanding of the scientific concepts and methods examining user exclusion, product usability and cognition, in relation to mental workload, were required. This identified gaps in the current literature from which research questions could be derived.

Upon establishing the research questions, a deeper understanding of usability issues experienced by people when interacting with existing heating controls was required. A combination of methods from inclusive design and human factors research were implemented at this stage. Four methods were used in this descriptive stage; quantification of user exclusion, task analysis, user observations and mental workload assessment. Specifically, this involved conducting a desk based Exclusion Calculation and Hierarchical Task Analysis for each control tested. The study participants were observed while completing a specific task to assess usability and identify where problems occurred in the programming process. After completing the task, participants in the second study were asked to complete Raw NASA Task Load Index rating scales. This gave an indication of the mental workload required to complete such a task.

The descriptive work outlined above was conducted prior to any new product development. The final stage of the research involved the development and initial evaluation of the heating control interface prototype. The initial evaluation of the prototype was two-fold; to assess whether the prototype was more inclusive than previous systems and to quantify the scale of potential energy savings of the new system. The four methods used previously were repeated to evaluate the usability and user exclusion of the prototype.

To quantify the scale of potential energy savings two example homes were modelled in Integrated Environment Solutions' (IES) Virtual Environment 6.4.0.8 software. Accurate heating profiles were developed based upon the user observations and the default settings of existing controls. The annual energy consumption of the different scenarios was evaluated for both homes. This provides an initial link between applying an inclusive design approach and potential energy savings.

Summary of Studies and Results

This thesis consists of four research studies, each completed to meet one of the research objectives. These studies also aimed to address the three research gaps identified from the literature. Firstly, while the quantification of user exclusion and the Exclusion Calculator tool were of particular interest, there has been no validation of the tool within the built environment. Secondly, a deeper understanding of usability issues and the reasons for design exclusion in relation to heating controls was required, especially for older people. The evaluation of cognitive issues within inclusive design research is currently limited and the application of mental workload assessment methods aimed to address this. Thirdly, there was an opportunity for the development of a more inclusive heating control, which reduces the cognitive demands of such a system.

In order to establish a baseline for the number of people excluded from programming their heating controls a pilot study was conducted. Chapter 4 examines the scale of user exclusion relating to digital programmable thermostats installed at a low-energy housing development in Suffolk. The novelty of this study was the comparison of the Exclusion Calculation results to the real-world results. This suggested the Exclusion Calculator underestimated exclusion levels for digital programmable thermostats. The calculation estimated that current products would place excessive demands upon the capabilities on 9.5% of the UK population over 16 years old. This estimated user exclusion increased to 20.7% for people over 60 years old. In an attempt to validate these results, twelve residents of a low-carbon housing development were asked to complete a task using their controls. Of the residents who attempted the task 66% of them were unable to complete it. This study established that the scale of user exclusion relating to digital programmable thermostats at the development was considerable and was higher than estimated by the Exclusion Calculator. The study suggested that the true user exclusion may be higher than the expected exclusion predicted. Hence, there was a need for further work in reducing user exclusion in relation to such products.

The main reason for the user exclusion, identified in Chapter 4, was the cognitive demands placed on the user. Chapter 5 investigated further usability and exclusivity issues of digital programmable thermostats, with particular reference to the cognitive issues experienced by older users. Two groups of participants (24-44 years old and 62-75 years old) were involved in the usability testing of three digital programmable thermostats. This highlighted the specific difficulties older people had using such controls. Both groups of participants were asked to perform the same task that involved setting both an on and off time and a temperature twice during a weekday and the same at weekends.

On the whole, older users found the task complex, frustrating and none of the older users were able to programme the settings for any of the controls. Similar to the previous study, the exclusion calculations underestimated the actual exclusion significantly for both age ranges ($p < 0.05$). Younger users had greater success with the task, however the time taken to complete the task was still considerable. The average time for a younger participant to complete the task without using instructions was 5 minutes 26 seconds. Furthermore, there was a significant difference in the task completion time between the younger users who required the instructions to complete the task successfully and those who did not ($t(12) = -5.2$; $p < 0.001$). The cognitive demands were evaluated using a subjective mental workload assessment method. The application of the Raw NASA Task Load Index found mental demand, effort and frustration levels were excessive. Overall workload tended to be higher for older participants than the younger group (mean 62.3 vs. 53.5, where the lower rating implying that the controls are easier to use).

To achieve the research objective of a product based outcome Chapter 6 documents the development of a more inclusive heating control interface. A proof-of-principle prototype was developed and tested with a variety of users, as part one of the contributions to knowledge of this research. The idea was to design an interface that could be used as a desktop or web application or via an in-home touchscreen to wirelessly control the heating system. Based on the findings of the previous studies, key areas for improvement were identified and addressed within the prototype. This study demonstrated a reduction in cognitive load compared to the controls assessed previously. The user exclusion associated with the prototype has been reduced compared to existing controls, particularly amongst the older participants. This is implied from a success rate of 56.3% for the older participants, in an average time of 5 minutes 32 seconds. Low levels of frustration, effort and mental demand were observed in younger participants and in successful older participants. However, frustration levels remained significant for the older users who were unsuccessful.

The results presented in Chapter 6 infer the system developed was more inclusive than the previous controls tested. However, the potential impact on energy consumption also required appraisal. Chapter 7 estimated the impact of user behaviour on heat energy consumption using two dwelling models. In this way the impact on annual energy consumption of certain user errors observed could be calculated. In the previous study one observation in particular was thought to effect energy consumption. This was that some users did not reduce heating temperature at the end of the heating period. In reality this could result in accidentally heating throughout the day and/or night, unbeknown to the users. The results from Chapter 7 demonstrated that the user error observed resulted in an increase in energy consumption of 14.5-15.6% annually.

Relating these results to the thermostat settings recorded at the low-energy housing development indicates that the observations do translate to real-world behaviours. The error was observed in 20% of the sample in Chapter 5 and 45% of the low-energy housing development sample. If this problem occurred nationwide that would equate to between 5.5 and 11.9 million households. Hence, designing a more inclusive heating control system may enable energy savings, while also improving the overall user experience of the system for a wide range of users.

Conclusions and Contributions

The core objective of this research was to design, develop and test a product for use within the built environment, which is both inclusive and sustainable. The research focus was on enabling users to interact with their heating controls in a successful and energy efficient manner. Hence, the core contribution of this research is the design, development and initial testing of a novel heating control interface. This is both inclusive and could enable energy savings. This product outcome has been achieved through the development of a proof-of-principle heating control interface, with the associated user testing. Further development and testing of such a product may help reduce heat energy consumption for older people living independently in the UK. The implementation of such a heating control in homes may also help reduce unnecessary periods of heating. This could make a significant contribution to reducing the CO_2 emissions associated with domestic heat energy consumption in the UK.

This research proposed three contributions to knowledge:

- The real-world application and validation of the Exclusion Calculator in relation to digital programmable thermostats
- The detailed understanding of usability issues relating to digital programmable thermostats, especially their impact on older people
- The design, development and initial testing of a proof-of-principle prototype for a novel heating control interface

The first proposed contribution to knowledge was published in the International Journal of Sustainable Engineering (Combe et al., 2011) and attempted to validate the Exclusion Calculator results in a real-world setting. The results reported in Chapter 5 constitute the second proposed contribution, which was published in the Journal of Engineering Design (Combe et al., 2012).

Within the field of inclusive design, this research additionally contributes a novel methodological approach. This research includes a published attempt to assess the mental workload, through the application of the Raw NASA TLX scales in the context of inclusive design research. The use of these scales has proven useful to understand the cognitive demands, an area where the existing means of assessment are not sufficient.

This research challenges the existing paradigm by applying an inclusive approach with the explicit aim of reducing both user exclusion and energy consumption. The possibility of using an inclusive design approach, with the aim to save energy, has been tentatively verified.

Chapter 1 - Introduction

1.1 Problem Statement

With the twin issues of the need to reduce carbon dioxide (CO_2) emissions and a rapidly ageing population, there is a requirement to include the widest possible range of people to achieve reductions of the scale required. The United Kingdom (UK) has committed to a target of an 80% reduction in CO_2 emissions by 2050 (DEFRA, 2009). Yet in achieving this, both large-scale reductions in domestic energy consumption and changes in our behaviour will be required. Residential buildings in the UK are responsible for CO_2 emissions, equating to 27% of the UK total, and space heating accounts for nearly 60% of energy consumed in homes (Boardman, 2007). This is partially due to average internal temperatures steadily increasing from 13°C in 1970 to 18°C in 2000 (Department of Trade and Industry, 2008).

Heating control systems are a specific techno-social system, which users interact with within their homes. This interaction, or lack of it, may be partly responsible for the large proportion of energy consumed as heat in homes. If an occupant wishes to reduce their domestic consumption, their ability to do so will in a large part be dictated by the design of their heating control systems. Inclusive design aims to design systems for use by the widest possible range of users. Specifically this research aims to apply such an approach to enable people to save energy within the home. By improving the control inhabitants have over their consumption of heat, reductions in domestic energy consumption could be made.

In recent years technology has rapidly advanced, as has the average age of the population in the UK. It is estimated that by 2020 50% of the adult UK population will be over 50 years old (Coleman, 2003). More recently, the 2011 Census confirmed the ageing population trend with the UK population aged 65 (16.4% of the total population) and equating to 1 in 6 people (Office of National Statistics, 2012).

People aged 50 or older are far more capable and active than their predecessors (Huppert, 2003). Developing techno-social systems that include older people presents a distinct challenge for designers. Langdon and Thimbleby (2010) highlight that developments in interactive systems are often not inclusive for older users. Hence, there is a demand for usable technologies, which meet the needs of the increasingly ageing

UK population. The development of any future environmental technology must take into account a wider range of users to ensure successful and satisfying interactions.

1.2 Scope of Research

This research contributes to the current understanding how people interact with digital programmable thermostats within their homes. As buildings become more efficient the impact of the occupants' use of the building is becoming increasingly important in reducing the associated emissions. The scope of research is therefore confined to heat energy consumption in UK residential buildings.

This research covers both new build developments and retrofitting of existing dwellings. It is inclusive design because it is people centred and housing is the one building type, which all people use. People have most influence over their heat energy consumption via the user interfaces of their heating control systems. Therefore the scope of research has been refined to examine the energy impact of user interaction with heating controls in domestic buildings, see Figure 1.1. This interaction between the user and the interface is of primary relevance to this EngD.

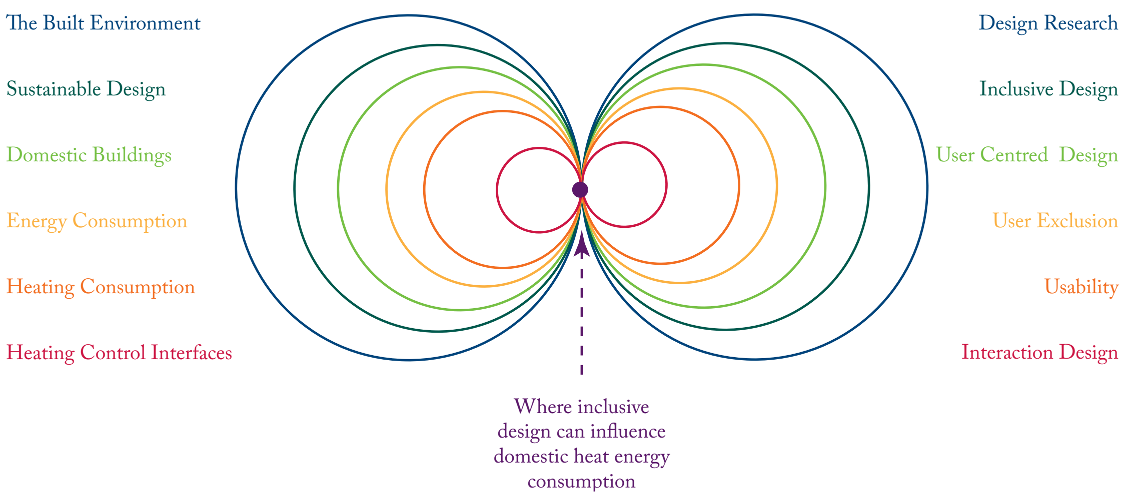


Figure 1.1 Research Scope

A variety of heating controls can be found in the domestic environment currently (see Figure 1.2). A full set of heating controls within domestic buildings consist of a room thermostat, a central programmer and thermostatic radiator valves (TRV's; Department of Communities and Local Government, 2009a). Such systems are commonly installed during heating system upgrades and in new build housing throughout the UK.

Having some control over the building's internal conditions, such as being able to open a window or control temperature, can give occupants a greater sense of satisfaction (Bordass and Leaman, 2001). Providing full control allows occupants to manage how much heat energy is delivered, where in the house it is delivered, and when.

Figure 1.2 Examples of Heating Controls (clockwise from top left: 1-programmable thermostat, 2-manual room thermostat, 3-thermostatic radiator valve on a radiator and 4-boiler interface with manual programmer)

To refine the scope of the research further this research focuses on the user interface of digital programmable thermostats, which control both duration and temperature of heating. Other elements of a full set of heating controls are therefore outside the scope of this project. Such systems can save energy through effective use; however, this research questions whether current systems are exclusive and do not enable users to achieve such energy savings.

1.3 Research Aim, Motivation and Objectives

The overall aim of this research was to understand how inclusive design may contribute to reducing energy consumption. It was thought that inclusive design may have environmental benefits as well as social benefits. The research set out to achieve the aim through the design, development and testing of a design intervention for use within the built environment that is both inclusive and sustainable. Implementing an inclusive design approach may improve the interaction between people and their heating systems. In turn this may enable associated energy savings. This research aims to provide a novel understanding of the environmental impacts of user interaction with techno-social systems within domestic buildings.

The motivation behind this research project was to implement an inclusive design approach to the design of a sustainable product or system. This motivation to develop a product based outcome of the research came primarily from the sponsor organisation. Buro Happold wanted to identify opportunities for collaboration and new product development between the Inclusive Design and Sustainability groups. Hence, this research was conducted within both groups of Buro Happold and the School of Engineering and Design, Brunel University.

In order to achieve the research aims, the research objectives were:

- To investigate the validity of existing tools for quantification of user exclusion in a real-world setting (Chapter 4)
- To understand the scale of and the reasons for user exclusion relating to heating controls products, especially amongst older users (Chapter 5)
- To design and develop an inclusive product or system which allows users to control their heating usage within the home (Chapter 6)
- To quantify the potential energy savings of any such system developed (Chapter 7)

Once the first and second objectives were achieved, the issues identified were addressed through the development of a new prototype product. The third objective aimed to create the novel product or system desired by Buro Happold, the sponsor organisation. The fourth objective was to evaluate the potential energy savings of the system developed and any reductions in associated CO_2 emissions, which can negatively impact the environment.

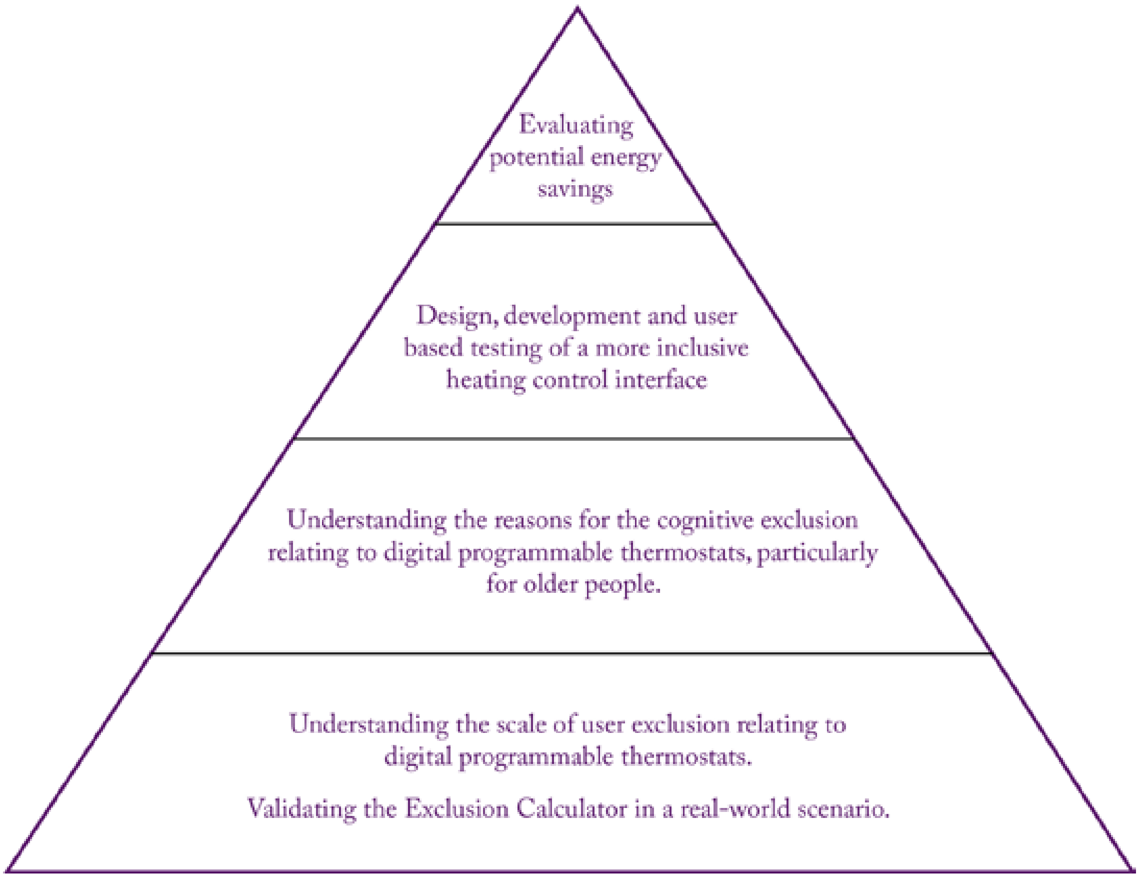


Figure 1.3 Pyramid Diagram of Research

1.4 Overview of Thesis

The first two chapters of this thesis provide the background to the research with Chapter 2 examining the literature in detail. This explores the background literature relating to inclusive design and the energy consumption of domestic buildings. Lastly, the overlap between these fields where user interaction with buildings influences their energy consumption is discussed. Chapter 3 discusses the Design Research Methodology and how this is applied in this context.

The exploratory work of this research consists of Chapter 4 and Chapter 5, which examine existing digital programmable thermostats in detail. The pilot study reported in Chapter 4 explored the scale of user exclusion and the validity of existing tools for quantification of user exclusion. Chapter 5 consists of a usability study of heating controls that focuses on the issues experienced by older people.

Building on this exploratory work the design, development and subsequent evaluation of an inclusive heating control interface is documented in Chapter 6. This interface reduces the cognitive demand placed on a range of users, which led to greater success in a programming task. Chapter 7 quantifies the possible energy savings through detailed energy modelling. This energy modelling suggests energy savings of up to 15% may be possible if this novel interface is implemented in homes. The research concludes with an overall discussion of the implications of the results in Chapter 8 and conclusions are drawn in Chapter 9.

Chapter 2 - Literature Review

Abstract

Chapter 2 reviews the pertinent literature in the field of inclusive design and current work in the area of domestic energy management systems. This chapter aims to identify gaps in the current literature from which research questions can be derived. The literature reviewed discusses research in three fields: inclusive design, energy consumption of buildings and how the interaction with people and buildings affects energy consumption.

The first part (Sections 2.1-2.3) examines the principles and methods of inclusive design and how this can lead to improved design of products, services and environments. The second part (Sections 2.4-2.7) examines energy consumption in the built environment, with a focus on domestic buildings. Finally, the influence people have over their energy consumption is examined, with specific references to how users interact with the available controls (Section 2.8 onwards).

Several studies recognise that the usability of heating controls and energy management systems can be poor. This lack of usability is thought to be a barrier to achieving the energy savings possible with technologies such as digital programmable thermostats (see Section 2.7.3). Similarly, is it recognised that older users in particular may struggle to use such controls and energy management systems (see Section 2.8.3), yet currently little has been done to address this (see Section 2.8.4). Hence, a need for more usable control systems, which include users and enable energy savings, has been identified from the literature.

2.1. Inclusive Design

Inclusive design is a people centric approach to design that considers the needs of the widest range of possible users (Keates and Clarkson, 2003). Vandenberg describes an inclusive environment as one where "everyone (or virtually everyone) has dignified and easy access to all the good things that civilised life has to offer" (pp. ix, 2008). An inclusive approach recognises that it is not possible for one particular design solution to satisfy the needs of all users.

The definition of inclusive design is standardised in BS 7000-6:2005 as the "design of mainstream products and/or services that are accessible to, and usable by, people with the widest range of abilities within the widest range of situations without the need for special adaptation or design" (pp. 4, British Standards Institute, 2005). The inclusive design principles defined by the Commission for Architecture and the Built Environment (CABE; Fletcher, 2006) are central to this research:

- Placing people at the heart of the design process
- Acknowledging diversity and differences
- Offering choice where a single design solution cannot accommodate users
- Providing for flexibility in use
- Providing buildings and environments that are convenient and enjoyable for everyone

While inclusive design terminology and approaches vary, the objectives of each approach are essentially the same. Inclusive design is used in the United Kingdom, Design for All in Europe and Universal Design in the USA. Inclusive design understands the differences between people, respecting and even celebrating these.

Universal design centres on making the product or environment usable by everyone and is defined as, "an approach to design that incorporates products as well as building features which, to the greatest extent possible, can be used by everyone" (Mace, 1988, cited pp. 1.5 in Preiser and Ostroff 2001). This approach, pioneered by the Center for universal design at North Carolina State University, originated in the built environment prior to being expanded to products and services (Coleman, 2003). Preiser and Osteroff (2001) feel that the approach has been misconstrued in the USA as the way to comply with the Americans with Disabilities Act. Although the minimum standards set out are deemed important these should not define the approach.

Design for All is a European approach, which the European Institute for Design and Disability defines as, "design for human diversity, social inclusion and equality" (2004) in its Stockholm declaration. It is an aspirational and philosophical approach towards design of products, buildings and services. Interestingly, it also has a focus on inclusive information and communication technologies (Keates and Clarkson, 2003).

Transgenerational design is a further concept that shares the ethos of inclusive design with a focus on age. As a response to the ageing populations in western societies Prikl (1994) developed an approach to include older people, while at the same not excluding younger, more dexterous and mobile consumers. It is strongly advocated that transgenerational design does not aim to produce specialised or adaptive products for older users but should promote independence and consumer choice (Prikl, 1994). The ageing population of both the UK and the USA is a significant driver for both inclusive and transgenerational design. Adopting both approaches may provide an increased potential market for products and services that are designed with age in mind.

Keates and Clarkson (2003) argue that above all, inclusive design is not design for disabled and older people but design for a range of users; it is user-centric and should improve the usability of products. To this end people may be excluded for using a product, building or service not only due to a disability but because of factors including: age, poverty, lack of education or other discrimination (Vandenberg, 2008). The terminology discussed in this section is often used interchangeably, due to the similarities and common goals of the approaches and will be referred to throughout this thesis as inclusive design.

2.2 Approaches to Inclusive Design

A variety of approaches within inclusive design have influenced this research, therefore it important to clarify these from the outset. The concepts discussed expand on the approaches discussed earlier; universal design, design for all and inclusive design, which share a common user focus.

2.2.1 Seven Principles of Universal Design

The principles of universal design were developed by a consortium of ten interdisciplinary researchers to provide guidance for designers of products, environments, buildings and communications at The Center for Universal Design (1997). The approach can be illustrated using the following seven principles:

1. Equitable – the design is useful and marketable to people with diverse abilities.
2. Flexible in use – the design accommodates a wide range of individual preferences and abilities.
3. Simple and intuitive to use – use of the design is easy to understand, regardless of the user's experience, knowledge, language skills or current concentration level.
4. Perceptible information – the design communicates necessary information

effectively to the user, regardless of ambient conditions or the user's sensory abilities.

5. Tolerance for error – the design minimises hazards and the adverse consequences of accidental or unintended actions.
6. Low physical effort – the design can be used efficiently and comfortably with a minimum of fatigue.
7. Size and space for approach and use – appropriate size and space is provided for approach, reach, manipulation and use regardless of the user's body size posture, or mobility.
(The Center for Universal Design, 1997)

The implementation of Universal Design principles will be considered as this research develops. Any solution or design intervention developed as part of this research should be simple, perceptible and flexible.

2.2.2 Top Down or Bottom-up Approaches

User pyramids are often used in inclusive design to define users and their level of capabilities. The most relevant of these pyramids is Benktzon's (1993) User Pyramid, shown in Figure 2.1, which can lead to a top down or bottom up design approach. A top down approach designs for users with the least functional capability and then aims to make the the product more mainstream (Keates and Clarkson, 2003). This can often result in highly specialised products. In contrast the bottom-up approach takes a mainstream design and aims to make it more usable. However, it is unlikely to cater for extremely disabled users (ibid.).

To design for the whole population three approaches are proposed: user aware design (at the bottom of the pyramid), customisable/modular design (in the middle of the pyramid) and special purpose design (at the top of the pyramid; ibid.). As people age their capabilities reduce and their level of disability may increase. Designing for older users may allow a product to be suitable, with some level of customisation, to users within the first and second levels of the pyramid.

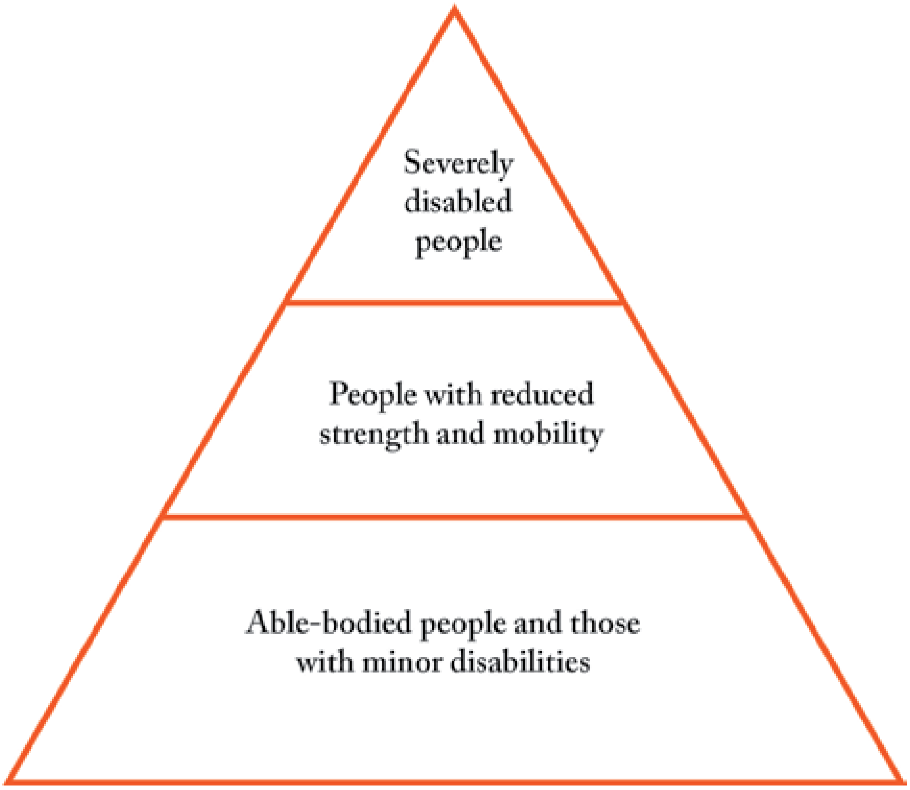


Figure 2.1 User Pyramids (adapted from Benktzon, 1993)

2.2.3 Defining User Capabilities

According to Card et al. (1983, cited in Keates and Clarkson, 2003), an error-free human product interaction can be described in three phases:

- The time to perceive an event (perceptual processor)
- The time to process the information and decide upon a course of responsive action (cognitive processor)
- The time to perform the appropriate response (motor processor)

These stages are performed in the order, perception, cognition then motor functions. Users rely upon sensory capabilities such as sight and sound to perceive an event. Thinking is classified as a cognitive capability, whereas dexterity and movement are motor capabilities. Capability demands are defined as the level of ability required to achieve a particular task (Waller, Langdon and Clarkson, 2009 and 2010). Understanding this level allows the quantification of users excluded by a product.

Furthermore, providing a focus on what users are and are not able to do, giving designers clear parameters to work within (Keates and Clarkson, 2003). These capabilities can be represented visually on the Inclusive Design Cube as shown in Figure 2.2.

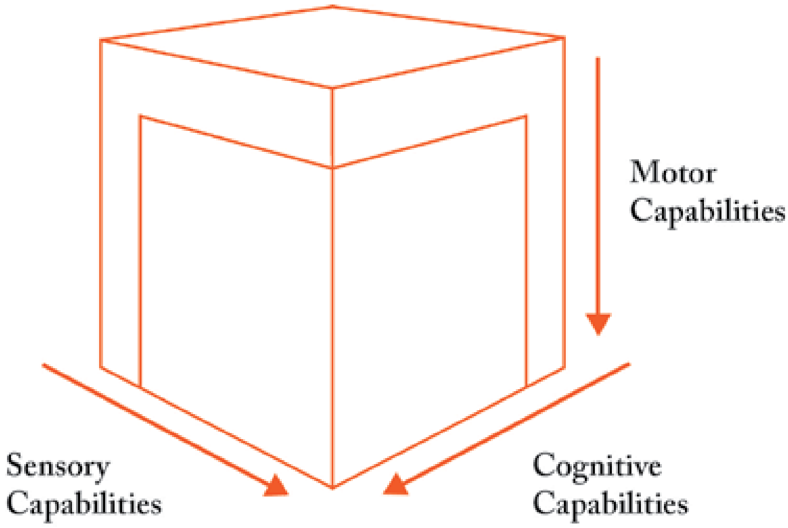


Figure 2.2 Inclusive Design Cube with Capability Demands Illustrated

2.2.4 Countering Design Exclusion

Design Exclusion identifies that by understanding "the capability demands placed upon the user by the features of the product, it is possible to establish the users who cannot use the product irrespective of the cause of their functional impairment" (pp. 68, Keates and Clarkson, 2003). This can be represented visually as the included population compared to the whole population on the inclusive design cube (shown in Figure 2.3). All users between these two populations are excluded, i.e. unable to use the product (ibid.).

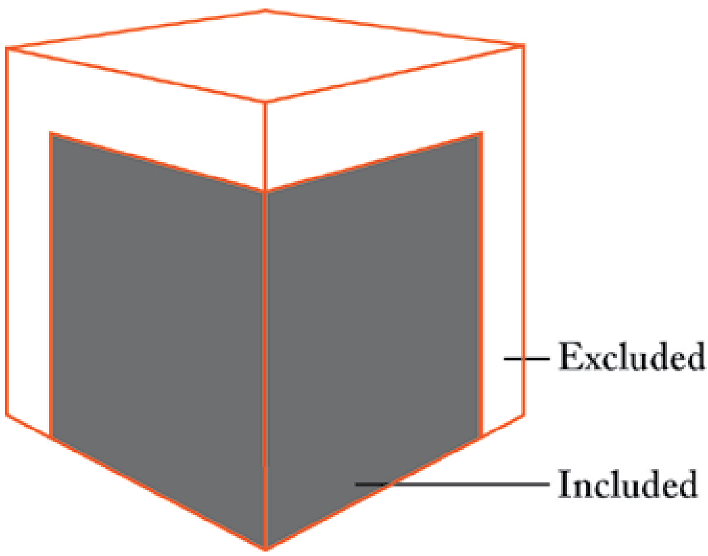


Figure 2.3 Inclusive Design Cube with Included/Excluded Populations

The level of design exclusion can then be assessed and quantified based upon available disability data. For designers it can help to identify areas of particular exclusion and remedy these during an iterative design process.

This research aims to counter exclusion found within the built environment. Such an approach aims to include a range of capabilities from the outset using a bottom up approach. The approaches reviewed here are by no means comprehensive however the theories are the most current and relevant to this research. The research methods from inclusive design, which are implemented in this research, are discussed in detail in Section 3.3 of the Methodology.

2.3 Drivers for Inclusive Design

The main drivers for the adoption of inclusive design in the UK are demographic changes and legislation. It is appropriate to understand these drivers to provide context for this research. By considering the relevant drivers for inclusive design this develops the argument that there is a need to design products within the built environment inclusively. The barriers to the implementation of inclusive design are comprehensively studied in Dong (2004) and are therefore not discussed in this research. Dong (2004) concludes that the most significant barriers were a lack of awareness of inclusive design, a lack of accessible user data and a lack communication between stakeholders.

2.3.1. Demographic Change

The rapid ageing of populations worldwide is dramatically increasing the need for inclusive products and services. This trend is set to continue for the foreseeable future expanding the potential market for these services and products further. The UK population is ageing, with one in six people now aged 65 and over (Office of National Statistics, 2012). Huppert suggests that today, "it is a mistake to think of the older user as a wheelchair user or as severely disabled, hard of hearing or partially sighted" (pp. 32, 2003). Furthermore, Abascal and Nicolle (2005) suggest there is little evidence to support the argument that people with disabilities dislike or reject new technologies more than any other user group.

With the UK population living longer there is an increased need for healthcare and other social services. For many people ageing can result in loss of hearing, eyesight, mobility, dexterity and/or memory on a varying scale (Haigh, 1993, cited in Coleman, 2003). One particular aspect of age-related disability is that the onset may be slow, however it commonly results in multiple disabilities (Coleman, 2003). Technologies that help people remain in their own homes for longer are of great interest to reduce the cost of care for older people. The increased prevalence of technology within homes provides an opportunity to support independent living by helping users control their environment and provide care services (Eguzkiza, Garay and Gardeazabal, 2003). This research focuses on making such in-home technologies inclusive, particularly for older people living independently.

2.3.2 Legislation

The introduction of legislation in the UK that made it illegal to discriminate against a person because of a disability and has been a second driver to adopting inclusive design in practice. The relevant legislation is summarised in this section. The Equality Act (2010) is the main legislation covering disability in the UK, which supersedes the Disability Discrimination Act (DDA). The threat of legal action under the DDA legislation was viewed as a significant incentive for businesses to adopt inclusive design practices (Keates and Clarkson, 2003). Furthermore, Imrie and Hall (2001) argue that legislation such as this gives people a means of both moral and legal reinforcement.

The Equity Act requires 'reasonable provisions' to be made yet there is debate regarding the definition of what reasonable provision constitutes (Equality and Human Rights Commission, 2011). This is still open to subjective interpretation and what is considered reasonable can depend on this interpretation. To ensure buildings are inclusive, users need to be able to interact with them successfully. It is this interaction between the building and the occupant where users can be excluded that is of specific interest to this research.

2.3.3 Social vs. Medical Model of Disability

The Equality Act (2010) is a driver for the social model of disability as an alternative to the definition as a medical condition. The social model of disability, developed in the UK by the Union of the Physically Impaired Against Segregation (UPIAS), defines disability as:

"the disadvantage or restriction of activity caused by a contemporary social organisation which takes no or little account of people who have physical impairments and thus excludes them from participation in the mainstream of social activities." (UPIAS, 1976, cited pp. 31 in Imrie and Hall, 2001)

In the UK the number of people with a disability now exceeds ten million people (Clay et al., 2011). To put this in context based upon the data from the 2001 Census:

- Wheelchair users represent 0.85% of the total population
- Around 5.6 million people have difficulty with physical coordination
- 14% of the UK's population have reduced or limited mobility
- There are in excess of 8 million people who are Deaf or hard of hearing
- Around 2 million people have a sight problem

(From Smith and Dropkin, 2008)

The medical model of disability implies the problems disabled people encounter are due to their impairment and not the environment (Imrie and Hall, 2001). It is defined as a "physical or mental impairment, which has a substantial and long-term adverse effect on their ability to carry out normal day-to-day activities" (pp. 11, Disability Rights Commission, 2006) putting the onus on person rather than their environment.

The social model of disability suggests that a disability is the consequence of society or an environment rather than a physical or mental impairment. This implies disability is caused by poor design and not a medical issue. It is this more progressive approach that underpins this research.

2.4 Energy Consumption of Buildings

As a society the UK relies predominantly on a fossil fuel based energy supply, a large percentage of which is consumed in the built environment. Buildings contribute nearly 50% of the UK's CO_2 emissions throughout their life cycle, particularly during their operation (DEFRA, 2009). Boardman (2007) argues that reductions in emissions from buildings are of paramount importance. This section reviews the scale of energy consumption, the main areas of energy consumption and how buildings contribute to this energy consumption.

2.4.1 Energy Consumption in the UK

Energy production and consumption are responsible for 95% of the UK's CO_2 emissions (as of 2004, Department of Trade and Industry 2006). Despite renewable energy production quadrupling between 1990 and 2005 (ibid.), it only accounted for

3.2% of total energy consumption in 2010. The UK has the third lowest percentage in Europe of energy from renewable sources (European Commission, 2012). The majority of electrical energy is produced from fossil fuel based sources with natural gas accounting for 41% of supply (Department of Energy and Climate Change, 2011a). In 2010 the three main consumers of energy were transport (37%), domestic use (32%) and industrial consumption (18%) (ibid.). These figures are by final energy consumption, i.e. the energy consumed by consumers, discounting the production losses, which are not considered in this research.

Since 1970 overall energy consumption has increased by 31.4% (Department of Energy and Climate Change, 2010a). UK consumption hit a peak in 2004 and decreased to its lowest point in 20 years in 2009, partially due to the economic downturn (Department of Energy and Climate Change, 2011a). However, energy consumption is heavily dependent on the weather due to the large impact of domestic space heating. Year-on-year energy consumption increased 13% between 2009 and 2010 principally due to colder external temperatures (Department of Energy and Climate Change, 2011a). This increase in consumption was due to an increase in energy used to heat homes during this exceptionally cold winter, illustrating the large impact the domestic sector has on overall energy consumption.

2.4.2 Energy Use in Domestic Buildings

The domestic sector consumed approximately a third of the UK's overall energy consumption in 2010 (Department of Energy and Climate Change, 2011a; Boardman, 2007). Between 1990 and 2001 domestic energy consumption increased by 17%; consistent with the trend of increasing consumption since 1970 (Department of Trade and Industry, 2008). Within homes the main areas of consumption are space heating, water heating, lighting and appliances, and cooking (Utley and Shorrock, 2008). Energy consumption relating to lighting and appliances has increased by 157% (1970-2000; Department of Trade and Industry, 2008). This has been driven by increased ownership of appliances, decentralisation of lighting provision to lamps and the standby feature on appliances (accounting for an estimated 6% of total in-home electrical consumption; ibid.). Consumption relating to cooking using ovens has decreased in recent years due to convenience foods and has shifted elsewhere due to the popularity of eating out (Department of Energy and Climate Change, 2011a).

The number of households has also increased 17% since 1990, which is disproportionate to population increases over the same period (Department of Energy and Climate Change, 2011a). Hence, there is now a higher proportion of one person households in the UK, increasing from 17% of households in 1970 to 32% in 2000 (ibid.). Projections estimate average household size will decrease further and that by 2031, 18% of the population in England will live alone (Department of Communities and Local Government 2009). Additionally, by 2020 an extra 3 million homes will need to be built, equating to approximately an 11.5% increase in housing stock (Department of Communities and Local Government, 2008a). With more people living alone and more space to be heated, a greater amount of energy is required per person.

Nonetheless, domestic consumption is dominated by space heating demands, accounting for 61% of total domestic energy consumption in 2010 (ibid.). Due to the dominant nature of space heating on energy consumption any reductions in this consumption will have a large impact. Three factors have been responsible for the increased heat energy consumption of UK homes; increases in internal temperature, an increase in the number of overall households and the increasing prevalence of central heating within homes (Department of Trade and Industry, 2008).

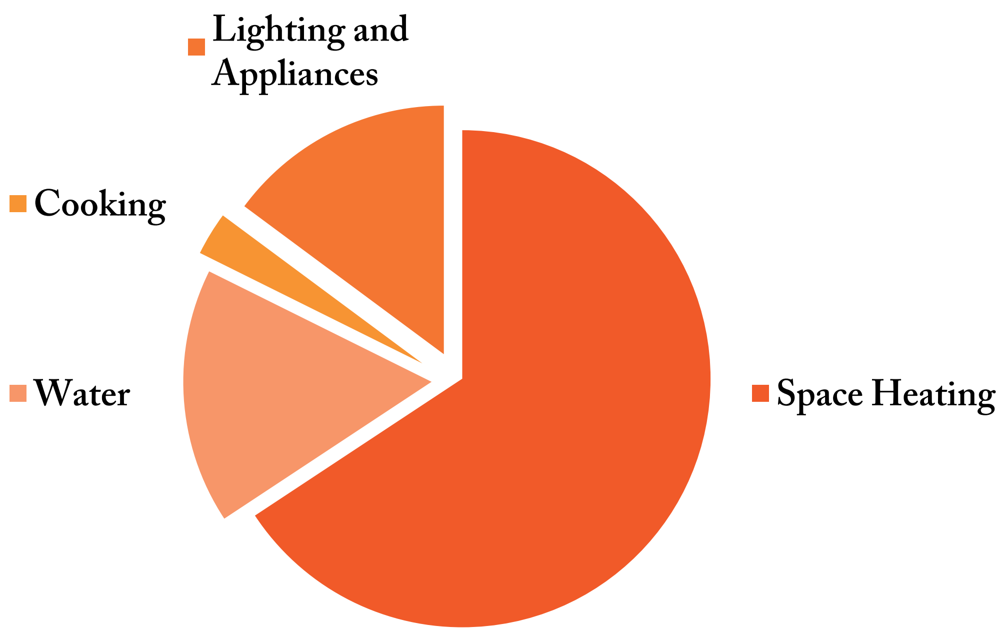


Figure 2.4 Energy Consumption by End-use In Homes

Average internal temperatures have increased from an average temperature of 13°C in 1970 to 18°C in 2000 (Department of Trade and Industry, 2008). This may be attributed to increases in average household income over the same period, the increase of central heating with homes and expected levels of thermal comfort. Thermal comfort is highly subjective, with large variations from person to person and it is often difficult to satisfy all users of a space (Race, 2006; ASHRAE, 2004). Thermal comfort can also be viewed as the absence of discomfort (Race, 2006). Although air temperature affects thermal comfort other factors including relative humidity, radiant temperature, air speed, clothing level and activity level, also have a significant impact (Race, 2006; ASHRAE, 2004).

This thesis focuses on reducing the large consumption of heat energy within domestic buildings, as this is an area largely influenced by occupant behaviour. Furthermore any reductions in heat energy consumption could have large impacts on reducing associated CO_2 emissions.

2.5 Overview of Legislation Relating to Buildings and Energy Consumption

This section provides an overview of the legislative context of the research. There are two key pieces of legislation aiming to reduce the UK's energy consumption which provide drivers for this research; the Climate Change Act 2008 and the Energy Act 2011. Since the research began in 2008 there have been several updates in policy and legislation, partially due to the change of government in 2010.

The Climate Change Act (2008) sets the UK's greenhouse gas emissions target, "to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline" (pp. 1, HM Government, 2008). This is an increase on the original target of 60% by 2050 set out by the Climate Change and Sustainable Energy Act of 2006. It provides the legislative driver to implement emission reduction strategies across all sectors in an attempt to avoid irreversible climate change and damage to the environment (HM Government, 2008).

The Energy Act (HM Government, 2011) determines two policy initiatives relevant to this research; the Smart Meter Rollout and the Green Deal. The fundamental principle of the Green Deal is that the payment for energy efficiency improvement is made wholly or in part by installment once the measure has been implemented (HM Government, 2011). This removes the barrier of the upfront cost previously associated to making such improvements to a property. Payment is then made to the energy supplier over time by the occupant through the energy bills, which include the energy savings associated with the improvement (ibid.). In order to be eligible for a Green Deal plan, the property and the improvements must qualify by meeting certain conditions. Qualifying measures are specified as:

- Improvements to the efficiency of use of electricity, gas or other energy source
- Measures which increase electricity or heat generated using microgeneration or low emissions sources and
- Measures which reduce the consumption of such energy (HM Government, 2011)

The Energy Act (2011) gave the Secretary of State powers to implement a roll-out of Smart Meters to homes and businesses in the UK. The Smart Meter rollout covers both electricity and gas consumption in every home and most small to medium size businesses in the UK by 2019 (Department of Energy and Climate Change, 2011a). It aims to make consumers aware of their consumption in real-time and to address the lack of sufficient and accurate information on energy consumption from a consumer perspective.

The Smart Meter Rollout will be spread over two stages; a Foundation Stage which began in April 2011, essentially a testing phase, and the mass rollout due to start in early 2014 (Department of Energy and Climate Change 2011b). Energy suppliers will be responsible for the installation of the appropriate metering by 2019, which would include:

- Gas and electricity meters with two way communication functionality
- An in-home display (IHD) for domestic customers
- A wide area network (WAN) module to connect to the central communications provider
- An internal home area network (HAN) to link different meters within the building to the wider network

(pp. 23, Department of Energy and Climate Change 2011b)

The current rollout includes feedback to the building occupant regarding both electricity and gas consumption. This feedback, from the IHD, provides an opportunity for an inclusive interface to enable users to potentially save a larger amount of energy.

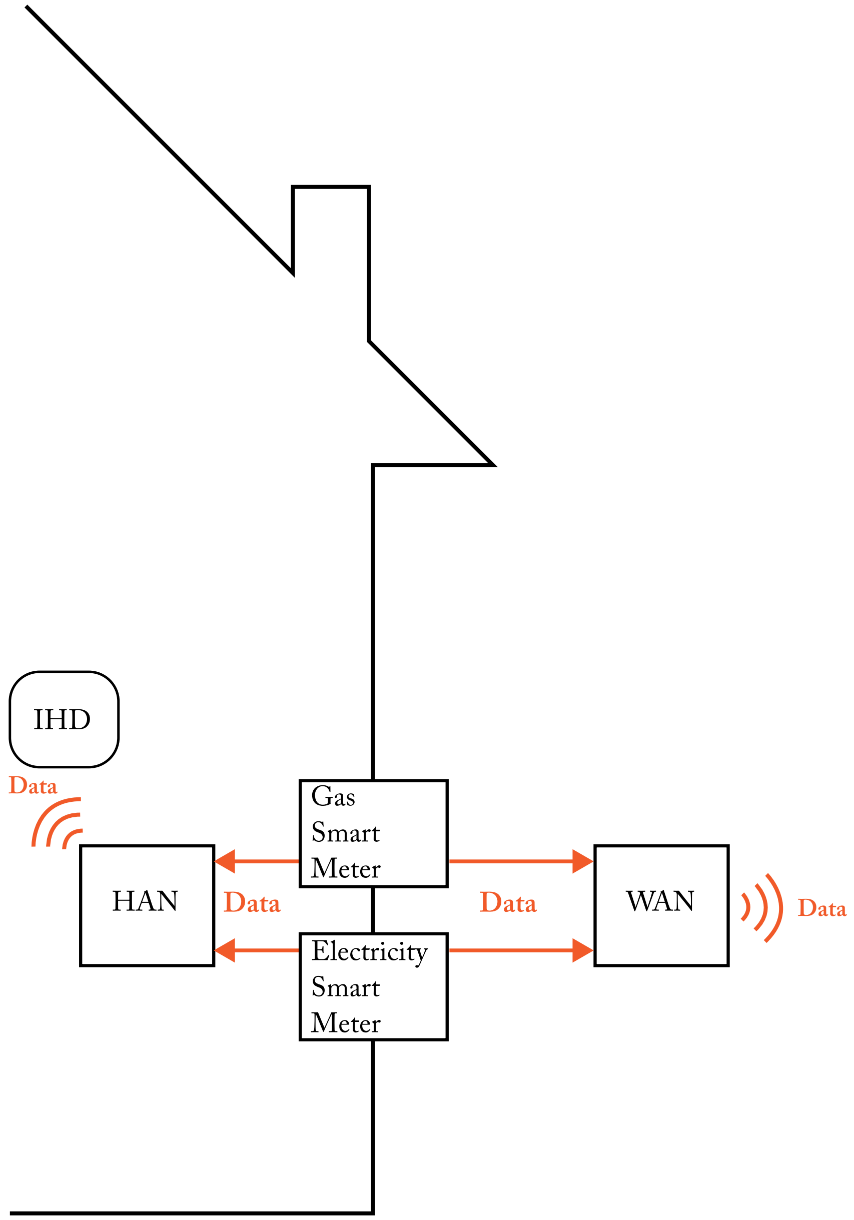


Figure 2.5 Two-way Communication of Domestic Smart Metering System

2.6 Existing Homes and Refurbishment

Improving the existing UK housing stock (known subsequently as "the stock") is vitally important because "an estimated 70% of the stock that will be inhabited in 2050 already exists" (pp. 14, Sustainable Development Commission, 2006). Increased levels of home insulation have helped reduce the impacts of heat energy consumption somewhat. Without such insulation it is estimated that the associated heat energy consumption would have been up to 59% higher in 2000 (Department of Trade and Industry, 2008). Therefore, the energy consumption of older buildings can be reduced through energy efficient refurbishment. This section highlights the needs for refurbishment and the relevant energy saving measures applicable.

2.6.1 Age and type of the English Housing Stock

In 2009 there were 22.3 million dwellings in England (Department of Communities and Local Government, 2009a), although by 2011 the number of dwellings had increased to approximately 25 million. Dwellings consist of four main categories in the England with terraced housing most common, making up 29% of the stock (ibid.). This is followed by semi-detached properties (26%), detached properties (23%) and flats (19%) (ibid.). Of all dwellings 67% were owner occupied in 2009 and nearly one quarter of these dwellings were detached homes (ibid.).

By age the largest proportion of housing in England was built before 1919 (21.5% of total stock). Another 16.5% of the stock was built between 1919 and 1944, whereas in the post-war years this increased to 20.2% from 1945-1964 and a further 20.2% from 1965-1980. This highlights that 78.9% of the stock was built before 1980. In the subsequent three decades the proportion of housing built only totals 17% of the existing stock. Although the Building Regulations set out high standards for new buildings, the refurbishment of the existing stock will be vital to achieving the required reductions in CO_2 emissions. (Department of Communities and Local Government, 2009a, data table SST1.1)

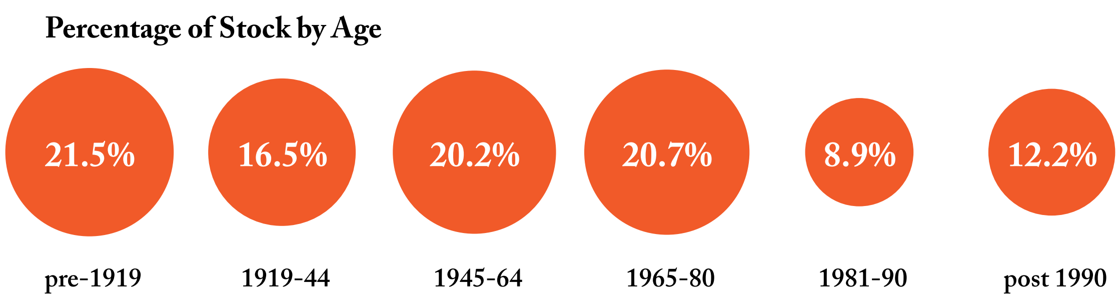


Figure 2.6 Age of UK Housing Stock

2.6.2 Types of Households in England

Households type and tenure varies by the age of the main occupants in England, for example households where the main occupant is between 16 to 24 years old are primarily privately rented homes (Department of Communities and Local Government, 2009b). Conversely, the majority of households that own the property outright are aged 55 years old and over. In 2009 the most common type of households were couples with no dependent children (36%), followed by couples with a dependent child or children (21%; Department of Communities and Local Government, 2009b). These households predominantly live in owner occupied or privately rented homes.

The English Housing Survey data divides single person households into two categories, those where the occupant is over 60 years old and those under 60 years old. Single people over 60 made up 24% of the social renting sector in 2009, whereas single-person household under 60 tended to rent privately. Older people were significantly more likely to live in bungalows than any other type of house and were less likely to live in flats (Department of Communities and Local Government, 2009b). Additionally households that had one or more resident with a disability or long-term illness tended to live in flats (18%) or bungalows (15%) and of this group 23% lived in the social rented sector (ibid.).

By 2031 predictions suggest that 32% of households will be headed by someone over the age of 65, which will influence the type of housing required in the future (Department of Communities and Local Government, 2009c). The design of future housing must take into consideration the future needs of the ageing population. Yet, understanding the make up of the current housing stock can help identify areas of opportunity for appropriate energy efficient refurbishments and inclusive building products.

2.6.3 The Potential for Refurbishment

The standard assessment procedure (SAP) is used to give an indication of the current stock performance, by scoring it from 1 (inefficient) to 100+ (highly efficient; Building Research Establishment, 2011). There has been steady improvement in the SAP ratings of English homes from an average of 42 in 1996 to 53 in 2009 (Department of Communities and Local Government, 2009a). The most efficient dwellings were owned by housing associations, partially due to the large proportion of these homes which are purpose built flats built since 1990 (ibid.).

The least efficient homes were primarily owner occupied and privately rented and in total 15% of English stock having a SAP rating of 39 or under (ibid.). Crucially many of these inefficient homes were occupied by older people (18.2%) who are more vulnerable to cold and damp conditions (ibid.). The proportion of people below the poverty line (15.1%) and households with a person with a disability or long term illness (14.5%) were also high in inefficient homes (ibid.). All of these homes would benefit from improvement to reduce energy consumption, while occupants would benefit from reduced energy bills. Yet, these are also households which may find it difficult to afford such refurbishments.

2.6.4 Energy Efficient Refurbishment Measures

On average an English dwelling emits 6.0 tonnes/CO_2 per year, which could be improved to 4.6 tonnes/CO_2 per year by implementing all improvements viewed as cost effective (Department of Communities and Local Government, 2009a). To apply all of the cost-effective refurbishments solutions the total cost would be £27.2 billion (ibid.). The three types of improvements deemed lower cost (under £500 to implement) are; cavity wall insulation, loft insulation and insulating hot water tanks (ibid.). The six types of improvement, which cost over £500 to implement yet still deemed cost effective are:

- Heating controls
- Boiler upgrade
- Storage heater upgrade
- Hot water cylinder thermostat
- Replacement warm air system
- Install biomass system

In England 19.3 million homes could benefit from some type of energy efficient refurbishment and often multiple improvements could be made (ibid.). Figure 2.7 shows the number of dwellings eligible for refurbishment by type Improvements such as these may be eligible for funding under the Green Deal. To clarify, double glazing is not deemed to be cost effective due to the high initial cost (ibid.).

Cavity wall insulation and loft insulation fall into the low cost to implement category yet can also be applied on a large scale. In 2009 half of the eligible properties had received cavity wall insulation however only 34% of eligible private rented homes had been treated. This is compared to 57% of housing association and 59% of local authority stock (ibid.). Loft insulation could benefit 8 million properties and currently only 41% of the stock have 150mm of loft insulation.

The installation of more efficient boilers and improvements in heating controls are discussed in Section 2.7 as the use of these products can impact the energy consumption significantly (ibid.). User behaviour can heavily influence the ongoing heat energy consumption of the dwelling through the heating controls. In comparison once either cavity wall or loft insulation is installed, the occupant has very little influence over the effectiveness of the insulation. However, installing a highly efficient boiler or providing a high level of control in no way guarantees that the dwelling will be heated in an efficient manner.

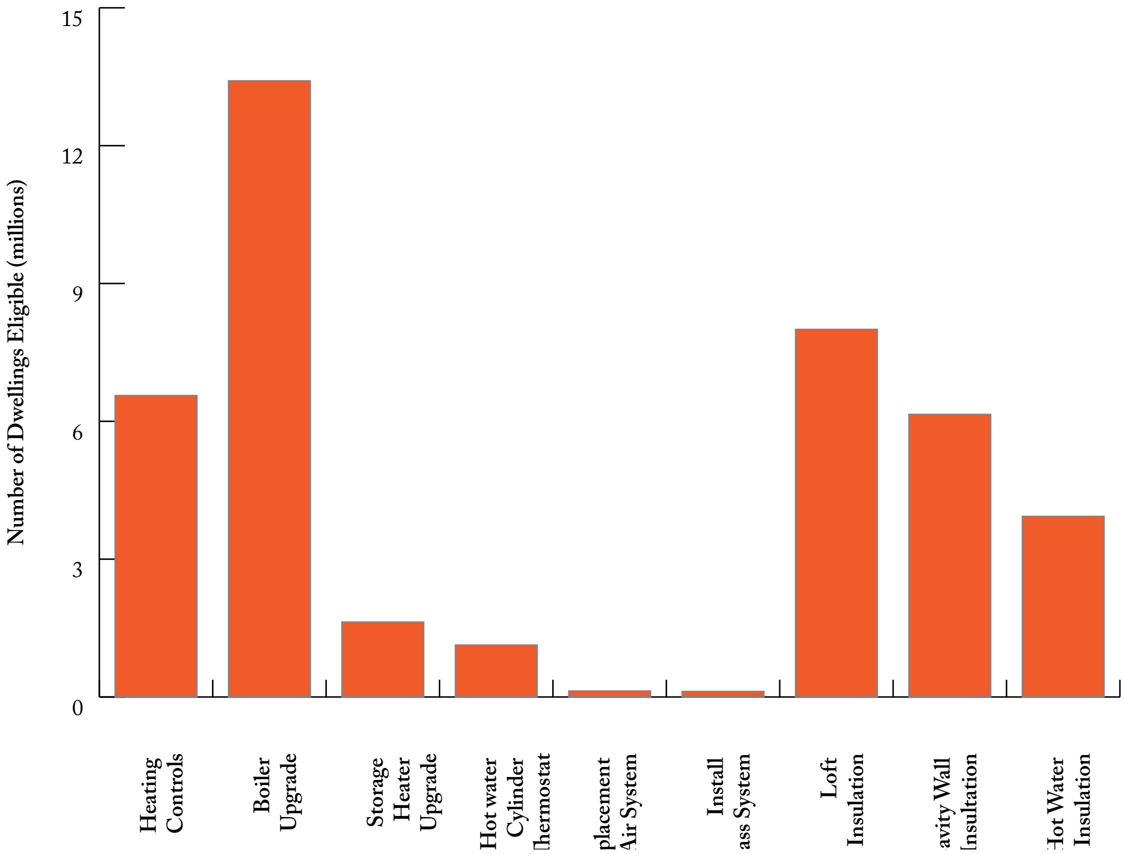


Figure 2.7 Number of UK Dwellings Eligible for Energy Efficiency Improvements

2.7 Heating Systems and Controls

This section aims to clarify what defines a heating system and heating controls. The energy consumed in maintaining indoor temperature depends on four factors: the efficiency of the heating system, the efficiency of the building fabric, the temperature difference between inside and outside, and the duration of heating input (Lomas et al., 2009, MacKay, 2009). Crucially two of these factors, indoor temperature and duration of heating, are directly controlled by the occupants.

Current research in the field of user interaction with heating controls and smart meter systems is also examined in detail. This user interaction presents an opportunity for the overlap between both inclusive design and sustainable design fields central to this thesis.

2.7.1 Heating Systems

Heating systems have evolved from a central point of heat within the home to be distributed throughout the home driven by a boiler. A boiler is defined as "a fuelburning apparatus for heating water, especially a device providing a domestic hot water supply or serving a central heating system" (The Concise Oxford Dictionary, cited pp. 9, Day, Ratcliffe and Shepherd, 2003). There are two requirements of such apparatus; to heat a continuous supply of water and to burn the fuel cleanly and efficiently to maintain a specific water temperature (ibid.). The amount of gas fuel burnt during this process directly impacts the CO_2 emissions of space heating. Therefore systems with a higher efficiency lead to fewer emissions.

In England 89% of homes have central heating systems, of which 84% are fuelled by gas (Department of Communities and Local Government, 2009a; Nowak, 2009). There has been a marked increase in the installation of highly efficient boilers since 2003, primarily driven by requirements in the Building Regulations. In 2009 24% of all boilers were condensing or combination condensing boilers, which do not require a separate hot water tank, up from only 2% in 2003 (Nowak, 2009). The Building Regulations also require newly installed condensing boilers to meet a minimum efficiency of at least 88% (Department for Communities and Local Government, 2011). Yet 29% of boilers are at least 12 years old, hence 13.4 million homes could benefit from upgrading the boiler under the Green Deal.

Considering both the large market opportunity and potential energy savings achievable, heating systems and in particular heating controls are the primary focus of this research. The installation of full heating controls could benefit 6.56 million households in England (Department of Communities and Local Government, 2009a). Full heating controls are defined to include a programmable timer, a room thermostat and thermostatic radiator values at each radiator (ibid.). Less than half (43%) of all homes with central heating had all three components installed in 2009 (ibid.).

2.7.2 Heating Control and Thermostats

In relation heating, control over duration of heating through either a full programmer or programmable room thermostat is required to comply with the Building Regulations when replacing domestic heating systems (Department for Communities and Local Government, 2011). Where the system provides instantaneous hot water through a combination boiler there is only a requirement to control the timing of space heating (Department for Communities and Local Government, 2011). To control temperature a room thermostat should be available in each heating zone within the home and thermostatic radiator valves (TRVs) should be available on each radiator. With 37% of boilers in English homes falling into the combination boiler category (Nowak, 2009), this research will focus only on the control of space heating time and temperature.

The difference between a manual and a programmable room thermostat is not widely understood and the terms can cause confusion amongst lay people (Energy Information Administration 2010 and 2011, cited in Peffer et al., 2011). A manual thermostat is not self-activating and requires human intervention, whereas a programmable thermostat can be defined by the automatic changing of temperature based on a timing schedule (Peffer et al., 2011). The focus on programmable thermostats in both this research and the research of Meier et al. (2011) is justified by the large percentage of programmable thermostats currently in homes and their installation in nearly 100% of new build homes in both the UK and USA.

The thermostat consists of four components: the temperature sensor, the actuator controlling the heating equipment, the feedback loops between these two components and the user interface. The user interface is defined as, "a means for the user to provide input for the thermostat control and view a display of information" (pp. 2531, Peffer et al., 2011). The user interface is the focus of this research specifically as it may be unnecessarily complex and could exclude users from operation, even at a basic level. Furthermore, there is a trend toward increased complexity identified in Peffer et al. (2011), which may further exclude users from being able to use programmable thermostats effectively.

2.7.3 Energy Savings of Improved Controls

Simpler, more useable, controls are advocated within the field as it could provide a double-dividend: greater thermal comfort and reduced energy consumption (Bordass and Leaman, 2001). Gupta, Intille and Larson (2009) agree that when programmed effectively controls can save substantial amounts of energy. Miller concurs that one of the best ways of reducing domestic energy consumption is encouraging proper use of heating controls by users (cited in Lomas et al., 2009). Simplification of these interfaces may encourage proper usage, in particular by focusing on levels of comfort rather than temperature (Gupta, Intille and Larson, 2009).

Thus, control systems should to be designed such that "environmentally-preferred behaviour is also the most logical and easiest accomplished" (pp. 125, Derijcke and Uitzinger, 2006). One of the biggest design challenges is how to accommodate the wide range of physical, sensory and cognitive abilities of people, as Bordass, Leaman and Bunn state, "well-designed controls with good user interfaces benefit everyone" (pp. 6, 2007).

The assumption from policymakers currently is that enhancing control of central heating will reduce heat energy consumption. However, Shipworth et al. (2010), echoed by Meier et al. (2010), conclude that simply providing control does not reduce energy consumption. Several studies reviewed by Peffer et al. (2011) from the USA showed no significant energy savings or changes to behaviour with the presence of a programmable thermostat over a manual thermostat. Moreover the US Environmental Protection Agency (EPA) concluded that people did not use programmable thermostats effectively because of "programming difficulties and a lack of understandings of terms such as setpoint" (pp. 2535, cited in Peffer et el. 2011). Subsequently an associated EPA rating system for programmable thermostats was abandoned.

Moon and Han (2011) highlighted that the largest reductions in energy consumption were correlated to reducing the night-time setback temperature. Despite this being most efficient behaviour it is in the minority in Scandinavian countries. In Norway less than 50% of people used night-time setbacks (Wilhite et al., 1996). Similarly, 38% of Swedish households studied also did not turn night time temperatures down (Linden, Carlsson-Kanyama and Eriksson, 2006). Conversely Japanese people were found to be disciplined about turning the temperature down or off at night, in a similar climate (Wilhite et al., 1996).

The importance of reducing the heating temperature has been highlighted by the Carbon Trust (2010) suggesting that reducing the temperature by 1°C can result in energy savings of 8%. Relating this to carbon dioxide emissions, for every percentage increase of heating demand temperature there is a disproportionately higher rise of 1.55% in associated CO_2 emissions (Firth et al., cited pp. 51 in Shipworth et al., 2010). For each degree Celsius increase in temperature there was an increase of 520.2kWh in energy consumption annually (Moon and Han, 2011).

Hence, it is established that there is a need for users to be able to properly programme domestic thermostats to match the building occupancy, as this is most effective in reducing energy consumption. Gupta, Intille and Larsson (2009), Miller (in Lomas et al., 2009) and Bordass, Leaman and Bunn (2007) concur usable control interfaces are required to realise theses energy savings discussed in this section. To enable these energy savings heating controls must be usable, as discussed next.

2.8 Designing Inclusive Interactions Between People and Buildings

Inclusive interaction design has become increasingly significance in recent years, specifically in relation to product and mobile interfaces. Langdon and Thimbleby introduced a special issue of Interacting with Computers in 2010 with a discussion of the main theme; 'Inclusion and Interaction'. The need for such a special issue was highlighted by the fact that although designing products for customers the 'user' is often not defined specifically. This can lead to designers basing their work on their own, somewhat limited, experiences (Langdon and Thimbleby, 2010). The main criticism of existing usability studies is the common focus on testing in laboratory settings using only student participants, often under 30 years old. It is concluded that there is a need for increased knowledge transfer from inclusive design to the human-computer interaction (HCI) community to help design more inclusive interactions (ibid.).

HCI is defined as "the study, planning, and design of how people and computers work together" (pp. 4, Galitz, 2007). Consequently user interface design is a sub-section of the wider HCI field (Galitz, 2007, Lauesen, 2005 and Nielsen, 1993). The user interface is the part of the system "that users can see, hear, touch, talk to or otherwise understand or direct" (pp. 4, Galitz, 2007). The user interface consists of both input and output components. Inputs are the way the user communicates their needs to the system and outputs being the feedback received from the system. The majority of user interaction with the system takes place through the user interface although, usability can include aspects throughout the products lifecycle.

2.8.1 Usability

Despite usability being an important aspect of inclusive interactions, usability and accessibility are not interchangeable. Both are requirements of successful interactions. As Coleman (2003) argues that an accessible building is not necessarily inclusive, similarly Abascal and Nicolle argue, "even if the services are accessible…it is also important that users can perform those tasks easily, effectively and efficiently" (pp. 486, 2005) through the user interface. Hence this section discusses the concepts of usability engineering, appropriate usability methods and the relationship with inclusive design.

Usability is a key attribute of any interface or system if a product is to be successful. A broad definition of usability testing is given by Lewis (2006) as testing that, "involves representative users attempting representative tasks in representative environments, on early prototypes of computer interfaces" (cited pp. 252, Lazar, Feng and Hochheiser). Schakel (1991, cited pp. 64, in Galitz, 2007) defines usability as "the capability to be used by humans easily and effectively". Primarily usability is how well a user may utilise the functionality of a system and not the functionality itself (Nielsen, 1993). Nielsen (1993) defines usability as a set of five aspects, which combine to produce an efficient and easy to use system. The aspects are precise, measurable and consist of the following:

- Learnability - the system must be easy for the user to learn
- Efficiency - the system must be efficient so the user can achieve their goals quickly
- Memorability - the system must be easy to remember to avoid repeated learning
- Errors - the user should make a low amount of errors while using the system and
- Satisfaction - the system should leave the user satisfied with their performance (pp. 26, Nielsen, 1993)

Nielsen (1993) strongly recommended user-based testing as a fundamental method in usability engineering because the insights gained are irreplaceable. Furthermore, Lauesen (2005) warns strongly against using expert evaluations as the primary approach to usability testing, as it is difficult to illicit ease of use problems. Wickens et al. (2004) suggest expert evaluation may be appropriate prior to full usability testing using multiple experts to aid identification of initial problems. Other methods that involve users advocated by Nielsen (1993) include observation, questionnaires, interviews, focus groups and logging actual use.

2.8.2 Usability and Inclusive Design

According to Nielsen's (1993) framework, accessibility is not considered either as a concern of usability or practical acceptability - Keates and Clarkson (2003) argue practical acceptability should be extended to cover this. It is also advocated that inclusive design can contribute to social acceptability of systems and therefore the overall system acceptability, see Figure 2.8. Current standardisation bases interaction accessibility on three principles; suitability for all users, robustness of the system or software and equitable use (BS EN ISO 9241-171, 2008 and BS EN ISO 9241-20, 2009). The application of such standards will not guarantee that all users will be able to use a system completely, however it may contribute to allowing most users some level of system usability.

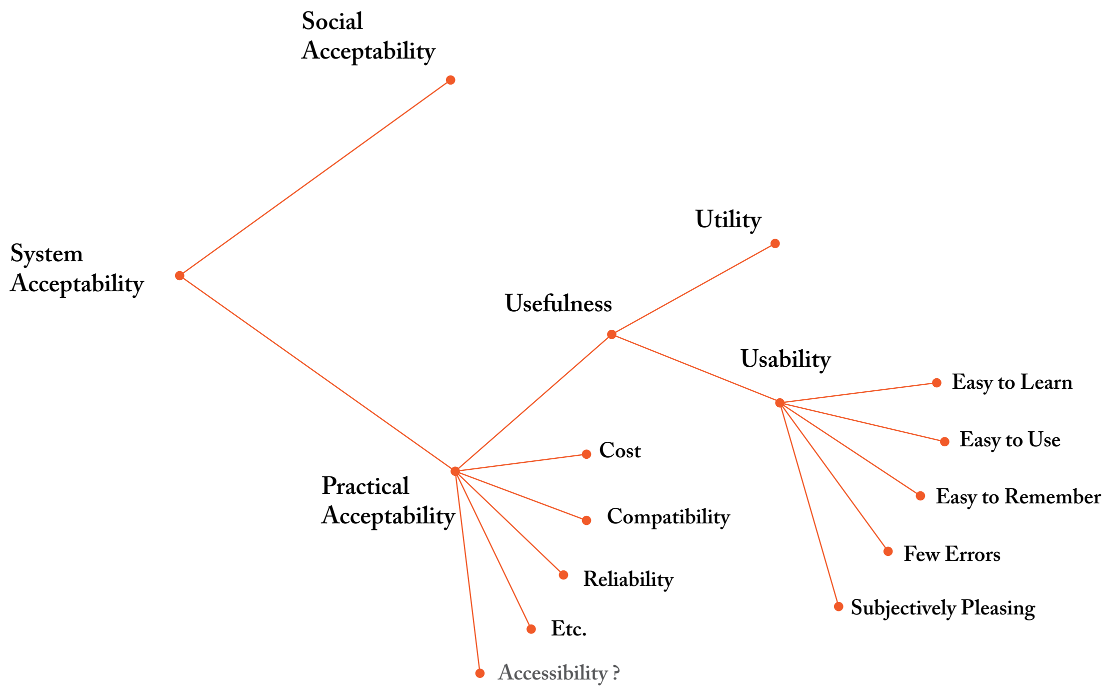


Figure 2.8 Nielsen's System Usability Diagram (1993; adapted to include accessibility)

Adopting such standards can help reduce demands of user capabilities and provide a structured method of producing more accessible information and communication technology systems. Although inclusive design can benefit the majority of people, designing interfaces to work for a variety of users can be complex (Abascal and Nicolle, 2005). One method of including users is the idea of "application-independent interfaces" (pp. 488). This separates the interaction of the system with the technology, from the user interaction with the system to allow greater flexibility and a reduction in the demands placed upon the user (ibid.).

Usability methods can be used in combination with inclusive design methods. Abascal and Nicolle (2005) argue that people with disabilities may have a high dependency on computers to allow access to communications, services and a level of control over their environment, which may not otherwise be possible. Clearly there is an opportunity for inclusive design to contribute to both practical and social acceptability as indicated on Figure 2.8. The concurrent assessment of usability using a combination of usability methods can also contribute to more inclusive solutions.

2.8.3 Designing Technology for Older People

Designing technology for older people can present unique challenges due to declines in motor, cognitive and sensory function associated with the ageing process.

Cifter (2011) argues that younger people may be more successful when trying to use a product or system for the first time. Older people tend to rely on their previous experiences, as immediate reasoning abilities decline with age (Czaja and Lee, 2007, cited in Cifter, 2011). This may not be possible some situations, especially with rapid developments in mobile technology. Hanson (2010) agrees that cognitive abilities are a central factor in successful computer interaction and that user's aptitude for using new technologies can decrease with age. Older users can be less likely to adopt a technology for the sake of it, unless it meets a direct need of the user (ibid.). However, Wolters et al. (2010) found that older users who had a high level of affinity to technology had increased rates of task success.

Several studies have recognised that older users may have difficulties interacting with heating controls and energy management interface. The "Taking Control" report by Etchell, Girdlestone and Yelding (2004) reviewed thermostat rating both visual and dexterity demands from one to five. The main aim of this report was to inform purchasing decisions, particularly amongst older users. Although the visual and dexterity demands were rated, the report did not assess the cognitive aspects of using the controls.

Heating controls are one of a range of energy efficient products discussed in a paper by Caird and Roy (2008) that argued the adoption of some energy efficient products has been slow. This can partially be attributed to insufficient consideration of user requirements and product usability (ibid.). Crucially, in terms of their usability, older people were found to struggle with the visual requirements of small buttons and displays as well as the cognitive elements of the task (ibid.). Caird and Roy's suggestions included the provision of feedback on energy consumption and controls that optimised energy performance and comfort automatically (2008).

The realisation that older users in particular may struggle to use product interfaces was not confined to Caird and Roy's study. Both studies by Zhang, Rau and Salvendy (2009) and Sauer, Wastell and Schmeink (2009) acknowledge the issues older users may have with smart home interfaces. When using a smart home interface to control a range of energy consuming activities within the home, older users took longer to complete tasks and made more errors than younger users (Zhang, Rau and Salvendy 2009). Thus, the perceived cognitive demand tended to increase with the complexity of the interface, particularly amongst older users.

The study by Freundenthal and Mook (2003) is one attempt at designing heating controls with specific consideration for older users. It examined new styles of interaction with an intelligent thermostat prototype with specific reference to older users. The prototype used voice prompts and instructions and responses from users were either via a touch interface or by voice input. It was found that older users appreciated the voice instructions and were successful using the prototype, although it frustrated some younger users (Freundenthal and Mook, 2003).

More recently, Wolters et al. (2010) examined the effect of audible help prompts for a smart home interface. This found younger users were more accustomed to interacting using voice commands than older users. However, placing the voice prompts at an early stage in the task was helpful for older users (Wolters et al., 2010). Huyck (2010) advocates the use of conversational based interfaces as it can include not only users with limited sensory and motor capability but also users with limited technical experience. The limitation of such conversational systems is the associated high cost of sophisticated dialogue systems (Huyck, 2010).

In the design of technological systems for older users a range of interactions styles should be considered to ensure the product or system is inclusive. The studies reviewed here also highlight the benefit of testing technological prototypes with older users to ensure the system is usable. However, the usability of thermostats in the domestic environment can be problematic for all users, as discussed next.

2.8.4 Usability of Heating Controls

The usability issues of heating controls and programmable thermostats was documented as early as 1982 with the usability of control systems existing at the time proving difficult for some users (Moore and Dartnall, 1982). Moore and Dartnall conclude that, "if users are to be able to realise the potential of such devices they must be provided with effective man-machine interfaces" (pp. 23, 1982) and thirty years later this potential is still to be realised.

The programming of thermostats is a particular area of user frustration yet is often required to achieve energy savings. Freundenthal and Mook (2003) suggest, "the main purpose of a thermostat, that is, saving energy by only heating the home when needed, often is not used" (pp. 55). Although the programming process is not ideal it was expected by Freundenthal and Mook (2003) to remain a component when controlling temperature within the home. Preliminary investigations suggest that 89% of respondents rarely or never programmed the thermostat for a weekday or weekend program (Meier et al., 2011).

Meier et al. (2011) found that time taken to complete a task using a programmable thermostat varied significantly between participants and not all participants were able to complete certain tasks. When testing usability directly with participants it was found that 26% of the sample could not turn the heating from off to on (ibid.). This was echoed by a further small study of twenty low-income homes in Wisconsin, which found that only 30% of thermostats were programmed despite 85% of respondents reporting the programming features were used (ibid.).

In Finland a large-scale survey of over 3000 participants reported that 60% of households used their thermostat either not at all or less than once a month (Karjalaninen, 2009). Of the remaining 40% who did use the thermostat only 20% used it regularly (i.e. weekly or more frequently; ibid.). Karjalaninen (2009) concluded that perceived control over indoor temperature might be improved by better availability and usability of thermostats.

Furthermore, with the addition of new features thermostats are becoming increasingly complex which may increase the barriers to effective use. Freundenthal and Mook (2003) suggest poor interface design and the application of outdated design principles are partly responsible for usability problems. Meier et al. (2011) suggest that there is anecdotal evidence that thermostats are already overly complex, with this complexity increasing rapidly. Much current research focuses on providing more functionality and information to reduce energy consumption rather than engaging people and providing more usable systems.

It is clear that the usability of heating controls forms a particular gap in the research, despite usability issues being highlighted by Moore and Dartnall as early as 1982. Peffer et al. conclude the "lack of usability studies is a critical weakness in the design of most advanced thermostats because usability is among the most frequent complaints about them" (pp. 2358, 2011). It has been suggested that new controls should be developed which are "intuitively usable...and make it easy for householders to reduce their heating energy use" (pp. 67, Shipworth et al., 2010). Similarly, Karjalaninen calls for user controls and thermostats that "are easily understandable and easy to use" (pp. 1244, 2009). It is concerning that despite poor usability of existing systems further complexity is being added to such systems.

This research aims to address the need for a more usable heating control system with specific reference to older users. Peffer et al. (2011) highlight the difficulties in the programming process, which this research will attempt to address. Despite not being ideal the programming process is still expected to be used in future systems (Freundenthal and Mook, 2003). This research aims to bridge the apparent gap between users and technology, which is designed to give them control over their thermal comfort and energy consumption.

2.9 Inclusive Design and Sustainable Behaviour

Recent developments with regard to design for sustainable behaviour have highlighted the environmental impact of the interaction between the product, building or service and the user. This section discusses approaches used to motivate changes in behaviour through the design of products. As Craig argues, "Technological improvements to reduce energy consumption needs to be complemented and reinforced by greater awareness of energy use and behavioural change" (pp. 74, 2008). This perspective is echoed by Slob and Verbeek (2006) who concur that failing to consider the user in technology and product development can result in unintended environmental impacts.

By definition sustainable development has a clear human element, which parallels inclusive design. The definition commonly referred to as the Brundtland definition was proposed in 1987. It defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987) proposing a balance between environmental, economic and social needs.

In the two decades since the Rio Declaration on Environment and Development (UNESCO, 1992), sustainability and its driving concepts have become ingrained within the national psyche. Despite this, the focus of most sustainability initiatives concentrating on the environmental sphere and not the social one. Therefore, there is an opportunity for inclusive design to contribute to both the fields of social sustainability and sustainable development more broadly.

One way inclusive design may influence sustainable development is by enabling users to behave in a more sustainable manner. In this context the behaviour to be influenced is the interaction with the product or service. The previous section investigated the need for designing such person-product interactions more inclusively. This section discusses current research regarding user behaviour and how inclusive design may contribute to this.

2.9.1 Design for Sustainable Behaviour

People can influence the environmental impact of a product throughout its lifecycle however this impact is generally greatest during the use phase rather than the manufacture or disposal of the product (Lewis and Gertsakis 2001). In recent years several researchers have demonstrated that design can be used to influence user behaviour and reduce a product's environmental impact (Lilley, 2009; Lockton, Harrison and Stanton, 2008; Wever, van Kujik and Boks, 2008; Wood and Newborough, 2003). Although behaviour change has been used only recently to have a positive environmental impact; human factors research has influenced behaviour for years to ensure safety.

Changing behaviour can be done in a variety of ways with different levels of involvement from the user in the decision making process, this is best described in Figure 2.9 from Lilley (2009) shown below.

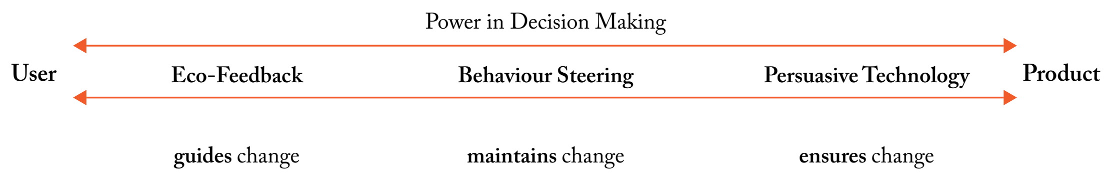


Figure 2.9 Strategies for Designing Sustainable Behaviour (adapted from Lilley, 2009)

Despite strategies for changing behaviour being identified by Lilley (2009) there is little guidance for designers on how to implement behaviour change strategies within their projects (Lockton, Harrison and Stanton, 2010). As a response the Design with Intent Method (DwI) was developed to provide such a resource with real-world examples of the strategies in use (ibid.). DwI is a comprehensive resource allowing designers to either take inspiration through a series of six 'lenses' or target specific behaviours through 'patterns' relating to a specific lens from strategies across the spectrum of interventions (ibid.). Such a method may be useful both to designers at an earlier stage of the product or service development but also to understand the implications of attempting to motivate more sustainable behaviours.

2.9.2 Persuasive Technology

At one end of the scale persuasive techniques can constrain behaviours to achieve a desired outcome. Fogg defines persuasion as "an attempt to change attitudes or behaviour or both (without coercion or deception)" (pp. 15, 2003) aiming to avoid the negative connotations, which could imply force and dishonesty. There are two classifications of persuasive technologies; 'microsuasion' where the persuasion is a by-product of use and 'macrosuasion' where the product has an overall persuasive intent (ibid.). To achieve a desired change in behaviour it is argued that two or three of the seven strategies presented by Fogg (2003) should be used in combination. The seven persuasive tools are: reduction, tunnelling, tailoring, suggestion, self-monitoring, surveillance and conditioning. Three of the strategies most relevant in relation to the development of inclusive technologies are:

- Reduction, which aims to reduce complexity to simple tasks, for example one-click shopping online
- Tailoring, which could provide the most relevant information to the user on an individual basis
- Suggestion, which recommends a specific behaviour at an appropriate time for the user to make such a decision (Fogg, 2003)

There is some ethical debate surrounding Persuasive Technology which concerns changing the user's environment without their consent. This is especially apparent when implementing strategies such as surveillance, tunnelling and conditioning. Fogg (2003) admits that persuasion can be used for both positive and negative outcomes depending on how the methods are used. Furthermore, designers may be held accountable for unintended consequences of using such methods. However, Wever et al. (2008) argue that the more persuasive the system, the greater the sustainability improvement achieved.

Lilley (2009) argues persuasion can be used without the knowledge or consent of the user bringing into question the ethics of persuasive technology. The acceptable level of intervention with different types of behaviours is still somewhat unclear (ibid.). This research will focus on Eco-Feedback and Behaviour Steering discussed subsequently, due to the inclusive focus of the research, which aims to enable users rather than control them.

2.9.3 Behaviour Steering

Behaviour steering is comprehensively discussed by Thaler and Sunstein's (2009) book Nudge, where they advocate the concept of 'Choice Architecture' to influence people's behaviour. A nudge is defined as "any aspect of the choice architecture that alters people's behaviour in a predictable way without forbidding any options or significantly changing their economic incentives" (pp. 6, Thaler and Sunstein, 2009). As a designer, structuring the way people make their decisions while using a product or system can influence their behaviour, and as a result their effect on the environment.

In a product context behaviour steering can be initiated through ambient feedback from devices that change colour during use such as an orb, energy monitor or power cord of the product (Thaler and Sunstein, 2009; Loftstrom and Palm, 2008). However, the decision over whether to change the power consumption based on the devices colour or brightness is still firmly within the occupants control. In the study by Schultz et al. (2006) the positive reinforcement given to residents in the form of smiley faces for using less energy can be seen as an effective example of a nudge, although they refer to it as an 'injunctive norm'.

Rowson (2011) is critical of the nudge approach due to the fact it does not transform peoples attitudes, values or motivations level which he argues leads only to relatively superficial changes in behaviour. Nudges aim to maximise user choice, however Rowson argues they, "change behaviour by stealth rather than engagement" (pp. 16, 2011). A holistic and reflective approach to changing behaviour is required if changes of scale required are to be cultivated (ibid.). Due to the large scale and long-term changes in behaviour required to meet our CO_2 reduction targets, enabling and encouraging people to change their behaviour is of paramount importance.

2.9.4 Eco-feedback

'Eco-feedback' has been a key strategy in social psychology work in recent years regarding water conservation (Van Vugt, 2001) and domestic energy consumption (Schultz et al. 2006, Wood and Newborough, 2003). The use of indirect feedback via improved billing has been linked to energy savings of around 10% (Wilhite and Ling, 1995) whereas direct feedback, resulted in potentially greater reductions of up to 15% (Darby, 2008). Darby (2001) gave examples of various types of direct feedback including interactive systems, cost plugs and prepayment meters. One of the best examples of direct eco-feedback is the in-home display (IHD) which provides users with information on their energy consumption from the smart meter.

In-direct examples include historic feedback, comparison to others and improved billing in general (ibid.). Darby concludes that "direct feedback, alone or in combination with other factors, is the most promising single type [of feedback]" (pp. 621, 2001). A range of behaviour interventions relating to those implemented in domestic buildings are comprehensively reviewed in Section 2.10.1 with a specific focus on feedback in Section 2.10.2 due to its relative effectiveness.

2.9.5 The Influence of Other People's Behaviour

If we are to bring about behaviour change on a scale appropriate to meet the CO_2 reduction targets such change needs to be en-masse. Earls (2007) argues that much of our behaviour as a human species is heavily influenced by other people as we are, "a super-social species" (pp. 7) and that we have an inherent herd nature. Similarly Maslow's hierarchy of needs places our need as a human to 'belong' before our own more selfish needs (Maslow, 1998). Earls (2007) proposes a seven-principle model to change mass behavior. As with Fogg's (2003) persuasion tools, not all are directly relevant or applicable to this context. Nevertheless the second principle 'influence' is key to this research due its common use in environmental research, as comparative feedback can influence energy consumption and in turn change behaviour.

The influence other people have on an individual's behaviour must not be underestimated as it can have a powerful effect (Nolan et al., 2008 and Earls, 2007). This effect is referred to as the social or subjective norm, which is a key component in the theory of planned behaviour (Ajzen, 1991). The Subjective Norm, Perceived Behavioural Control and the Attitude toward the behaviour all influence the user's intention to perform a specific behaviour (ibid.).

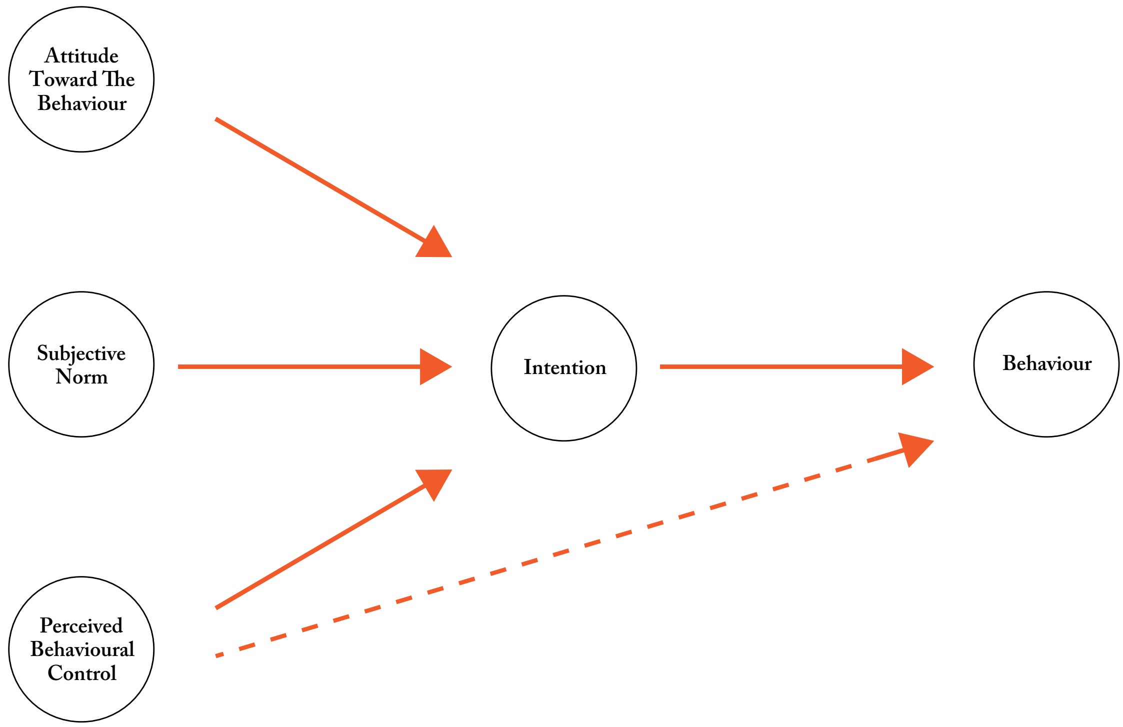


Figure 2.10 Azjen's (1991) Theory of Planned Behaviour

In areas where there was a strong sense of community or belonging, Van Vugt (2001) found financial incentives were less important in motivating behaviour change. Both Van Vugt (2009) and Pink (2010) agree that only by engaging all motives simultaneously will behaviour change be truly sustainable in the long term.

Although subjective norms can be used to influence behavior, inclusive design can also play a key role in the level of perceived behavioural control. If the user anticipates a positive outcome from the interaction then it is more likely the user will achieve the desired behaviour, i.e. reducing their energy consumption. Hence, by improving user's sense of perceived control, inclusive design may help enable more sustainable behaviour.

2.10 Behavioural Interventions to Reduce Energy Consumption

Although design for sustainable behaviour being a relatively new field of research, a vast amount of literature exists documenting attempts to reduce energy consumption through changing behaviour within buildings. The interventions implemented in such studies have little focus on the design of the intervention itself. The drivers for much of this early research were primarily insecurity of supply and potential resource shortages due to oil crises in the 1970's caused by political instability. More recently since the 1990's the motivation behind such studies is the mitigation of anthropogenic climate change. Although the motivation may differ, the outcomes are relevant to consider in the context of this research, which aims to enable users to reduce their energy consumption.

Despite Fischer's review (2008) concentrating solely on electrical consumption, the Abrahamse et al. review (2005) considers both gas, electricity and in certain cases water consumption. With the UK smart meter rollout to include information regarding gas and electricity consumption, feedback on both is to be available in every home by 2020. Research, such as this is relevant in relation to the interface of the in-home display. Although feedback is one type of behavioural intervention, it is important to review all types of behavioural interventions to understand which ones may be applied in conjunction with such feedback.

In relation to this research it is anticipated that the gap between control systems and feedback systems will narrow. With trends towards the increased functionality of heating controls it is logical that feedback on consumption may be included to enable changes in behaviour.

2.10.1 Types of Behavioural Interventions

A "Taxonomy of Behavioural Interventions" is proposed by Geller et al. (1990) to categorise the types of intervention which may change behaviours (shown in Table 2.1). Abrahamse et al. (2005) uses this taxonomy to categorise the types of interventions into two broad categories: antecedent and consequence strategies. Antecedent strategies are implemented prior to the behavioural action in question whereas consequence strategies are implemented once the behaviour has been performed (Abrahamse et al., 2005).

Table 2.1 Taxonomy of Behaviour Interventions

Communication Interventions	**Activator Interventions**	**Consequence Interventions**
Lecture	Written/Oral Communication	Feedback
Demonstration	Goal Setting (assigned or personally set)	Reward
Policy	Competition	Penalty
Intervention Agent	Incentive	-
Commitment	Disincentive	-
Discussion	-	-

Table 2.2 was adapted from Abrahamse et al. (2005) and Fischer (2008) with addition of several relevant studies since 2005. The studies conducted in the pre 1990 period primarily came from North America whereas more recent studies were primarily from the UK, The Netherlands, Norway, Sweden and Japan.

Table 2.2 Summary of the Available Literature by Intervention Type, Number of Participants, Duration and Energy Savings Achieved

Authors	**Monitoring**	**Type of Intervention**	**No of Households**	**Duration of Study**	**Savings Achieved**	**Persistency**	**Notes**
Darby (2006)	Electricity Consumption	Feedback	n/a	n/a	10-15%	n/a	
van Dam, Bakker and van Hal (2010)	Electricity Consumption	Feedback	189 93	4 months initial	7.8% average	2.86% average over 11 months	
Schultz et al. (2006)	Electricity Consumption	Feedback (weekly)	287	6 weeks	1.22 kWh per day relative to the baseline	n/a	Saving depending on type of feedback given
Gill et al. (2008)	Electricity, Water and Heat Consumption	Monitoring	26	+1 year	Variance of 51% in heat and 37% in electricity	n/a	
Loftstrom and Palm (2008)	Electricity Consumption	Visual feedback from a single socket	6	2 months	n/a	n/a	Cited in van Dan, Bakker and van Hal (2010)
Gupta, Intille and Larsson (2007)	Heat Consumption	GPS tracking via smart phone	1	14 days	Up to 7%	n/a	

Authors	**Monitoring**	**Type of Intervention**	**No of Households**	**Duration of Study**	**Savings Achieved**	**Persistency**	**Notes**
Ueno et al. (2006)	Electricity Consumption		9	40 weekdays (8 working weeks)	Average 9%		Conducted in Japan, cited in Fischer (2008), compared to baseline
Sexton et al. (1987)	Electricity Consumption	Feedback (continuous)	51	10 months	1.2% reduction in use during peak period (shift to off peak usage seen)	No reduction in overall consumption	Cited in Fischer (2008) and Abrahamse et al. (2005)
Dobson et al. (1992)	Electricity Consumption		25	60 days	12.9% less than control group		Cited in Fischer (2008)
Wilhite and Ling (1995)	Electricity Consumption	Feedback through improved billing	1450	3 years with feedback once a year	In second year 7.6%	In third year 10%	Conducted in Olso
Ueno et al. (2006)	Electricity Consumption		19	28 weekdays	12% reduction in end energy, 17.8% in electricity		Conducted in Japan, cited in Fischer (2008)

Authors	Monitoring	Type of Intervention	No of Households	Duration of Study	Savings Achieved	Persistency	Notes
Mansouri and Newborough (1999) and Wood and Newborough (2003)	Electricity Consumption		31	56-84 days	14 households saved more than 10% and six of these more than 20%		Conducted in UK, cited in Fischer (2008)
Pallak and Cummings (1976)	Gas and Electricity Consumption	Commitment (public and private)	65 (gas) 142 (electricity)	1 month	Lower rate of increase in gas and electricity consumption for those who made public commitment	6 month follow up, effect maintained	Note no savings, cited in Abrahamse et al. (2005)
Becker (1978)	Electricity Consumption	Goal Setting Feedback + Goal Setting	100	1 month	20% goal-4.5% 2% goal–0.6% 20% goal + feedback 15.1% 2% goal + feedback 5.7%	n/a	Cited in Abrahamse et al. (2005) 2% goal consumption increased

Authors	**Monitoring**	**Type of Intervention**	**No of Households**	**Duration of Study**	**Savings Achieved**	**Persistency**	**Notes**
McCalley and Midden (2002)	Electricity Consumption washing machine usage	Goal Setting Feedback + Goal Setting	100	20 washing loads	Self set goal 20.5% Assigned goal 21.9%	n/a	Cited in Abrahamse et al. (2005) Feedback + goal more successful
Winett, et al. (1982-83)	Electricity Consumption	Information Provision (audit)	51	1 month	21% reduction post audit	n/a	Cited in Abrahamse et al. (2005)
Hirst and Grady (1982-83)	Gas Consumption	Information Provision (audit)	850	n/a	1 year post audit 2% reduction	2 years post audit 4% reduction	Cited in Abrahamse et al. (2005)
McMakin, Malone and Lundgren (2002)	Gas and Electricity Consumption	Information Provision (tailored)	1231 175	1 year 4 months	10% reduction in Washington (heating load) 2% increase in Arizona (cooling load)	n/a	Cited in Abrahamse et al. (2005)
Hutton et al. (1986)	Gas and Electricity Consumption	Feedback (continuous)	300	n/a	Canadian cities reduced 4-5% US cities did not	n/a	Cited in Abrahamse et al. (2005)

Authors	Monitoring	Type of Intervention	No of Households	Duration of Study	Savings Achieved	Persistency	Notes
Van Houwelingen and Van Raaij (1989)	Gas Consumption	Feedback (continuous and monthly)	285	1 year	12.3% reduction continuous feedback 7.7% reduction monthly feedback	1 year increase seen for all participants	Cited in Abrahamse et al. (2005)
McCelland and Cook (1979-80)	Electricity Consumption	Feedback (continuous)	101	11 months	12% average reduction	n/a	Cited in Abrahamse et al. (2005)
Bittle et al. (1979)	Electricity Consumption	Feedback (daily)	30	42 days	4% reduction compared to baseline	At day 24 the study reversed. The group that initially received feedback continued to save energy.	Cited in Abrahamse et al. (2005)
Winett, Neale and Grier (1979)	Electricity Consumption	Feedback (daily)	71	1 month	13% saving with feedback	10 week follow up effect maintained	Cited in Abrahamse et al. (2005)

Authors	**Monitoring**	**Type of Intervention**	**No of Households**	**Duration of Study**	**Savings Achieved**	**Persistency**	**Notes**
Seligman and Darley (1977)	Electricity Consumption	Feedback (daily)	40	1 month	10.5% saving with daily feedback	n/a	Cited in Abrahamse et al. (2005)
Hayes and Cone (1981)	Electricity Consumption	Feedback (monthly)	40	4 months	Feedback group 4.7% reduction Control group 2.3% increase	2 month follow up- Feedback 11.3% increase Control group 0.3% reduction	Cited in Abrahamse et al. (2005)
Brandon and Lewis (1999)	Gas and Electricity Consumption	Feedback (comparative)	120	2 months	Comparative: 4.6% Individual: -1.5% Cost: 4.8% Leaflet: 0.4% Computerised: 4.3%	n/a	Cited in Abrahamse et al. (2005)

Authors	Monitoring	Type of Intervention	No of Households	Duration of Study	Savings Achieved	Persistency	Notes
Midden et al. (1983)	Gas and Electricity Consumption	Feedback (individual) Feedback (comparative) + Reward	91	12 weeks	Feedback (individual) Electricity 18.8%, Gas 18.4% Feedback (comparative) Electricity 18.4%, Gas 5.8% Feedback (comparative) + reward Electricity 19.4% Gas 17.5%	n/a	Cited in Abrahamse et al. (2005)
McCelland and Cook (1980)	Gas Consumption	Reward (financial)	500	12 weeks	6.6% savings	Not maintained over time	Cited in Abrahamse et al. (2005)

Authors	**Monitoring**	**Type of Intervention**	**No of Households**	**Duration of Study**	**Savings Achieved**	**Persistency**	**Notes**
Staats, Harland and Wilke (2004)	Gas, Water and Electricity	Feedback (comparative between EcoTeams)	150	8 months	Gas: 20.5% Water: 2.8% Electricity: 4.6% Waste: 32.1%	Reduction after two years - Gas: 16.9% Water: 6.7% Electricity: 7.6% Waste: 32.1%	Cited in Abrahamse et al. (2005)
Winett et al. (1978)	Electricity Consumption	Reward (financial)	129	8 weeks	Low reward 4.5% High reward 3.5%	n/a	Cited in Abrahamse et al. (2005)
Slavin, Wodanski and Blackburn (1981)	Electricity Consumption	Reward (financial)	166	8-14 weeks	6.2% average saving	n/a	Cited in Abrahamse et al. (2005)
Slavin et al. (1981)	Electricity Consumption	Reward (financial) + Goal Setting	255	8-14 weeks	6.9% average saving	n/a	Cited in Abrahamse et al. (2005)
Pitts and Wittenbach (1981)	Heat Consumption	Reward (tax credit)	146	n/a	No effect on uptake of insulation	n/a	Cited in Abrahamse et al. (2005)

Of the studies reviewed, few paid attention to the design of their interventions with the exceptions of Loftstrom and Palm (2008) and Wood and Newborough (2003). These studies were particularly interesting because specific attention was paid to the design of the intervention. Loftstrom and Palm (2008) introduced the Power-Aware Cord into households which glows more intensely the greater the energy consumption. This aimed to evoke consideration of energy use in the home through a glance at the cord. The ambient feedback provided by this design intervention, may be more inclusive as there are no reading or numerical reasoning capabilities required from users.

Similarly Wood and Newborough (2003) focused solely on feedback on cooking appliance energy consumption through paper based or electronic feedback. Although the trial was successful in reducing energy consumption further research is required focusing on the user interaction with energy consumption indicators (ibid). It is suggested that such specific feedback is integrated into the appliances, which could reduce the cognitive demand of separate feedback and controls.

The recent study by Jain, Taylor and Peschiera (2012) verified the link between user engagement with eco-feedback interfaces and reductions in energy consumption, although the scale of said reductions are not reported. In relation to this research, this could imply increased interaction with heating controls may result in energy savings. Jain, Taylor and Peschiera (2012) echo Wood and Newborough (2003) in concluding that a better understanding of how users interact with eco-feedback interfaces is required to maximise the energy savings achievable.

Chiang, Walker and Natarajan (2011) examined in detail the user interface design of energy displays. This study found red information on a white background captured user attention in the shortest time. Also information presented in the top left corner of the interface was both effective and attention grabbing compared to other locations around the screen (ibid). Studies such as this may help contribute to the design of such behavioural interventions in the future, however the type and volume of information presented should also be evaluated. Similarly, design for sustainable behaviour methods and strategies may also help contribute to the design and evaluation of future interventions.

A further interesting theme is that the majority of the studies did not assess the persistence of the intervention over the longer term. Sustaining changes in behaviour can be particularly difficult. Although initial energy savings of 7.8% were reported by van Dam, Bakker and van Hal (2010) these savings were not maintained in the medium to long-term. The initial trail lasted four months after which savings were not maintained despite users developing habits to check their energy monitors regularly (total length 15 months; van Dam, Bakker and van Hal, 2010). Similarly, participants in the studies by Faruqui, Sergici and Sharif (2010), McCelland and Cook (1980; cited in Abrahamse et al. 2005) and Van Houwelingen and Van Raaij (1989; cited in Abrahamse et al. 2005) were unable to sustain energy savings in the long term.

There is still a lack of data available from long term studies as most trials are less than four months and usually only a matter of weeks. In addition Abrahamse et al. (2005) have concerns regarding the small sample sizes of some studies and the lack of statistical analysis conducted within existing studies. From the studies reviewed it can be concluded that provision of information alone is not sufficient to motivate or sustain changes in behaviour, although combinations of interventions can be more successful.

2.10.2 Effectiveness of Feedback Interfaces

As established in Table 2.2. informing users of their resource usage has proven successful in several studies and has been the focus of much of the research to date. Continuous and daily feedback, such as the type provided by an IHD, was particular successful resulting in savings of 4-13% (Hutton et al. 1986; Van Houwelingen and Van Raaij, 1989; McCelland and Cook, 1979-80; Winett, Neale and Grier, 1979; Seligman and Darley, 1977; all cited in Abrahamse et al. 2005).

Comparative feedback was not seen to have more value than individual feedback (Abrahamse et al., 2005). Despite this in the study by Staats, Harland and Wilke (2004; cited in Abrahamse et al., 2005) comparative feedback produced large savings sustained over time for participants that were already engaged with energy saving initiatives. Schultz et al. (2006) also showed by utilising the power of the social norm reductions in domestic energy consumption could be made. Providing comparative feedback meant the highest consuming users reduced their consumption and the lowest consumers remained low, achieved by providing positive reinforcement of good behaviour (ibid).

In relation to a variety of feedback interventions the Centre for Sustainable Energy found that the "experience of seeing the numbers, bars or colours change [on the IHD] when they flicked their switches was far more powerful" (page 9, Anderson and White, 2009) than information provision alone. The trial period in this study was only eight days therefore although the users were engaged during the trial the long-term impacts of in-home displays was not assessed. Faruqui, Sergici and Sharif (2010) reviewed the implementation of IHD's and found average electrical savings of 7% from such schemes, with savings almost double if the electrical supply had to be pre paid.

Hayes and Cone (1981; cited in Abrahamse et al. 2005) found that although there was an initial reduction in energy consumption with monthly feedback there was an increase in consumption once the feedback was withdrawn. Rebound effects, where energy consumption actually increases once the intervention ceases, were also observed in the studies by McMakin, Malone and Lundgren (2002) and Brandon and Lewis (1999: both cited in Abrahamse et al. 2005).

Sauer, Wastell and Schmeink (2009) focused on the information provided by the interface. It was hypothesised that providing more advanced support for users could result in benefits, such as reduced energy consumption. Although, historical data has proven useful in reducing energy consumption a more proactive strategy was thought to be the use of predictive information (ibid). Predictive information anticipates future consumption and resulted in improved energy savings over any other display types. Predictive display information also helped lower working memory load by reducing the need to plan in advance (ibid). Despite improved usability not being a primary concern in the study it was recognised that it could produce additional gains.

Fischer (2008) concludes feedback is most effective when "given frequently and over a long time, provides an appliance-specific breakdown, is presented in a clear and appealing way, and uses computerised and interactive tools" (page 79). More active control and management of energy by users is therefore thought to be more persistent than the provision of feedback and information alone. There is also a need for further research regarding how users interact with eco-feedback interfaces, as highlighted by Jain, Taylor and Peschiera (2012) and Wood and Newborough (2003). The energy savings discussed are only possible if users are able to interact successfully with such interfaces.

2.11 Literature Review Conclusions

It is clear from the spike in energy consumption in 2009 that domestic heating has a large impact of the UK's CO_2 emissions (Department of Energy and Climate Change, 2011a). If the UK is to meet the required reductions in emissions by 2050 then reductions in domestic heating consumption will be needed.

There is a growing body of evidence that users have a significant impact on heat energy consumption through the heating control systems. The importance of having control over the environmental conditions of a building is highlighted by Bordass and Leaman (2001) and Miller (in Lomas et al. 2009). Gupta, Intille and Larson (2009), Bordass, Leaman and Bunn (2007) and Miller (in Lomas et al. 2009) all support the argument that properly programmed controls can save a considerable amounts of energy. Yet programming these controls can prove difficult for some users.

This research aims to respond to the call from Derijcke and Uitzinger (2006) and Shipworth et al. (2010) to ensure that it is easy, logical and intuitive to use heating control systems. This in turn would make it easier to behave in an energy efficient manner.

However, in contrast to this is the poor usability of programmable thermostats first reported 30 years ago by Moore and Dartnall (1982) and is still an issue today. Peffer et al. (2011) highlight this saying "[the] lack of usability studies is a critical weakness in the design of most advanced thermostats because usability is among the most frequent complaints about them" (page 2358). This leads to the conclusion that there is still a need for further research in the area of control usability, which this research aims to contribute to.

The studies by Caird and Roy (2008), Freundenthal and Mook (2003), Zhang, Rau and Salvendy (2009) and Sauer, Wastell and Schmeink (2009) acknowledge that older users may have problems using both existing and new energy control interfaces. This provides a gap in the research where an inclusive design approach could improve the usability of heating controls for a variety of users.

This research is inclusive design as it builds on Keates and Clarkson's theory of Design Exclusion (2003) and uses the social model of disability, which implies the product is the reason for this exclusion not the person. Reducing the user exclusion associated with heating controls and energy management systems could potentially save energy. Based upon Azjen's Theory of Planned Behaviour (1991) enhancing the user's sense of perceived behavioural control through a more inclusive solution, may directly influence the users performance of the behaviour.

It is suspected that this user exclusion may relate in part to the cognitive demands of the systems which are difficult to evaluate in current inclusive design research (Clarkson et al., 2007 and Persad, Langdon and Clarkson 2007). The numerical data produced by the Exclusion Calculator is useful to understand the number of people unable to use a product effectively (Waller, Langdon and Clarkson, 2010). However, its' application thus far has been limited to the visual and dexterity requirements of heating controls (Etchell, Girdlestone and Yelding 2004). This provides a two-fold opportunity for novel research in this area; the real-world validation of the results from the Exclusion Calculator and further understanding of the cognitive demands of heating control systems.

In summary, the literature review has identified three areas of opportunity in the overlap of inclusive design and control of domestic heat energy consumption.

These are:

- The application of inclusive design methods to heating controls and their validation in a real world scenario
- The detailed reasons for such design exclusion especially in relation to cognitive issues, the evaluation of which is currently limited within inclusive design research
- The development of a new heating control system which applies an inclusive design approach to enable people to reduce their heat energy consumption

The subsequent chapters of this research aim to address these gaps within current research. Secondly, it aims to demonstrate that inclusive design can have a positive environmental impact. Lastly, it aims to support the argument that inclusive design could enable more sustainable behaviour.

Chapter 3 - Research Methodology

Chapter 3 examines how best to address the research gaps identified in the literature reviewed in Chapter 2. This is done by looking at appropriate methodologies, prior to discussing the selected methodology in detail. Methodology provides the framework under which research is conducted, hence, approaches from social and design research are critically reviewed.

The methodology selected is DRM, a Design Research Methodology, a four-stage approach developed specifically for use by designers by Blessing and Chakrabarti (2009). The first stage of the methodology clarifies the research questions and overall hypothesis. This chapter reviews appropriate methods to answer the research questions and describes those selected for use at each stage of the methodology. The chapter concludes with a summary of where these are evidenced in the thesis.

3.1 General Research Methodologies

This research is both social and design research as from the outset it involves people in a real-world context and the development of a design intervention. Furthermore, the research is applied research as it is taking place in the 'real-world' with a focus on solving issues which impact people directly. In order to define the methodological framework used in this research several different research methodologies were reviewed (Robson, 2011; Kumar, 2009; Eckert, Stacey and Clarkson, 2003; Blessing and Chakrabarti 2009). Methodology in this context is defined as how the research questions are answered (Kumar, 2009) and "is concerned with turning the research questions into projects" (pp. 70, Robson, 2011).

Robson (2011) provides a five-stage framework for designing social research involving users. The practical applicability of this approach would suit this research with its real-world focus. Although not explicitly outlined in the research framework the ethical implications of any study must be considered prior to conducting the research (ibid.).

The process is outlined in five stages:

- Defining the purpose of the study
- Developing the conceptual framework
- Establishing the research questions
- Selecting the data collection and analysis techniques
- Defining the participant sample from which to collect the data

(from pp. 72, Robson, 2011)

Kumar (2009) proposes a similar eight-step process for social researchers using either qualitative or quantitative data collection methods. The eight steps listed below are subdivided into three categories relating to deciding what to do (step 1), planning how to do it (steps 2-5) and actually doing the research (steps 6-8):

1. Formulating the research problem
2. Conceptualising a research design
3. Constructing an instrument for data collection
4. Selecting a sample
5. Writing a research proposal
6. Collecting data
7. Processing data
8. Writing a research report

(pp. 19, Kumar, 2009)

Although these methods provide generic frameworks for social research, specific design research methodologies are more applicable to this research due to the expected design outcomes. Eckert, Stacey and Clarkson (2003) suggest the Spiral of Applied Research, an eight-stage design research process with an iterative focus. These stages include:

- Empirical studies of design behaviour
- Evaluation of empirical work
- Development and evaluation of theory

- Development and evaluation of tools and procedures
- Introduction of tools within industry
- Evaluation of the research dissemination

(Eckert, Stacey and Clarkson, 2003)

The stages of the Spiral of Applied Research are completed in any order or even in parallel (ibid.). This framework is of particular interest due to the acknowledgement that research within industry and academia has potentially different outcomes.

DRM, a Design Research Methodology published in 2009, offers a four-step framework specifically for design research (shown in Figure 3.1). The stages of the methodology are completed to a varying level of depth, however should be carried out in order (Blessing and Chakrabarti, 2009). The knowledge gained in the course of the Descriptive Study I is implemented in the Prescriptive Study through the development of design support. Subsequently an initial evaluation should be completed, with further testing in the Descriptive Study II.

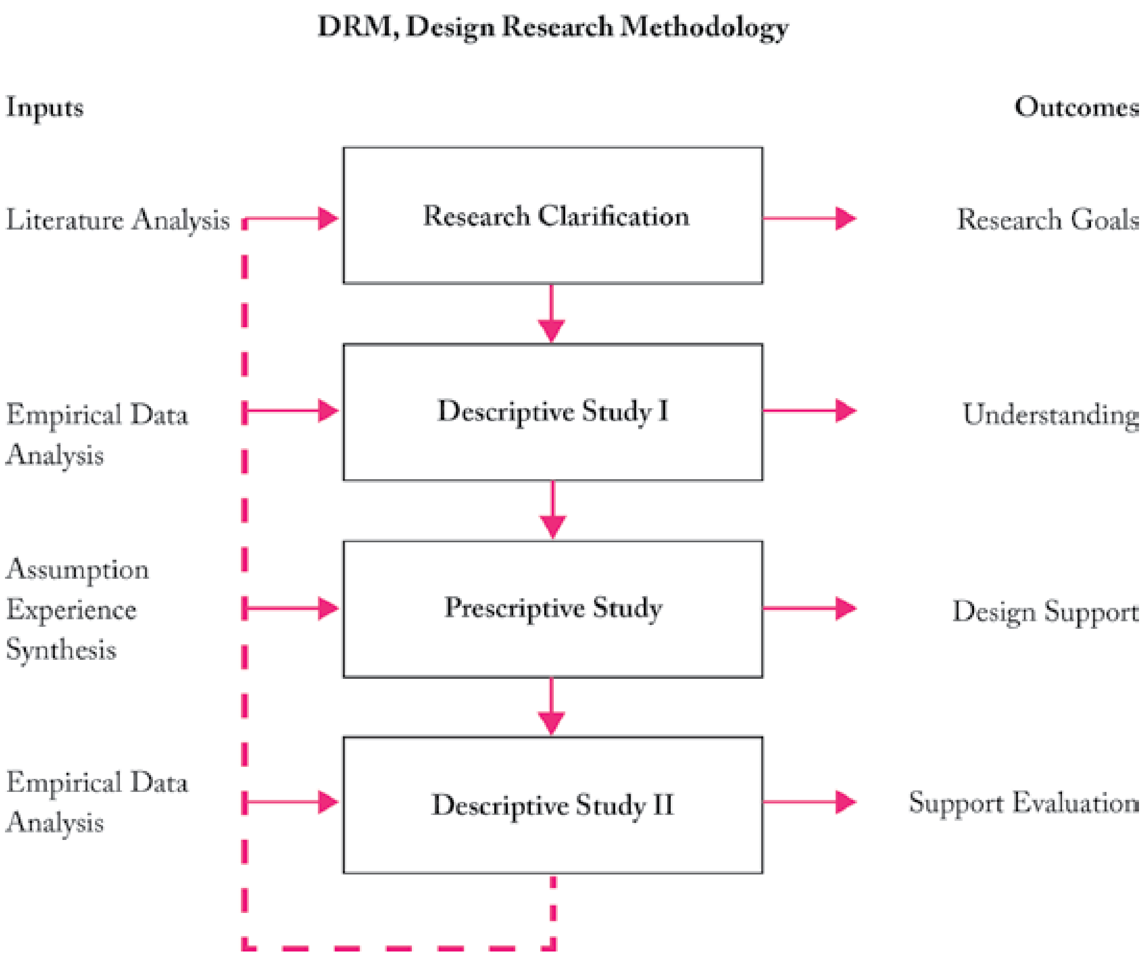


Figure 3.1 The DRM Methodology Framework (adapted from Blessing and Chakrabarti, 2009)

3.2 Selected Research Methodology

This research adopts the DRM methodology, which has enabled the research to develop in a structured manner. DRM has been used in several PhD theses to date, see Dong (2004), Cardoso (2005), Gupta (2007) and Cifter (2011). This methodology is the most appropriate because of the tangible outcome produced in the Prescriptive Study, which is appropriate considering the objectives of this research. Each stage of the framework is described in detail subsequently.

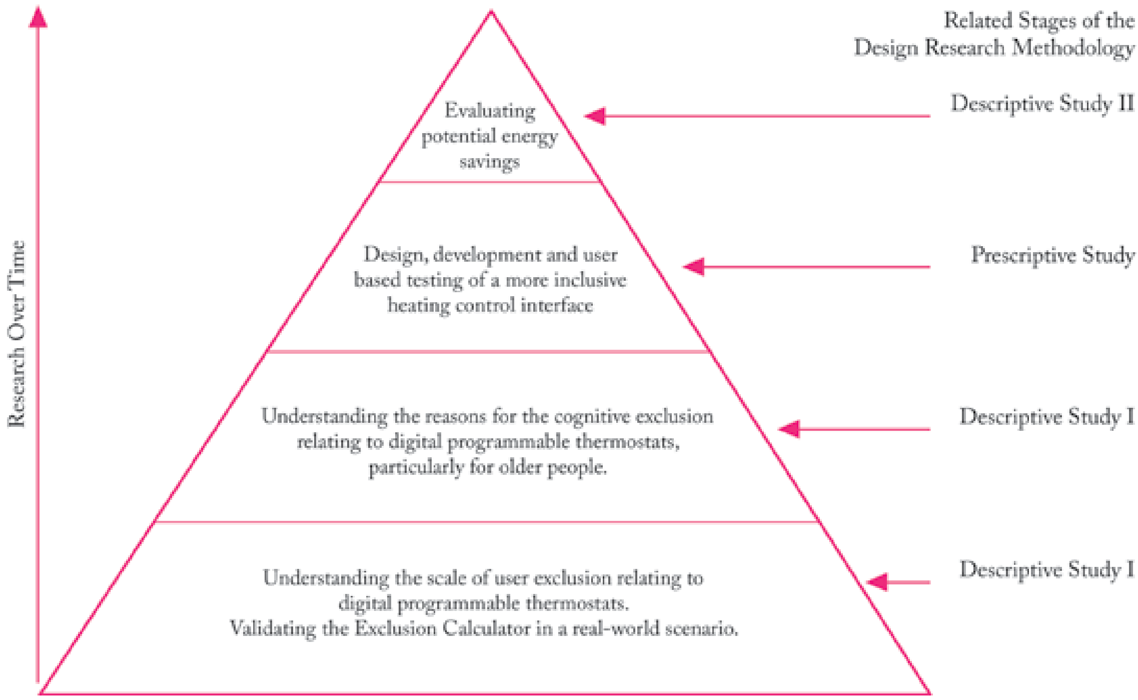


Figure 3.2 Pyramid Diagram of Research with Methodological Links

3.2.1 Research Clarification

Chapters 1 and 2 of this thesis form the Research Clarification stage. Chapter 1 clarifies the overall aims and objectives and provides the context in which the research is conducted. Chapter 2 identifies gaps in the current literature where this research aims to contribute. Hence, the following research questions are proposed and the chapter, which aims to answer them, is contained in parenthesis.

- **Research Question 1**: What is the scale of user exclusion relating to digital programmable thermostats? (Chapter 4)
- **Research Question 2**: What are the reasons, in particular the cognitive reasons, for this user exclusion? (Chapter 5)

- **Research Question 3**: Can the exclusion relating to digital programmable thermostats be reduced? (Chapter 6)
- **Research Question 4**: Does this user exclusion have an effect on the associated heat energy consumption? (Chapter 7)

It is anticipated that the research questions will be answered sequentially through the different stages of the DRM. In answering these research questions, it is expected that the overarching hypothesis can be tentatively verified. A hypothesis is defined by Blessing and Chakrabarti as, "a tentative answer to a research question in the form of a relationship between two or more variables" (pp. 92, 2009). Work towards verifying the research hypothesis is expected to form part of this thesis' contribution to knowledge. The overall hypothesis of this research is that:

More inclusive heating control systems could enable reductions in domestic heat energy consumption.

3.2.2 Descriptive Study I

The Descriptive Study I (DS-I) can be either review based, drawing conclusions based on literature review, or comprehensive, involving one or more empirical study (Blessing and Chakrabarti, 2009). The DS-I consisted of two empirical studies reported in Chapters 4 and 5, which aim to gain a deeper understanding of the reasons for user exclusion. Chapter 4 was a small scale study that successfully addresses Research Question 1 establishing the scale of user exclusion in relation to digital programmable thermostats. Chapter 5 aimed to illicit a deeper understanding of the cognitive exclusion relating to digital programmable thermostats, which was required to answer Research Question 2.

The five-stage comprehensive DS-I process is shown in Figure 3.2, where for a review based DS-I only the first and last are completed. The outcomes of all five stages are; a deeper understanding of the problem defined in the research clarification stage, the data generated during the empirical study and a direction for further investigation or development (ibid.). This stage also aims to provide an understanding of the success criteria and implications for the support to be developed in the Prescriptive Study (ibid.).

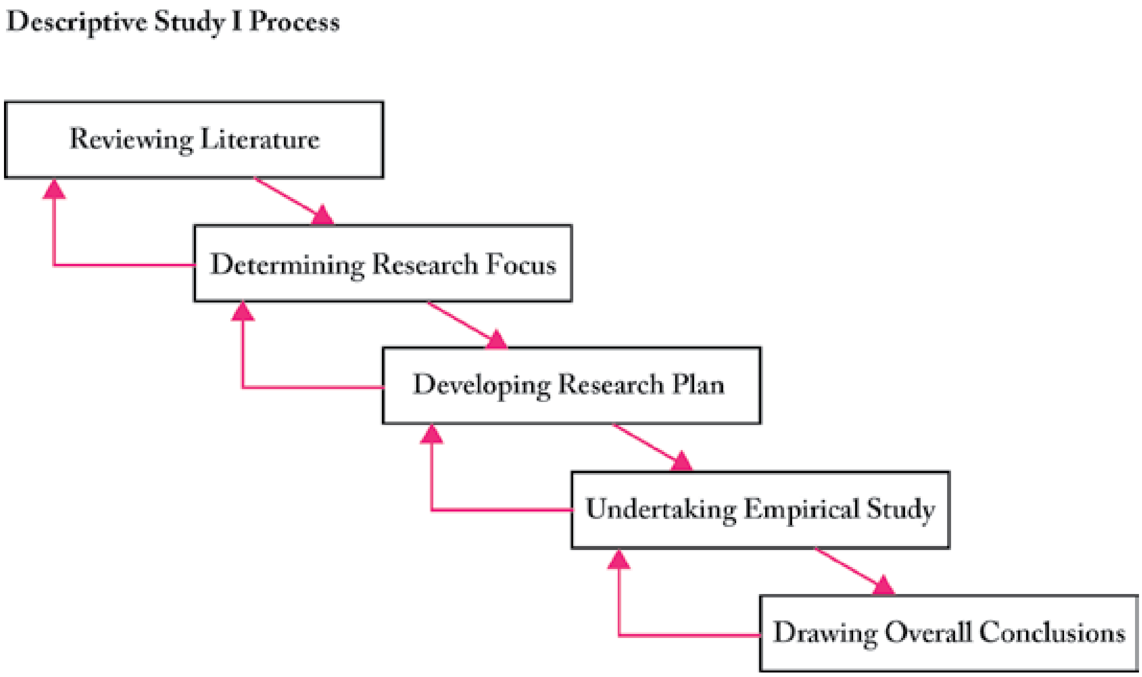


Figure 3.3 The Five Stages of Descriptive Study I (adapted from Blessing and Chakrabarti, 2009)

3.2.3 Prescriptive Study

Traditionally, research is concerned with description, understanding or explanation (Robson, 2011) however the focus of this research is directional. The desired outcome of the research is not only a change in user energy consumption but also a reduction in it. The Prescriptive Study (PS) is concerned with the development of 'design support', commonly in the form of tools, methods, guidelines or knowledge to support the design process (Blessing and Chakrabarti, 2009).

In this research, the PS consists of the development of a heating control interface. This aims to both reduce the cognitive user exclusion and enable energy reductions to be made. The interface applies an inclusive design approach to enable people to reduce their heat energy consumption. However, rather than 'design support', this interface may be more appropriately classed as a 'design intervention'.

The methodology has been adapted at this stage to cover the development of the design intervention and its subsequent evaluation with users, rather than with design practitioners. The development of a design intervention rather than design support is a recognised deviation from the methodology. However, the main motivation for this adaption of the methodology was the industrial nature of this research and the desire of the sponsor organisation to have product/intervention based outcome.

The development and evaluation of the 'design intervention' has consistently followed the structure provided in DRM as shown in Figure 3.4. The results of the evaluation are expected to be a worthwhile contribution to reducing cognitive exclusion relating to digital programmable thermostats. This may establish a tentative link between an inclusive design approach and potential energy savings.

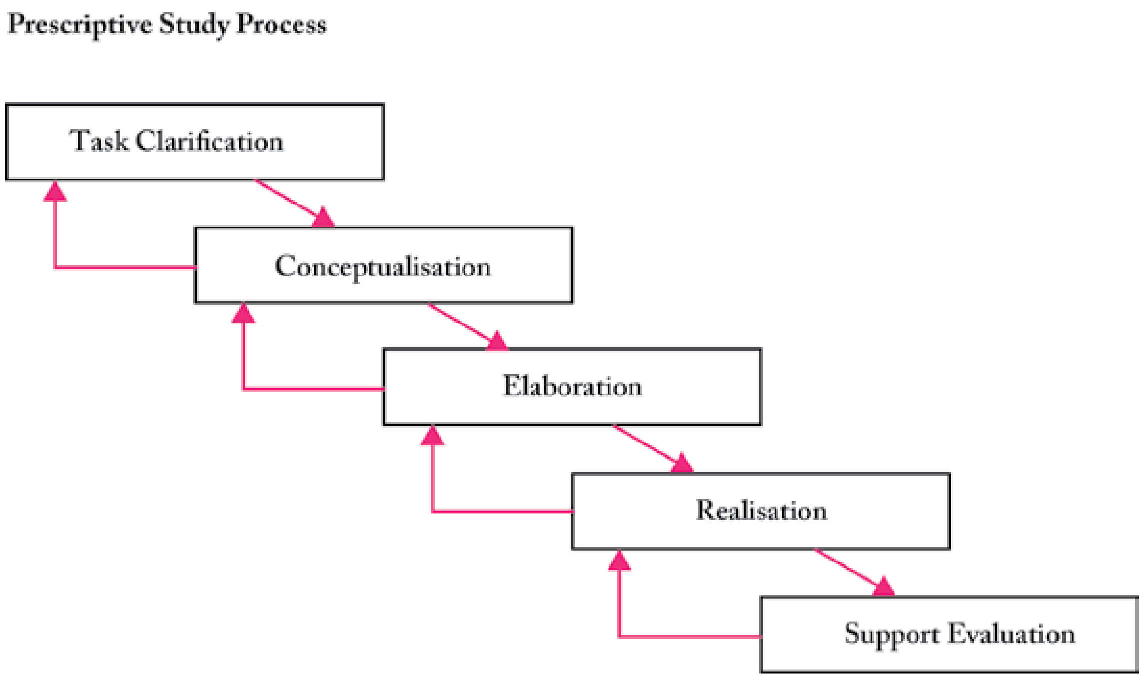


Figure 3.4 Main Stages in the Prescriptive Study Process (adapted from Blessing and Chakrabarti, 2009)

3.2.4 Descriptive Study II

The Descriptive Study II (DS-II) aims to evaluate the usability, applicability and usefulness of the support developed in the PS (Blessing and Chakrabarti, 2009). This has been completed to an initial stage in Chapter 6. This gives an indication of whether support can be used effectively and whether the support fulfils the requirements for which it was intended (ibid.). A comprehensive DS-II includes success evaluation, which is often difficult due to the time required and can often form the basis of further research (ibid.). The process of completing the DS-II is similar to that shown in Figure 3.2 previously with a focus on evaluation rather than pure understanding.

3.3 Research Methods

A range of methods used in inclusive design and human factors research have been reviewed to ensure the selection of appropriate methods. Tools and methods used in inclusive design tend to fall into two categories: those that involve users directly and those that do not. It is commonly reported within inclusive design that there is little substitute for involving users directly with the design process. Clarkson et al. deem it, "essential to understand the needs and goals that the product will address" (pp. 3-52, 2007).

Those that involve user participation, such as user observation, user trials, interviews or focus groups, can prove expensive and time consuming yet are seen to be more accurate (Cardoso, Keates and Clarkson, 2004). Methods that do not involve users such as simulation, expert appraisal, task analysis and self-observation are used to gain insight into problems at specific stages of the interaction (ibid.). In areas where inclusive design methods are limited, methods from humans factors research have been reviewed.

The methods described in this section will be implemented at varying stages of the research based upon the specific needs of the study. In order to implement inclusive design successfully, involving users at the earliest stage is of paramount importance. This allows feedback to be incorporated into final design solutions. Furthermore, to design inclusively a combination of the methods and tools described in this section should be used. In the same way no solution will satisfy all users, the application of no single method will lead to an inclusive solution.

3.3.1 Methods Involving Users

Newel and Gregor (2002) argue that inclusive design should be a mindset amongst designers rather than an application of specific guidelines or checklists. Involving users directly in the design process can help aid the development of a more inclusive mindset. Goodman and Waller (2007) suggest three main ways of involving users; by asking them directly, by observing their behaviour or by getting users to participate in the design process directly.

3.3.1.1 Asking Users

A variety of methods, which ask users about their thoughts, feelings, needs or goals are commonly used in social research; including interviews, focus groups, questionnaires and surveys. People's opinions and thoughts are particularly valuable when trying to assess social acceptability of a product (Keates and Clarkson, 2003). Robson (2011) discusses surveys, questionnaires and interviews in depth as key methods of people focused research. Lazar, Feng and Hochheiser (2010) strongly advocate asking users about their wants and needs in human computer interaction research. This is especially useful in combination with other research methods such as usability testing and ethnographic investigations.

Questionnaires and surveys can be good for gathering qualitative and quantitative data without introducing interviewer bias or leading participants (Keates and Clarkson, 2003). The main approaches to data gathering using questionnaires, are self-completion (including web based surveys), face-to-face surveys or telephone surveys all of which can be applied in inclusive design (Robson, 2011).

The three types of interviews are defined by Robson (2011) as structured, semi-structured and unstructured. Fully structured interviews have predetermined questions asked in a specific order, whereas semi-structured interviews are more flexible. This allows the addition of questions during the interview to illicit further information from the participant (ibid.). Unstructured interviews develop around a theme of interest to the researcher and are particularly informal (ibid.). The main disadvantage of interviews is while the data can be extremely useful and insightful, it is particularly time consuming to obtain (ibid.). Within inclusive design research structured and semi-structured interviews are more common as research tends to have a particular focus on a specific product or problem.

3.3.1.2 Observing Users

Ethnography, or observational research as it is more commonly referred to, can be used to highlight design opportunities or inform the design process at a variety of stages (Lebbon, Rouncefield and Viller, 2003; Lazar, Feng and Hochheiser, 2010). It is mainly viewed as an inspirational tool rather than a validation tool (Lebbon, Rouncefield and Viller, 2003). Primarily it involves watching and listening to how people use products, within a realistic environment, to help the participant behave naturally (Keates and Clarkson, 2003). The advantage of this approach is that it can offer in depth insight into ways in which people use products that they may be unaware of or find difficult to articulate (Lebbon, Rouncefield and Viller, 2003). This insight can be increased if participants are asked or encouraged to talk through the process they are experiencing. For user observation to be successful, it is extremely important to observe the correct user or user groups. Langdon and Thimbley (2010) highlight this by calling upon designers to include a wider range of participants in user based testing.

Similarly, to the methods used in social sciences and inclusive design, methods of assessing usability can involve either novice users or experts (usually the designers themselves). Usability assessment of a system is either user based think aloud tests, real system testing and prototype testing or expert based, heuristic evaluation (Lauesen, 2005). The International Standards Organisation has produced ergonomic standards relating to usability for the last fifteen years under the committee of ergonomics of human-system interactions. Several parts of the ISO 9241 standard are relevant to this research and cover usability (part 11), accessibility in general (part 20), software accessibility (part 171) and human centred design for interactive systems (part 210). The standards provide both frameworks and guidelines to implement.

In human factors research, user observations are extensively used to gather information regarding physical or verbal aspects of a task (Stanton et al., 2005). These are most commonly direct and structured observations where the participants know they are being observed (ibid.). This may mean the observations are subject to the Hawthorne effect, where participants behave differently because they know they are being observed (Robson, 2011). However, Robson (2011) argues that formal, structured observations can provide higher validity and reliability than informal approaches and are a way of quantifying user behaviour.

3.3.1.3 User Based Prototype Testing

Prototyping is a common tool in the product design field, where user involvement comes at the testing stage. Low-fidelity prototypes are considered more useful at an early stage in the design process. This allows high-level usability issues to be addressed and for improvements to be made at a later stage of the design process (Dumas and Fox, 2007). Where a later stage working prototype is available user trials can show how participants would interact with the prototype to perform a task. This is often combined with interviews or questionnaires to record participant feedback (Keates and Clarkson, 2003).

Usability metrics are the parameters which user testing will measure in its evaluation. Commonly these are; ease of use, task performance time, number of errors and subjective satisfaction (Lauesen, 2005 and Wickens et al., 2004). Choosing the appropriate usability metrics to measure depends on the context of use, the type of information required and the target user group for the product (ibid.). The number of participants in usability testing is a point of some debate, however is recommended to be no less than 10 (Nielsen, 1993). Wickens et al. (2004) argued that when using more than 6–8 users, the value of the information gathered on the usability issues diminishes. Similarly, Snyder (2003) recommends the use of 5 to 8 participants with the same user profile conducting identical tasks using low-fidelity prototypes. Virzi (1990 and 1992, cited in Dumas and Fox, 2007) found 80% of usability issues were uncovered using between 5 and 20 participants. Such findings were also echoed in studies by Faulkener

(2003) and Law and Vanderheiden (2000, both cited in Dumas and Fox, 2007). In inclusive design research a minimum of ten participants is advised, with a minimum of three users of each level of ability (Clarkson et al., 2007). Involving extreme users with significant capability loss can help inspiration within the design process (ibid.).

Paper prototyping is one early stage usability method used in human-computer interaction to illicit any major usability problems (Snyder, 2003). Lazar, Feng and Hochheiser (2010) advocate the use of paper prototyping as they are low cost and participants often feel it is more acceptable to be critical when the prototypes do not look highly developed. Prior to involving users, the user profile is developed as a set of selection criteria to ensure valid representation of users (Snyder, 2003). The tasks examined should be defined based on user goals that elicit action and these should be walked through prior to the user involvement (ibid.). Each screen of the interface is represented by an individual sheet of paper. When the user interacts with the screen the resultant paper screen is provided by the researcher (acting as the computer) to simulate how the system would operate. Once the task is completed the participant is invited to give opinions on the interface to elicit further preferences. This information is used to plan further changes to the interfaces in the next stage of development.

3.3.1.4 Assessing Mental Workload

To understand and measure the cognitive load placed upon users, methods from human factors and ergonomics have been considered. Measurement or assessment of mental workload can take place either during or after user interaction with a product. The measurement of perceived workload can contribute to the overall assessment of usability. This measurement can be task-related, subjective or physiological (Wickens et al., 2004 and Stanton et al., 2005). Measurements of mental workload (MWL) can be categorised into primary and secondary task performance measures, physiological measures and subjective rating techniques (Stanton et al., 2005).

From the outset, physiological measurement of participants was deemed too physically invasive and high cost for use in this research. While task performance measures were considered, they were discounted due to the difficulty in distinguishing between levels of workload and the overlap with the usability metrics measured. Subjective rating scales have the advantages of being low-cost, easy to use and quick to implement (Stanton et al., 2005). The rating scales can be multi or unidimensional, with the multidimensional scales providing a greater level of granularity as to where the workload occurs (ibid.).

Two commonly used multidimensional subjective rating scales are the subjective workload assessment technique (SWAT) and the NASA Task Load Index (NASA TLX). SWAT is a widely used and validated method of MWL assessment, which rates time, mental effort, and stress loads. However, it is reported that SWAT is less sensitive, especially with regard to low mental workloads, when compared with the NASA TLX scales (ibid.). This lack of sensitivity led to the selection of the NASA TLX as the method for MWL assessment throughout this research.

The use of the NASA TLX, developed by Hart and Staveland (1988), aims to complement the use of exclusion calculations and the usability testing. The NASA TLX is a widely validated, multidimensional, subjective, rating measurement that was applied after task completion so as not to interfere with task performance (Stanton et al., 2005). The method rates six dimensions, which are: mental demand, physical demand, temporal demand, performance, effort and frustration level. These are rated on a scale from low (1) to high (100), except in the case of performance, where the scale goes from good (1) to poor (100) (Gawron, 2008). In the study of an automated communication system done by Knapp and Hall, a score of 40 was defined as the threshold of a high mental workload (1990, cited in Gawron, 2008).

A full application of NASA TLX requires a weighting procedure; however, an alternative is the Raw Task Load Index (RTLX). RTLX is a simplified alternative to traditional TLX where the sum of the scales is divided by the number of scales to give the overall workload estimate (RTLX = SUM/6). Hendy, Hamilton and Landry (1993) and Byers, Bittner and Hill (1989) concluded that the RTLX scales are sufficient for producing an estimate of overall workload. Byers, Bittner and Hill (1989) found a strong correlation between the full TLX and RTLX and concluded that they were essentially equivalent, hence the RTLX scales are employed in this research.

3.3.2 Methods That Do Not Involve Users

3.3.2.1 Physical User Data

Physical or anthropometric data can help design for a range of users, commonly from the 5th to 95th percentile measurements. Dong, Nickpour and McGinley (2009) found that experienced designers expressed a preference for using physical prototypes and working directly with users as opposed to raw anthropometric data. This may be due to the design of available anthropometric data tools, which were perceived to be text-heavy, and of poor graphical quality (Nickpour and Dong, 2011). Further work to develop useful, relevant and desirable tools for designers to collect and manage anthropometric data is currently underway (ibid.).

3.3.2.2 Capability Simulation

Capability simulators can help designers understand the reduced capacity to perform a task from a user's perspective in a cost-effective manner by replicating a loss of capability. This can help designers understand the impact of certain capability losses on user exclusion (Clarkson et al., 2007). These simulators can recreate a reduction in certain motor and sensory capabilities. Nevertheless, it is particularly difficult to simulate a loss of cognitive function (ibid.). Cardoso and Clarkson (2010) argue simulation provides a compromise between subjective assessments of product interaction and full user involvement, which can prove expensive. This can help the design process where users with certain capability losses cannot be directly involved, although simulation should not replace user involvement (ibid.).

Computer aided design software of capability profiles has been developed called HADRIAN (Human Anthropometric Data Requirements Investigation and Analysis) for use by product designers to help implement inclusive design (Porter et al., 2004). This combines anthropometric data, user capability data from tasks and video recordings of coping strategies (Marshall et al., 2002). Data was collected from one hundred users including ambulant disabled people, wheelchair users, able-bodied people and older people to build models to help designers understand whom their products exclude and why (ibid.). Use of a task-based model helps identify where in the use of the product users are excluded and how this might be resolved at the design stage (Porter et al., 2004). One criticism of HADRIAN is it has a limited number of profiles and deals primarily with physical rather than cognitive capabilities, which are typically difficult to represent (Persad, Langdon and Clarkson, 2007). This echoes Clarkson et al. (2007) earlier who argue it can be difficult to represent cognitive losses accurately.

3.3.2.3 Task Analysis

Breaking down the overall user goal by function into its sub-functions can graphically represent the demands of using a specific product or service. Hierarchical Task Analysis (HTA) is a central method in ergonomics research as it evaluates both the cognitive and physical elements of any task (Stanton, 2006). Developed in the early 1970's by Annett and Duncan, HTA works by breaking down a task into its individual parts and identifying which parts of the task may result in errors and forms the basis of up to twelve further methods of analysis (Stanton et al., 2005). Although this method does not propose any solutions it can highlight key requirements, how they relate to other requirements and form the basis of further analysis (Clarkson et al., 2007). By highlighting the functions and stages of user interaction with the product areas of difficultly for the user can be identified at an early stage.

The process begins with an overall 'goal', which is broken down into 'sub-goals' until a basic operation, or action step is reached (Stanton et al., 2005). In relation to this research, it is particularly useful in its visualisation of the cognitive elements of the task. This visualisation is referred to as the 'plans', which represent how the 'goal' and 'sub-goals' are achieved. 'Plans' can be linear, non-linear, cyclical, selective or simultaneous depending on the goal or sub-goal (ibid.). The one significant criticism of the method is its reliability, which is often dependent on the experience of the analyst. However, the usefulness lies in being able to visualise the different capabilities that are required to complete a task successfully.

3.3.2.4 Quantification of User Exclusion

Central to this research is quantification of user exclusion through the Design Exclusion Calculator (hereafter referred to as the Exclusion Calculator), developed by the Engineering Design Centre at the University of Cambridge. This tool can be used to estimate the number of people currently excluded by a product. An exclusion calculation and a detailed task analysis form the basis of the Exclusion Audit process described by Clarkson et al. (2007). It is intended to help inform decision making at the beginning of the design process and to work in parallel with other tools to ensure a holistic design approach (Waller, Langdon and Clarkson, 2010).

The calculation is based on a subjective analysis of the capability demands of using the control, which may cause variable results and induce errors. Experience of the analyst is therefore critically important. The Exclusion Calculator currently requires the analyst to select the number of everyday tasks, which are applicable to the interaction from a given list. Several of these were not seen as appropriate for the product design process by respondents in the study done by Waller, Langdon and Clarkson (2009). Additionally, the calculation results represent the number of people excluded by the product not the number of households. It is likely that someone within the household could potentially use the heating controls under study; however, this is not consistent with the social model of disability used in inclusive design.

Other consumer products that have been assessed to date based on the data from the Disability Follow-up Survey include:

- Mobile phones (Waller, Langdon and Clarkson, 2009)
- Kettles (Dong, Keates and Clarkson, 2002)
- Heating controls, in terms of their visual and dexterity requirements (Etchell, Girdlestone and Yelding, 2004) and to compare the effectiveness of inclusive design tools (Cardoso, 2005), not to suggest design improvements
- Digital television across three stages of the lifecycle; getting started, basic use and advanced use (Klein, Karger and Sinclair, 2003).

3.3.2.5 The Exclusion Calculator

The Exclusion Calculator is a publicly available software tool (http://www.inclusivedesigntoolkit.com) used to estimate the number of people currently excluded by a product. This is done by considering how challenging each task is, then rating it for the associated capability demands, as shown in Figure 3.5 (Goodman and Waller, 2007). User capability is defined as, "an individual's level of functioning, along a given dimension from very high ability to extreme impairment, which has implications for the extent to which they can interact with products" (page 275, Johnson et al., 2010).

Of specific interest is the numeric data produced which allows comparison of results with the user testing results. This data was originally established from the Office of National Statistics 1996/97 Disability Follow-up Survey capability scales (Grundy et al., 1999; Clarkson, Keates and Dong, 2002; Cardoso, Keates and Clarkson, 2004). The Disability Follow-up Survey uses thirteen capability categories to assess levels of impairments, seven of which directly relate to product interaction; seeing (vision), hearing, intellectual function, communication, locomotion, reach and stretch and dexterity (Waller, Langdon and Clarkson, 2010). The capabilities assessed in the calculation are:

- Vision
- Hearing
- Dexterity
- Reach and stretch
- Locomotion
- Thinking (intellectual function and communication abilities are combined under 'thinking')

Figure 3.5 Enter Data screen of the Exclusion Calculator showing an overview of all capabilities

The Exclusion Calculator considers how demanding each task is using a scale from low to high demand for each capability (Goodman and Waller, 2007; Figures 3.6 and 3.7). The scales relate to the type of demand required by the interaction, with intermediate points of increasing demand along the scale. The level of demand required is then correlated with the number of people who would find the task impossible.

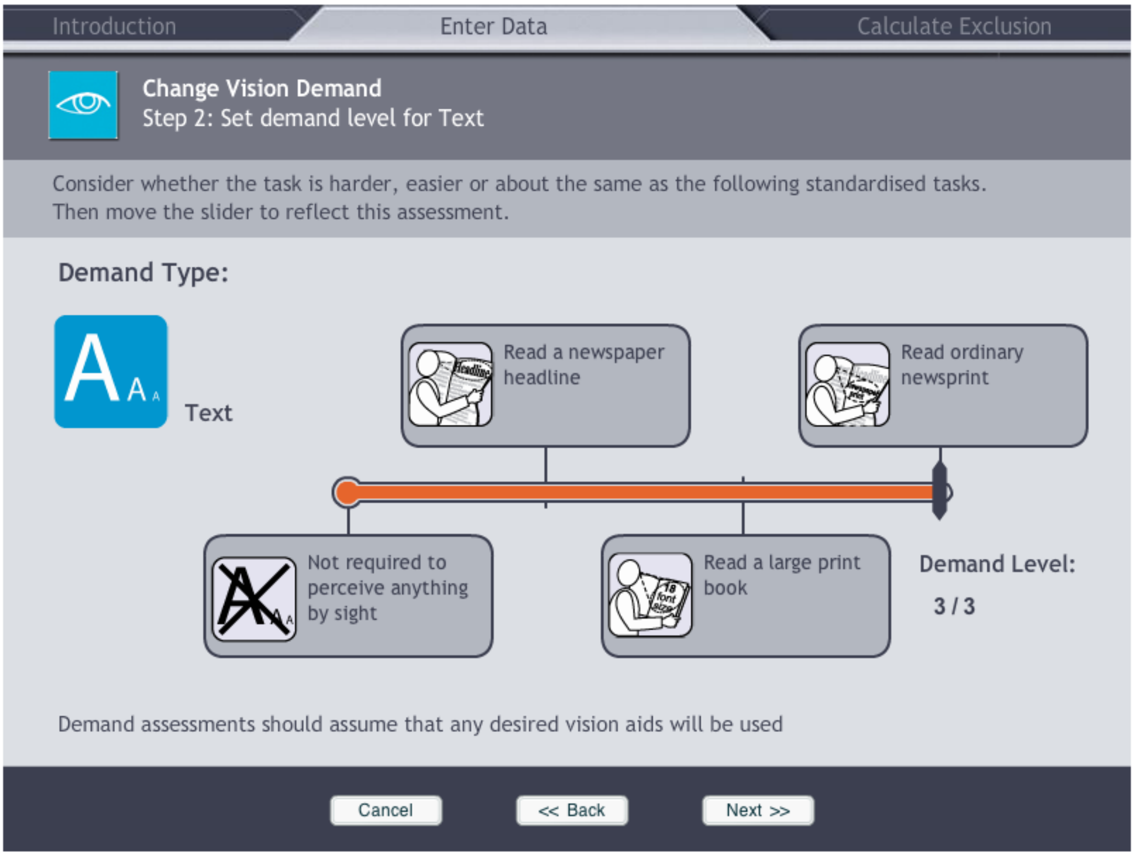


Figure 3.6 Screenshot of the data input screen for part of the visual demand capabilities

Figure 3.7 Screenshot of the data input screen for the cognitive demand capabilities

Calculating the exclusion then gives an overall percentage of the population excluded and the number of people excluded by each type of capability demand, shown in Figure 3.8. This can be calculated for varying age ranges and the exclusion can be filtered by gender as well.

Figure 3.8 Example calculation results screenshot from the Exclusion Calculator

The limitations of the Exclusion Calculator must also be considered. One potential source of error is that the calculation is based upon population data from 1997. The data comes from the Disability Follow-up Survey reported by Grundy et al. (1999), which used 7263 face-to-face interviews regarding people's physical and mental capabilities. The dataset is not ideal; it was originally used to plan welfare payments and is subject to sampling biases and self-reporting errors (Waller, Langdon and Clarkson 2009). Despite the data being somewhat dated it is currently the best available data for use in inclusive design (Johnson et al., 2010). Cognitive capabilities are particularly difficult to elicit from users and the measurement of these is acknowledged as a particular weakness of the Exclusion Calculator (Cardoso and Clarkson, 2012).

Work is on-going to develop a more appropriate and up-to-date survey to collect relevant disability data in the UK (Waller, Langdon and Clarkson, 2010). Undoubtedly, the data will have changed in the ensuing years, particularly considering the rapidly ageing population in the UK today. Currently, there is a new UK-wide study being conducted by the University of Cambridge, aiming to collect data on disability prevalence specifically relevant to product design (ibid.). The updated survey aims to help address current limitations of the tool, in particular relating to cognitive demands and ensuring that data is specifically relevant for use by product designers.

Although the Exclusion Calculator does not require a Hierarchical Task Analysis it can provide a formal and rigorous basis for this calculation, as well as a range of other methods. One draw back of using the HTA in this context is that the calculation is performed for the overall task and not the sub-tasks of the HTA. While the calculation itself accounts for people with multiple capability losses, it means that simply summing individual calculations does not necessarily provide the overall exclusion. Therefore, conducting a calculation for each sub-task then summing all the sub-tasks would not equal the overall exclusion. It is recognised that each sub-task would require multiple capabilities to achieve the task, however the calculation would only consider the dominant capability of each sub-task. Hence, the rudimentary colour coding of the HTA in Chapters 4 and 6.

While there are some drawbacks to the method, the Exclusion Calculator is unique in its approach to quantifying user exclusion. In comparison to Wierwille and Eggmeier's (1993) method selection criteria for metal workload methods, the Exclusion Calculation tool is not intrusive to users, is easy to implement and easy to transfer between product contexts. It also has a relatively high level of sensitivity and diagnosticity as to where the exclusion may occur in a product interaction. The Exclusion Calculation should be used with caution and should not replace testing products with a variety of users within the design process. However, it can provide an indication of where the most demanding capabilities may lie, prior to involving users.

3.4 Selection of Research Methods

The methods selected for use at each stage of the research are described in this section. They were selected based on the critical review of relevant methods from inclusive design, ergonomics and human factors research, in section 3.3 and five further criteria. These criteria were:

- Ease of implementation
- Validation in other studies
- An acceptable level of intrusion on participants
- Transferability between environments
- Cost of implementation

Three of these criteria are suggested by Wierwille and Eggmeier (1993) for the selection of mental workload assessment methods. However, it is suggested that these criteria may be useful in a generic context when selecting research methods. Although not considered by Wierwille and Eggmeier (1993), validation and cost criteria are also deemed important in this research.

The methods selected from inclusive design were the Design Exclusion Calculator, user trials and observations. These were used as they are cost effective, easy to implement and widely validated in inclusive design research. User trials and observations can also be applied in both the context of users homes or laboratory settings as required.

To support these methods two methods were adopted from human factors; Hierarchical Task Analysis and NASA Task Load Index to assess mental workload. Hierarchical Task Analysis was selected due to its wide validation and to formalise the task analysis used in conjunction with the Exclusion Calculator. The NASA Task Load Index was selected because of its high level of diagnosicity as to where the workload occurs and the limited intrusiveness upon the participant's task performance.

When assessing the usability of both the existing and prototype systems the following of Nielsen's (1993) usability criteria were assessed: learnability, efficiency, errors and satisfaction. The criterion of memorability was not formally assessed, however the additional criterion of accessibility was. An explanation of how each of the criteria was assessed follows:

Learnability was assessed through observations regarding instruction usage; with the need for instructions implying the interface does not support the user sufficiently to enable them to complete the task.

Efficiency was assessed by timing the usability task and noting the success of the participants. Ideally, all participants could achieve the task both quickly and successfully.

Errors were predefined and counted during the observation of the prototype usage and compared to the idealised HTA created for the prototype system. General errors were also noted during the observations of existing control systems.

Satisfaction of the participants was based on the feedback verbally expressed by the participants during the user trials and the subjective mental workload rating of perceived performance.

Accessibility was assessed based on the results of Design Exclusion Calculator and compared to actual task success rates. The NASA Task Load Index was also used to give an estimated of participants perceptions of both physical and mental demands.

Due to the research involving users throughout, each study was reviewed and approved by the School of Engineering and Design Ethics Committee, Brunel University, prior to completion. This ensured that participants gave informed consent to take part in the study, understood they had the right to withdraw from the study at any point, that data would be made anonymous and may form part of a publication and thesis.

It is important that the research methods selected are suitable for use with older participants and do not induce stress or fatigue in the participants. Therefore the level of intrusiveness of the methods upon participants was of critical importance in terms of the ethical review. A risk assessment for each empirical study was conducted to ensure that any risks to the participant or researcher's safety were fully considered.

In order to implement an inclusive design process successfully, involving users at the earliest stage is of paramount importance. This allows feedback to be incorporated into final design solutions. Furthermore, to design inclusively a combination of the methods described in this section should be used. In the same way no solution will satisfy all users, the application of no single method will lead to an inclusive solution.

3.4.1 Methods Used in Descriptive Study I

Both studies from the DS-I used a multi-strategy design to obtain both quantitative and qualitative data. In preparation for an exclusion calculation a HTA is conducted to break down the elements of the overall task into its constituent parts. Then these are related to the capability demands placed on the user. HTA represents the stages of the interaction with the product from which capabilities used to complete the task can be easily understood. This allows the Exclusion Calculation to be conducted in a rigorous manner.

After the initial desk-based analysis user based testing was completed, observations of products were conducted to establish where capability demands were excessive. User comments were audio recorded to gather qualitative data from the usability testing. The RTLX scales were then used to assess levels of mental workload placed upon users. This aimed understand in detail the perceived user experience and mental workload placed upon the participant.

3.4.2 Methods Used in the Prescriptive Study

The heating control interface prototype was developed as a proof-of-principle to help answer the third research question, 'Can the cognitive exclusion in relation to digital programmable thermostats be reduced?'. Hence, the Prescriptive Study involved simulation of the proposed system functionality through the development of a prototype control interface. The initial paper prototypes were developed as static interfaces and were evaluated using low-fidelity paper prototypes. This was to identify any high-level usability issues at an early stage, prior to adding full interactivity to the system. The working prototype was then developed further and was utilised in the full user testing described in Chapter 6.

3.4.3 Methods Used in Descriptive Study II

In this research, an initial proof-of-principle prototype has been developed in the PS stage of the research. An initial evaluation of the prototype has been conducted and is described in Chapters 6 and 7 of this thesis. The DS-II of this research project involves an initial user-based evaluation reported in the user testing in Chapter 6. This uses the results of the DS-I from Chapter 5 as a baseline for tentative comparison to evaluate whether an improvement has been made to the system usability. To evaluate the success of the PS in reducing heat energy consumption a tentative evaluation of potential energy savings is reported in Chapter 7 to estimate the scale of any energy savings achievable. The initial DS-II allows conclusions to be drawn regarding whether the design intervention meets the success criteria and identifies areas for improving the support.

3.4.3.1 User-based Evaluation

The user-based evaluation aims to address whether the design intervention developed in the PS fulfills the task for which it was intended. The key questions during this evaluation are:

- Is the support/intervention usable?
- Does it address the cognitive exclusion of the system directly?
- Is the cognitive exclusion reduced?

To ensure the intervention was usable paper prototypes were tested with 6 participants to ensure the development of an appropriate design intervention. Secondly, an exclusion calculation was conducted based on the capability demands of the interactive proof-of-principle prototype. to understand where exclusion may occur when using the system. Thirdly, usability testing with a range of users allows the evaluation of whether the core functionality of the system can be used as intended and to observe where users were excluded. The usability metrics assessed during the usability testing were task success, time taken to complete a task and use of help features. Finally, upon completing the usability testing participants were asked to complete the RTLX scales to help evaluate whether or not the cognitive exclusion has been reduced.

3.4.3.2 Evaluation of Potential Energy Savings

The evaluation of potential energy savings aims to address the usefulness of the design support or intervention, in this case could the intervention enable energy savings. Blessing and Chakrabarti (2009) argue this type of evaluation is often difficult and requires the application of the intervention in practice over a long period. Hence, Chapter 7 forms an initial attempt at answering the fourth research question, 'Does user exclusion from being able to programme thermostats result in increased energy consumption?'. Chapter 7 estimates the scale of the energy savings achievable and compares this to real-world energy monitoring data.

3.5 Summary of the Methodology

This chapter discusses a range of appropriate methodological approaches and specifically the application of the DRM framework to this research. DRM, is the most appropriate methodology for this research as it provides a rigorous structure to approach both the empirical studies and the design intervention development. To illustrate the application of DRM, Table 3.1 summarises the methods used at each stage of the DRM methodology, the outcomes and where these are evidenced in the thesis.

Table 3.1 Summary of Methodology Application

Stage of Research	Methods Used	Outcomes	Related Chapter of Thesis
Research Clarification	Literature Review	Research Question and Hypothesis Formulated	Chapter 2
Descriptive Study I	Quantification of User Exclusion	Scale of exclusion better understood	Chapter 4 and 5
	Task Analysis	Cognitive demand better understood	Chapter 4
	User Observation	Verification of exclusive capability demands	Chapter 4 and 5
	Mental Workload Assessment	Verification cognitive demands excessive	Chapter 5
Prescriptive Study	Paper Prototyping	Initial usability issues identified	Chapter 6
	Simulation and Prototyping	Intended support developed	Chapter 6
	Simulation and Prototyping	Actual support developed as proof of concept	Chapter 6
Descriptive Study II	Usability Testing	Feedback on the support	Chapter 6
	Mental Workload Assessment	Tentative verification of reduced perceived cognitive demands	Chapter 6
	Quantification of User Exclusion	Tentative verification of reduced user exclusion	Chapter 6
	Energy Modelling	Further Work identified for long term in-situ testing Tentative suggestion of scale of expected energy savings	Chapter 7

Chapter 4 - Assessing The Number Of People Excluded By Digital Programmable Thermostats

Abstract

This chapter forms the initial investigation into the scale of user exclusion with regard to digital programmable thermostats. The main contribution of this study is the novel comparison of the Exclusion Calculation results to real world data. This suggests the predictions underestimate exclusion levels for these types of products. It was accepted for publication in May 2010 in the International Journal of Sustainable Engineering and the full version of the paper can be found in Appendix 1.

Calculations performed using the Exclusion Calculator suggest that the current design placed excessive demands upon the capabilities of at least 9.5% of the UK population over 16 years old. This increased to 20.7% for users over 60 years old. In an attempt to validate the results, residents of a low-carbon housing development, designed by Buro Happold, were asked to complete a task using their controls. Of the residents who attempted the task 66% of them were unable to complete it, suggesting that the true user exclusion may be higher.

The calculation also identified the demand placed on the 'vision', 'thinking' and 'dexterity' capabilities were disproportionate. Therefore, a more detailed analysis of the cognitive demands is required to understand where problems within the programming process occur. Further research focusing on the cognitive demands is therefore required. This research will work towards a solution that may allow users to behave easily in a more sustainable manner.

4.1 Introduction

Having identified gaps in the research regarding how people use their thermostats and the difficulty people have using such devices, a pilot study was conducted. The aim of this study is to quantify the level of exclusion relating to the heating controls using the Exclusion Calculator. This estimate of user exclusion then compare this to data gathered at a specific housing development. Using real-world participants, who had lived in their homes for over one year, gave a realistic picture of the level of design exclusion relating to digital programmable thermostats. The participants were all adults under 50 years old and did not disclose any disabilities to be considered. Therefore, any exclusion found would strengthen the argument that more inclusive controls would benefit everyone.

The novel aspects of the study are twofold; the application of the Exclusion Calculator in the context of a digital programmable thermostat and the validation of the calculation results with a trial of real-world users of the control. The study applied the Exclusion Calculator from the University of Cambridge, which highlights the areas likely to result in people not being able to achieve a task. A detailed hierarchical task analysis (HTA) of the controls formed the basis of this calculation to reduce the subjectivity of the assessment. The quantifiable results allowed a comparison of the calculation results with the actual capabilities of users.

This study is not meant as a criticism of the design of one particular control. Furthermore, the study elucidates further understanding of design exclusion issues in heating control design. Through observation of the participants attempting a specific task insights were gained into where design improvements could be made. To this end, recommendations towards improving the design of these specific controls are suggested. The lessons learnt from this study will inform a systematic study of a wider range of programmable heating controls by a more varied group of participants. By identifying these design issues, any subsequent interventions will attempt address these specifically, resulting in a more inclusive and usable solution.

4.2 Materials and Methodology

4.2.1 Design

The study design was based upon the Exclusion Audit process described by Goodman and Waller (2007), which combined a detailed task analysis and a calculation of the level of exclusion based upon user capabilities. This method combines a HTA from ergonomic literature and the Exclusion Calculator from inclusive design research at the University of Cambridge. This type of study design is referred to as 'multi-strategy design' (Robson, 2011) and in this scenario more specifically 'sequential explanatory design' (Creswell, 2003, cited pp. 165 in Robson, 2011). This is distinguished by the collection of quantitative data prior to qualitative data to aid the explanation of the quantitative part of the study (ibid.).

Although two quantitative methods selected did not involve users, the benefits obtained were the added rigour of using the HTA for task analysis and the quantifiable results from the Exclusion Calculator. This part of the study was a desk-based study completed after one visit to the site, which established the controls the participants had available to them.

The final qualitative stage of the study was to involve users to gain a deeper understanding of the exclusion relating to heating controls. This site was preselected due to the wide variance of heat consumption identified during a post-occupancy evaluation of the buildings conducted by Zack Gill (2010). This pilot aimed to achieve the first research objective, "To investigate the validity of existing tools for quantification of user exclusion in a real-world setting", by answering two questions:

1. Are users excluded from using their controls at this particular site?
2. If so, is the scale of this exclusion consistent with the results from the Exclusion Calculator?

To answer these questions users were asked to perform a task, which involved setting the time and temperature twice during a weekday and the same at weekends. This task was both timed and observed by the researcher. Participants gave their informed consent and the study was approved by the School of Engineering and Design Research Ethics Committee on 4th February 2010.

4.2.2 Procedure

The study procedure involved two site visits and a desk based study of the controls. Firstly, a visit to the site was made to discern what type of controls the residents had available to them and the level of functionality of the controls. Based upon this, an example task was developed for use in the HTA, which was defined as, "Set the home to heat for a whole week". The HTA assisted in providing a more objective assessment of the controls using the Exclusion Calculator.

The second site visit involved the in-home observation of the residents as part of the wider post-occupancy evaluation interviews. Upon conducting the HTA the complexity of such a task became apparent. Hence, the task was simplified to entering four individual settings for the entire week to reduce the length of time the task would take to avoid overwhelming the participants. This task required the residents to enter two setting on the controls, one in the morning at a specified temperature and a second specified temperature in the evening, for both weekdays and weekends. However, the system had the capability to enter five different settings per day.

Upon obtaining the residents consent, the original thermostat settings were recorded. Prior to the test the controls were reset to the factory default settings in order to give a consistent starting point for each participant. The participants were allowed to use the product instructions displayed on the inside of the panel door to aid them, however, no assistance was provided by the researcher during the test. To finish the test the participant either had to indicate they wished to stop the task or that they had finished to the researcher. The participants then returned to the main interview, while the researcher restored the original thermostat settings.

4.2.3 Participants

To estimate the true exclusion of the heating controls, 12 residents were asked to complete a task using the controls while being observed and timed. These participants consisted of 11 females and 1 male who lived in the Elmswell 'Clay Field' Housing development. The predominantly female sample reflected the occupants of the houses during the daytime. The site, shown in Figure 4.1, comprises 13 two-bedroom and 9 three-bedroom houses, plus 4 one-bedroom flats, each constructed to the same design specification. The development was awarded BRE's EcoHomes Excellent certification and it exceeded the requirements of the Building Regulations for UK dwellings.

Figure 4.1 The Houses at the Elmswell "Clay Field" Development

4.2.4 Methods

The heating control design under study is the Salus RT500 used within the domestic environment to control the heating system. It does not control hot water consumption within the home, which is instantaneous. Both the duration and temperature of the heating can be specified for up to three periods per day. Once the user has located the control, they are required to open the control panel door and select whether they want to set the time and temperatures for the weekdays or the weekend. This is done using the arrow buttons and the select button, as shown in Figure 4.2. For each of five time intervals, the temperature needs to be specified, again using the arrow buttons and the select button. This is then repeated for both weekdays and weekends. Once a temperature has been specified for each time interval, the set button is pressed to ready the system and the door is closed. Relevant dimensions of the interface are also shown in Figure 4.2.

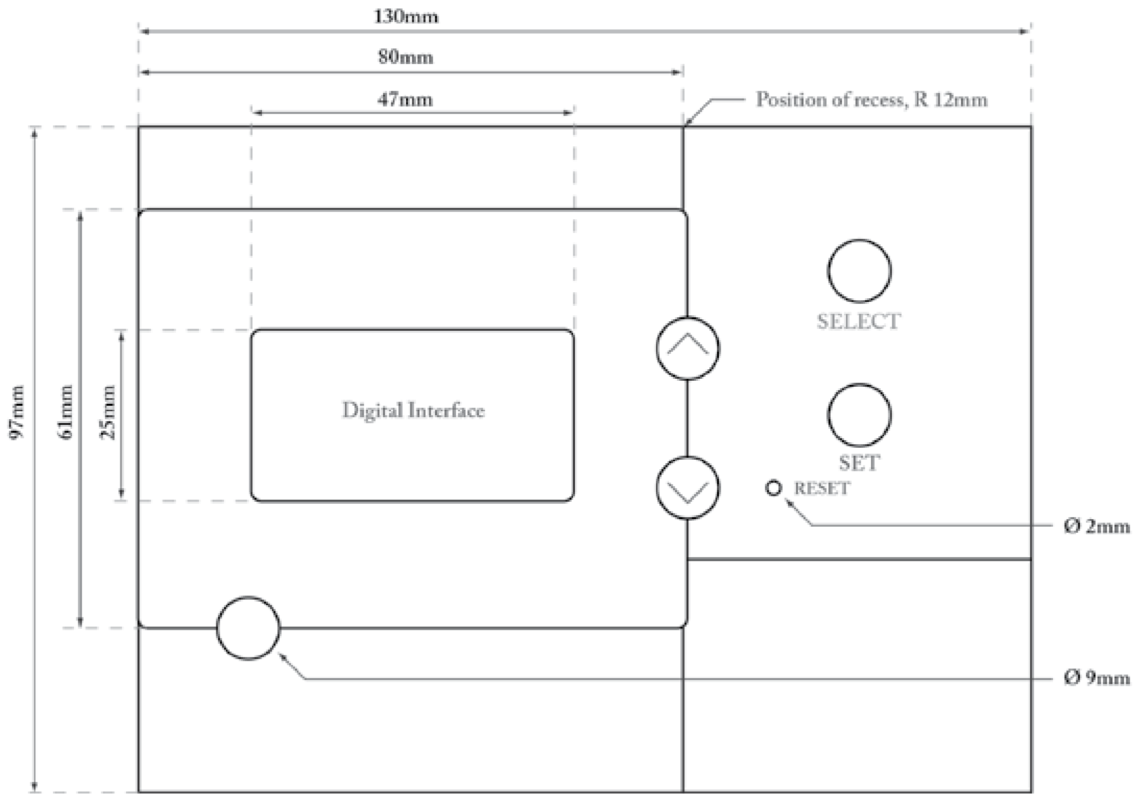


Figure 4.2 Interface Available to Users

4.2.4.1 Hierarchical Task Analysis

A HTA was conducted to clarify the tasks required to programme the control. HTA works by breaking down a task into its individual parts and identifying which parts of the task may result in errors. The HTA, shown in Figure 4.3, shows the 27 decision tasks, as well as a range of physical and sensory tasks, which must be completed in a specific order to achieve the goal of programming the control for a whole week. The same HTA has been colour coded to give a visual representation of the main capability required to complete the specific task or subtask detailed in the analysis (shown in Figure 4.4).

Although many of the individual tasks were physically similar (e.g. pushing a button), the complexity of the system lay in the cognitive element of the task. The plans on the HTA illustrate the cognitive processes (decision tasks are shown in the diagram in the diamond-shaped boxes), while the rectangular boxes represent tasks of a physical nature. In order to achieve the overall goal of heating the home, it is necessary for the user to complete all of these tasks in order from left to right.

Figure 4.3 Hierarchical Task Analysis of the Digital Programmable Thermostat

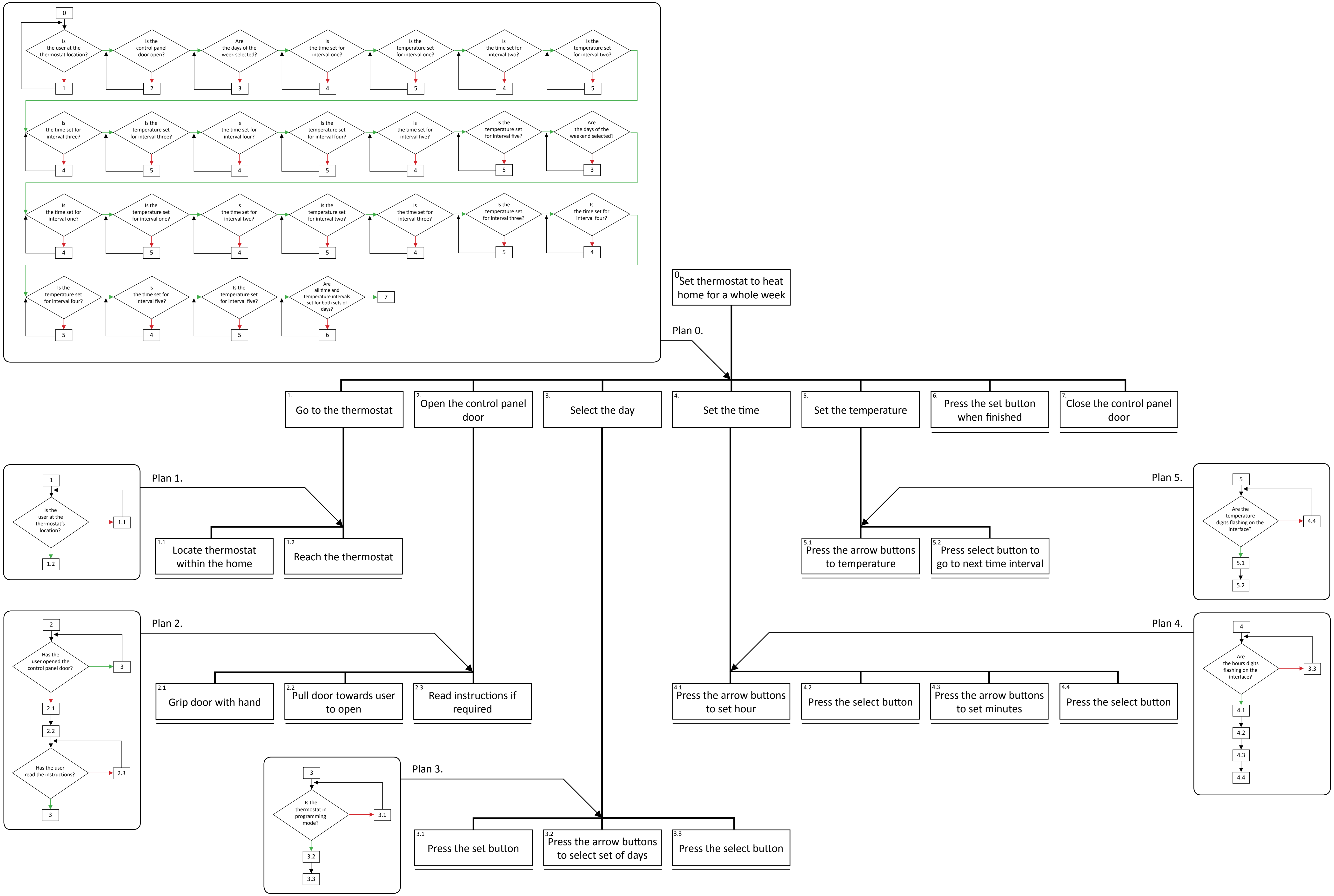
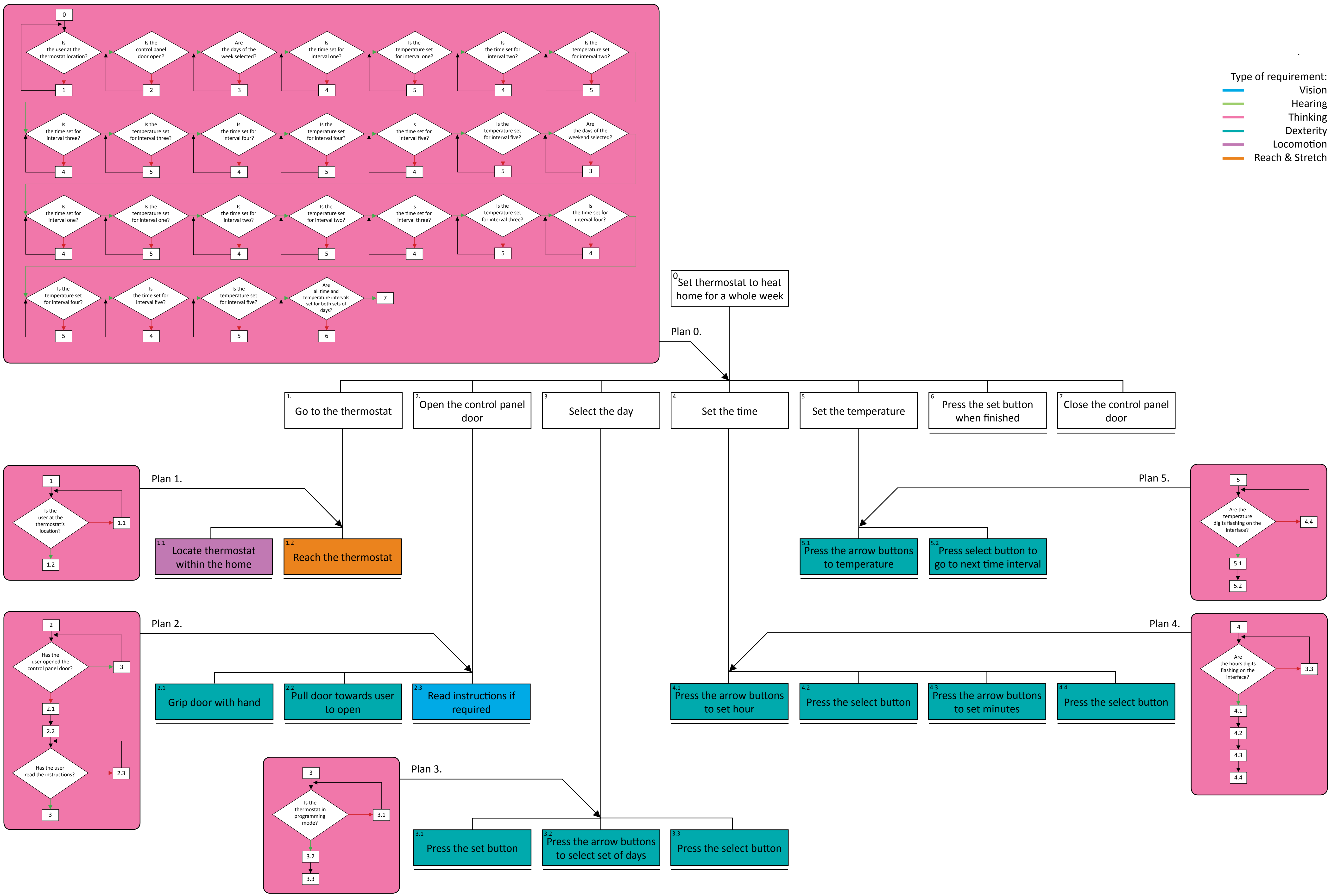


Figure 4.4 Hierarchical Task Analysis of the Digital Programmable Thermostat, Colour Coded by Main Capability Demand



4.2.4.2 The Exclusion Calculator

The Exclusion Calculator was used to ascertaining the level of demand required to complete the task. This requires the analyst to choose between generic demands, such as reading text or recognising a person at distance, and then setting the appropriate level of demand. Table 4.1 details the options selected and the justification for the level of demand set by the researcher, which form the basis of the calculation results. In some cases, the level of demand is difficult to judge, however, it can be set along the scale between two demand examples. For example, the dexterity required to open the control panel door is felt to be between picking up a safety pin and holding a pen. The calculation is based on a subjective analysis of the capability demands of using the control, which may cause variable results and induce errors. Experience of the analyst is therefore critically important.

Table 4.1 Assessing the Type of Demands of the System

Capability	**Type of Demand**	**Level of Demand**	**Reason for Choice**
Vision	Reading text at various distances	Read ordinary newsprint	Small instruction text inside door and small size of text on digital interface
Hearing	None	None	The system has no audio feedback
Thinking	Think clearly without muddling thoughts Do something without forgetting what the task was while in the middle of it Tell the time of day without any confusion Count well enough to handle money Remember a message and pass it on correctly	Not applicable	The thought process primarily has to deal with sequences and number These phrases were judged most relevant to the scales available

Table 4.1 Assessing the Type of Demands of the System (continued)

Capability	Type of Demand	Level of Demand	Reason for Choice
Dexterity	Performing fine-finger manipulation with either left or right hand	Between "pick up a safety pin" and "use a pen"	To open the control panel door, the top and bottom of the door must be gripped then pulled to open and pushed to close
Reach and Stretch	Reaching one arm out for a long period	Reach one arm out in front (for long periods)	Controls are manually operated and situated in front of the user
Locomotion	Walking various distances on level ground	Below "Walk 50m without stopping"	Transfer to control system is likely to be less than 50m

The limitations of the Exclusion Calculator must also be considered at this stage. The calculation results represent the number of people excluded by the product not the number of households. It is likely that someone within the household could potentially use the controls, however, this is not consistent with the social model of disability used in inclusive design.

4.2.4.3 Observation of Users

Observing users in their own homes was felt to be representative of typical use of the controls and where users experienced problems in the task. During the post-occupancy evaluation of the Elmswell development, an interview was conducted with residents. This was divided into general lifestyle questions and then questions regarding occupants' water, heating and electricity consumption. After the section of the interview regarding heating consumption, participants were asked to complete a task using their heating control system, which was observed by the researcher. The task was to set their heating controls to match the heating profile given in Table 4.2.

Table 4.2 Task Settings Provided to Participants

Day	**Time**	**Temperature**
Monday - Friday	6am	19°C
	7pm	22°C
Saturday and Sunday	6am	21°C
	10pm	17°C

4.3 Results Part I - Applying the Exclusion Calculator

The results of the Exclusion Calculator are presented in this section alongside a discussion of design improvements, which could help reduce design exclusion. The results of the HTA are presented in Figures 4.3 and 4.4 shown previously. However, these results are also considered in the discussion of the results in Section 4.4.2.

4.3.1 Results of the Exclusion Calculation

According to the Exclusion Calculation results, the controls currently exclude approximately 9.5% of the UK population aged between 16 and 102 (see Table 2). User exclusion increases dramatically to 20.7% for the sector of the population that is over 60 years old (see Table 4.3). This is broken down by the type of capability requirement as follows in Tables 4.3 and 4.4, with thinking, vision and dexterity being the largest demands placed upon users.

Table 4.3 Calculated Exclusion (people aged 60 – 102)

Capability requirement	**Number of people excluded aged 16-102**	**Percentage of population aged 16-102**
Vision	1 525 000	3.4%
Hearing	0	0%
Thinking	2 070 000	4.5%
Dexterity	1 670 000	3.7%
Reach and Stretch	318 000	0.7%
Locomotion	895 000	2%
Total Exclusion*	4 327 000	9.5%

* Total adjusted by calculator to account for overlap between disabilities

Table 4.4 Calculated Exclusion (people aged 60 – 102)

Capability requirement	**Number of people excluded aged 60-102**	**Percentage of population aged 60-102**
Vision	1 009 000	8.6%
Hearing	0	0%
Thinking	964 000	8.2%
Dexterity	981 000	8.4%
Reach and Stretch	200 000	1.7%
Locomotion	580 000	5%
Total Exclusion*	2 430 000	20.7%

* Total adjusted by calculator to account for overlap between disabilities

The results confirm that a large cognitive demand is placed upon users, which became apparent at an early stage through the use of HTA. The advantage of the calculation results are that it allows the most demanding capabilities to be prioritised relative to each other. Furthermore, it is important to consider different age ranges, as the prevalence of disability increases with age.

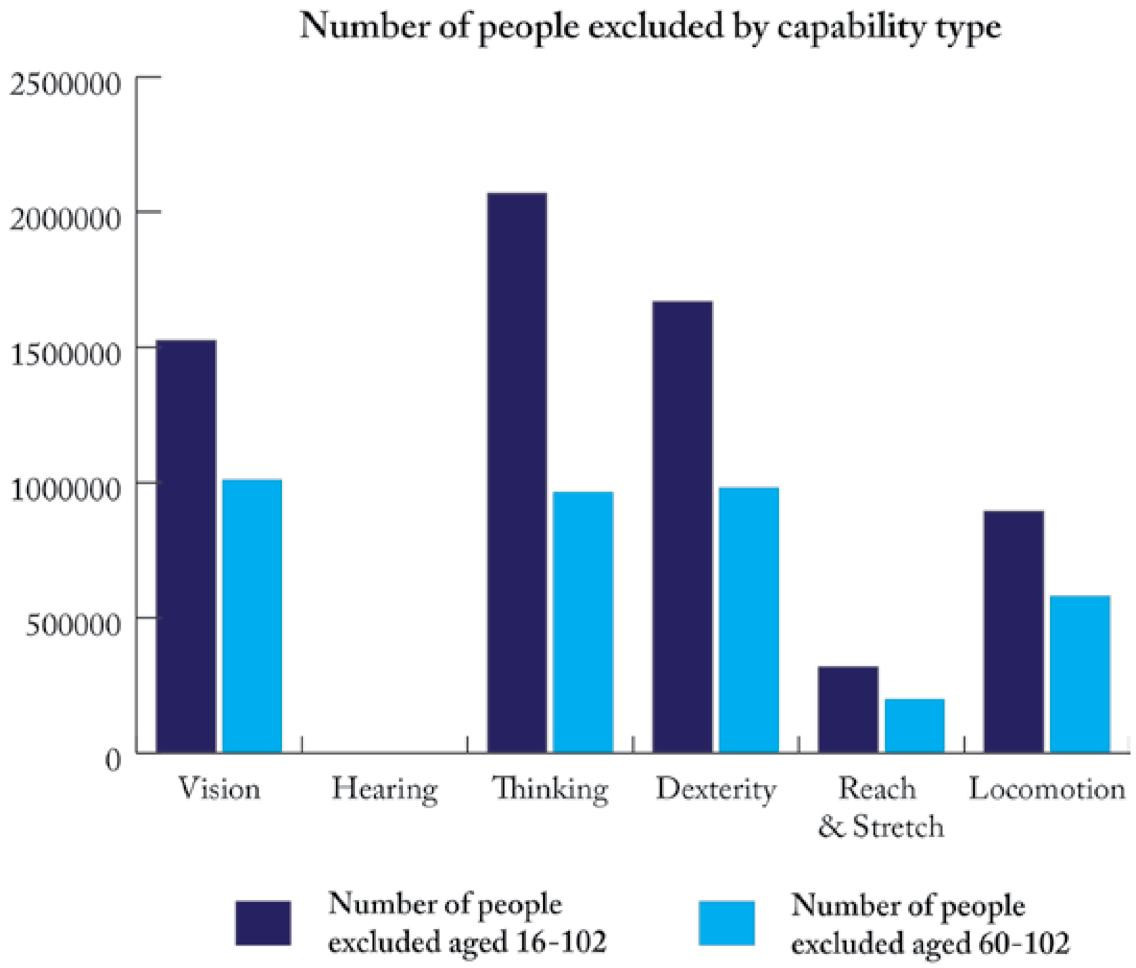


Figure 4.5 Number of People Excluded by Capability

In order not to count people with multiple capability loss twice, when the demands are too high for a person to complete tasks, they are marked. Once marked, this person will be excluded from any further results where another demand is beyond their capability. This explains why the total exclusion is not simply the sum of all the excluded people given in the results Tables 4.3 and 4.4.

4.3.2 Discussion

The three areas found to be excluding the largest number of people are 'vision', 'dexterity' and 'thinking' requirements. Future design effort should concentrate on trying to reduce the requirements in these areas. A summary of the most effective improvements includes:

- Provision of audio feedback
- Larger, higher contrast, buttons
- A larger, clearly laid out screen
- Improved tactility of the interface
- Simplified programming
- Removal of the control panel door

4.3.2.1 Sensory Requirements

To reduce visual demands it is important to pay particular attention to the digital interface and the information it conveys. The layout and presentation of this information is also crucial in reducing the cognitive demands. Currently, the area of the digital screen accounts for less than 10% of the whole interface. This is extremely small for such a critical part of the control. The layout of the information is crowded, the size of the display text is small and there is little visual contrast between the text and the background, all of which place large visual demands upon the user.

No audio feedback is provided by the system at present; therefore, there are no hearing requirements. However, the provision of audible feedback could help users, particularly those with visual impairments. Audio feedback could also be haptic by confirming the current settings of the control, which could in turn improve user confidence in the system and encourage adjustment as appropriate.

4.3.2.2 Cognitive Requirements

From a cognitive perspective, it is not necessarily the number of tasks required that proves difficult but the complexity of the overall task, the repetitive nature and the lack of flexibility within the system. The volume of information provided in such a small space on the digital interface may also increase the cognitive demands on the user, leading to confusion. When a mistake is made there is no facility to go back to a stage, resulting in frustration for the user. The system also requires an understanding of temperature scale, which some users may find difficult and somewhat abstract nature.

4.3.2.3 Dexterity Requirements

There are two dexterity requirements to be addressed: the opening of the control panel door and the pressing of the buttons. Opening the control panel door is the more exclusive of the two actions, as it requires substantial grip strength from one or both hands, a potentially painful but essential step for the user. Removing the door completely would result in the biggest reduction in exclusion related to dexterity. Pushing the buttons does not require a significant level of force, however, improving their contrast and size could reduce visual and dexterity demands further.

4.4 Results Part II - Comparing the Exclusion Calculator Results to Real World Exclusion

To relate this user exclusion to a real-world context, a study was designed to assess whether or not the occupants at the Elmswell 'Clay Field' Housing development could use their controls successfully. As part of a comprehensive post-occupancy evaluation study at the site, the heat energy consumption of each occupied dwelling was monitored. The data showed that average annual heating consumption accounts for 54% of the total energy consumed within the dwelling. Average heating consumption was 73kWh/m^2/year, including space heating and hot water. Within individual dwellings this consumption ranged between 46 and 145 kW h/m^2/year. Low in-use carbon emissions and utility consumption is facilitated by the measures highlighted in Figure 4.6.

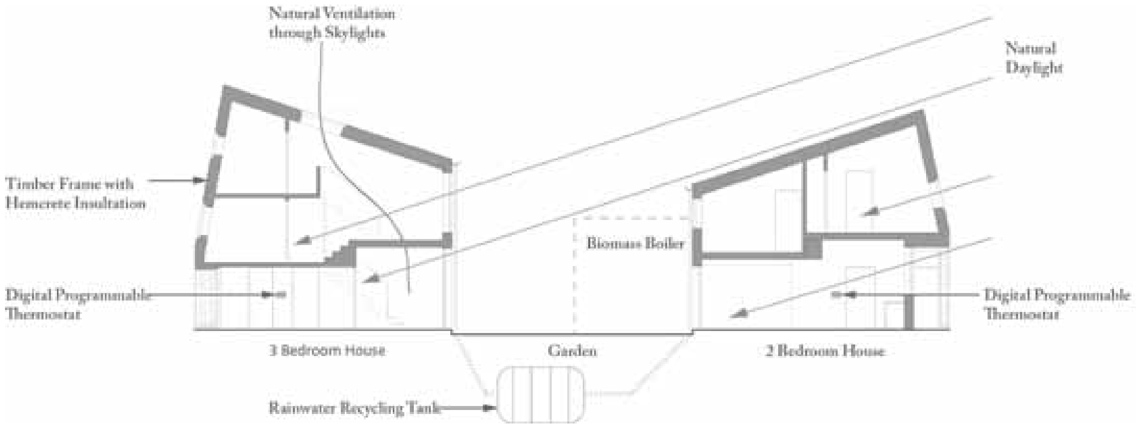


Figure 4.6 Sustainability Features of the Development

According to an Organisation for Economic Co-operation and Development (2000) report, approximately 20% of the UK adult population have difficulties with basic literacy. These figures increase to 40% of the population when considering those who have difficulties with basic numeracy (DfEE, 1999, cited in McIntosh and Vignoles, 2000). This implies this alone could exclude around 9 million adults over 16 years old, using 1997 population figures. These people would not perhaps be classed as having a disability and consequently would not be counted under the Disability Follow-up Survey (Grundy et al., 1999). Combining this with the results of the Exclusion Calculation, the exclusion could be in the region of 30% of the UK adult population.

4.4.1 Task Completion Results

Of the 12 participants, 8 could not complete the task (66.6% of the sample). The average time before participants stopped and gave up was 2 minutes and 38 seconds while the four participants who could complete the task did so in an average time of 1 minute and 34 seconds. The times participants spent attempting the task whether they were successful or not is shown in Figure 4.7.

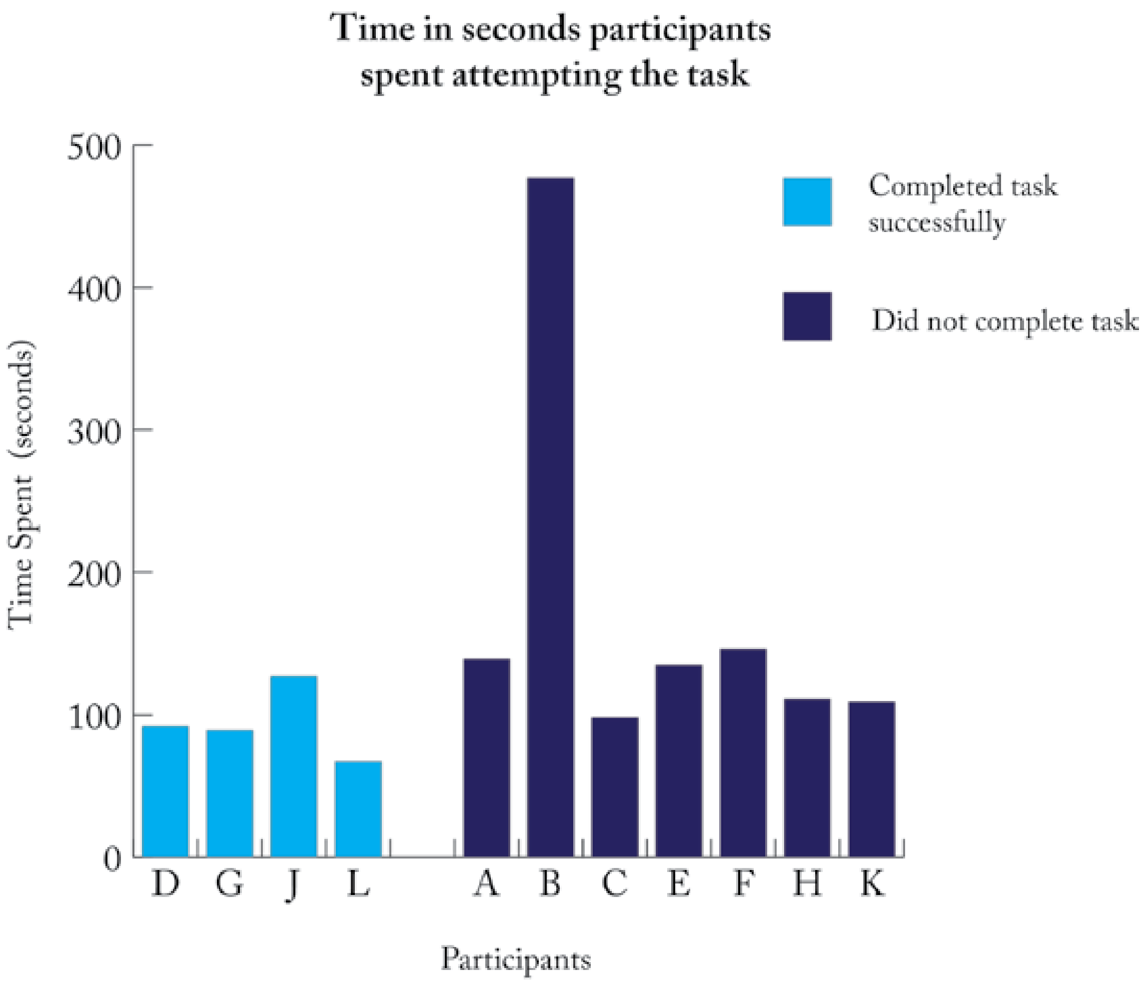


Figure 4.7 Time Spent Attempting Task

Of the participants, four admitted another member of the household was responsible for the programming of the controls. A further four participants, who were the sole users of the controls within the house, admitted they did not know how to use the controls before attempting the test. It is pertinent to note that the maximum and minimum consumers on-site both occupied three-bedroom dwellings. These households had similar occupancy in terms of the number of occupants and time spent in the house and both participated in the usability testing.

Prior to attempting the task, one participant stated "I don't really know how [to use the controls], it's stupid, I just use the up and down buttons", which with a default 17°C set-point, may help to explain their low consumption. In comparison, the maximum consumer whose set point was always above 21°C said "well I'll tell you now, no I can't use it" despite being part of the minority who could programme their controls. Additionally, the participant expressed an interest to receive help to programme the settings more efficiently. The intimidating perception of the controls deterred the occupant from making changes to reduce consumption. Furthermore, in the initial lifestyle questions, one other participant stated that "I'm struggling to program it [the heating] to come on when I want it to". This implies that the inability to use their controls was a problem of high priority.

4.4.2 Observed Issues with the Controls

Three common problems participants encountered were:

- The controls not being intuitive enough to use without help of instructions
- Participants not entering programming mode and instead resetting the clock repeatedly, hence the instructions not fulfilling their role
- Pressing the set button instead of the select to attempt to move between time or day settings

All participants used the instructions, shown in Figure 4.8, as reference, and two spent the first 30 – 40 seconds of the test reading them before pressing any buttons. The first instruction given in the controls was how to set the system clock and not programming the heating system, which came second. This resulted in the second problem of repeatedly resetting the clock rather than entering programming mode. This resulted in two users thinking they had completed the task successfully when they had not.

Figure 4.8 Instructions Shown on Inside of Control Door

A further common error made was that participants struggled to move from one stage in the process to the next as they instinctively pressed the set button after they entered the first time and temperature settings. This exited the programming mode and sent the participant back to the start of the process, which commonly resulted in frustration for participants. Although the sample size was small, it was representative of the occupants of the development, all of whom had all lived there for over 1 year. As a result, the findings are only valid for this development and may not be representative of the general population.

4.5 Conclusions

The control design under study was estimated to place excessive demands on the capabilities of at least 9.5% of the UK adult population, with this exclusion doubling for users over 60 years old. These calculation results were estimates according to the Exclusion Calculation. The three most demanding capabilities were found to be vision, thinking and dexterity. Design efforts should centre on reducing these demands as a priority. It was confirmed that many of the users at this development could not interact effectively with their controls, with 66.6% of the sample unable to complete the programming task. Secondly, the calculated exclusion significantly underestimated the actual exclusion found at the site.

There is a consensus in the literature that efficiently programmed heating controls can save energy, yet, usability problems are little understood. More detailed analysis of the cognitive demands is required to understand where problems within the programming process occur. A reduction in the cognitive demands placed upon users should make the heating controls easier to use. By designing a more inclusive control system, heating controls may be used more effectively, decreasing associated energy consumption. With this focus on how people interact with heating control systems within their homes, a solution that allows users to behave easily in a more sustainable manner may be achieved.

Chapter 5 - Investigating Usability and Exclusivity Issues Amongst Older Users For a Range of Digital Programmable Thermostats

Abstract

As highlighted in the conclusions of Chapter 4 there was a need for greater understanding of the barriers to effective use of digital programmable thermostats, especially the reasons behind the excessive cognitive demands. This study elicits the reasons for user exclusion in relation to three digital programmable thermostats. Specifically it examines usability issues older people (aged 60-80 years old) experience when using the thermostats. The findings were accepted by the Journal of Engineering Design for publication in June 2011 and a full version of the paper can be found in Appendix 1.

Exclusion calculations were used to estimate the percentage of the population excluded from the use of three digital programmable thermostats. Full user testing was then conducted to identify usability problems of such products. The participants were 14 younger users (aged 24–44) and 10 older users (aged 62–75). Similarly to the previous study, the exclusion calculations underestimated the actual exclusion significantly for both age ranges ($p < 0.05$). Additionally, the cognitive demands of these systems were evaluated using a subjective workload assessment method, based on the NASA Task Load Index, and were found to be excessive. Observations of the users are reported to highlight areas of particular confusion during the task.

This study makes recommendations to facilitate the design of more inclusive digital programmable thermostats. It is argued that such changes could result in reductions in domestic heat energy consumption, principally by eliminating the confusion regarding on and off times. A further outcome of the study was the development of a set of interface guidelines. It is thought that by considering the ten points described during the design process, more inclusive and usable interfaces could be produced.

5.1 Introduction

The goal of this study is to understand usability problems associated with three heating control interfaces, especially those issues that may lead to increased energy consumption. The aim is to understand in detail the cognitive reasons for user exclusion to help enhance the design of future products. The study also achieved the second research objective - to understand the scale of and the reasons for user exclusion relating to heating controls products, especially amongst older users. Specifically it aimed to understand where the cognitive demands of programming the controls in an energy efficient manner were excessive for users.

The Exclusion Calculator is used to estimate the number of users excluded by each product. Subsequently, the estimated exclusion is compared with the actual exclusion found through usability testing. This study responds to the call in the literature from Peffer et al. (2011) which highlights the lack of usability studies concerning advanced digital programmable thermostats. This study investigates why some users, older users in particular, have difficulties in using heating controls effectively. Hence, usability testing has been performed with two user groups.

One outcome of the study is a set of design principles for heating controls and energy management systems, which have been formulated based on the user observations. The consideration of these design principles at the start of the design process may help the design of more usable and inclusive interfaces. By designing controls inclusively, in order that pro-environmental behaviour is easily accomplished, considerable energy savings could be made.

5.2 Materials and Methods

A range of data collection methods were used to gather both qualitative and quantitative data. A full explanation of the methods used including the Exclusion Calculator, the Raw NASA Task Load Index scales (RTLX, Hart and Staveland, 1988) and usability testing, can be found in Chapter 3. Direct user involvement is strongly recommended in inclusive design research and when trying to understand the cognitive demands of a product. This section discusses the study design, procedure and the application of the research methods.

5.2.1 Design

The study design was multi strategy to illicit in detail the difficulties users had when trying to interact with digital programmable thermostats. A within-group study design was utilised to reduce the number of participants required during the user testing. This allows the same participants to complete the testing with multiple controls. However, this has the disadvantage of potential learning effects from the experience and fatigue, especially with the older user group (Lazar, Feng and Hochheiser, 2010).

The study used a quantitative initial assessment using the Exclusion Calculator, qualitative observations during the testing and finally a quantitative evaluation of the user experience by the participants themselves. The Exclusion Calculator served as a basis for understanding the expected exclusion and where capability demands were deemed excessive. This allowed the observations to look specifically for issues relating to dexterity, vision and cognition.

As an extension from the Exclusion Audit process, the RTLX scales were utilised. This helped participants convey the cognitive demands of using the products in a quantitative manner. The RTLX assessment is not commonly used in inclusive design research. However, this evaluation gave insight into the overall experience for the participants and provided quantitative data to support the user observations.

5.2.2 Participants

The participants of the study were 14 self-selected people working in the Buro Happold London office and 10 from the Brunel Older People's Research Group. The group from Buro Happold were aged between 24 and 44 (mean = 28.7 years, male = 8, female = 6). In comparison, the participants at Brunel University were between 62 and 75 years old (mean = 69.6 years, male = 5, female = 5). Participants gave their informed consent and the study was approved by the School of Engineering and Design Research Ethics Committee, Brunel University.

5.2.3 Procedure

The study procedure, shown in Figure 5.1, is similar to the Exclusion Audit process described by Waller, Langdon and Clarkson (2009). This audit process aims to consider the range of capability losses across a specified population sample, in this case the UK. This study uses a combination of exclusion calculations, user testing and subjective mental workload assessment to establish the usability and exclusion issues with current control systems.

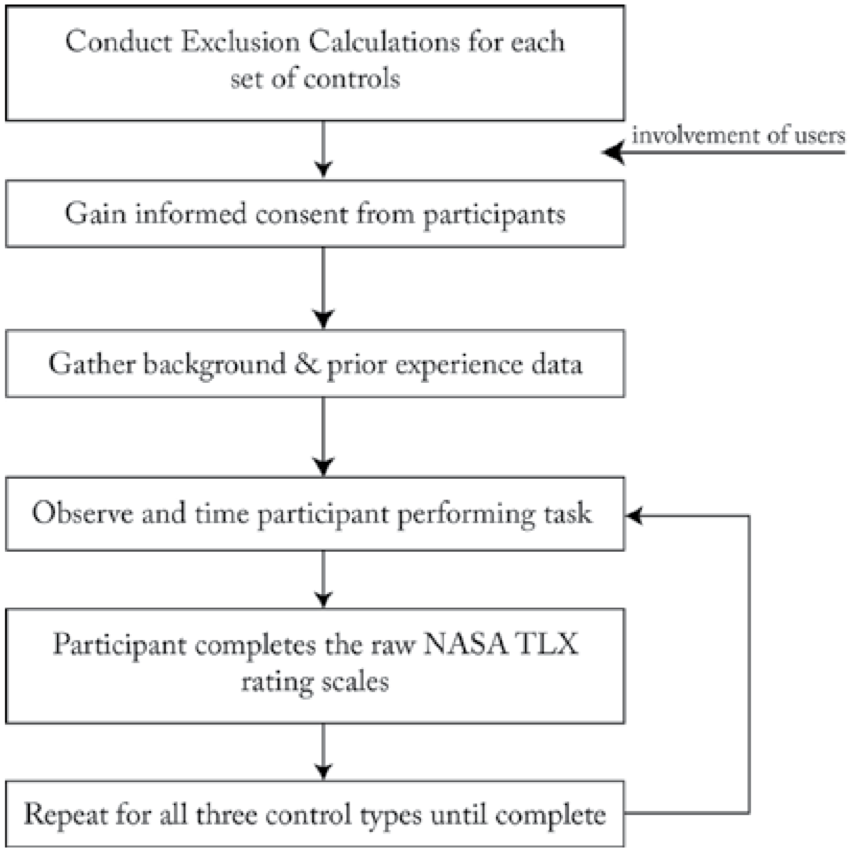


Figure 5.1 Illustration of Study Procedure

Firstly, exclusion calculations were completed on each set of controls prior to involving users. Then, a paper-based survey gathered demographic data and information regarding prior usage of digital thermostats, computers and mobile phones. Participants were then asked to perform a set task to programme each of the controls while being observed and timed. This assessed the ease of learning of the interface, task performance time and level of instruction use. Lastly, perceived mental workload was assessed by completing the RTLX scales directly after the completion of each task.

5.2.4 Methods

5.2.4.1. Exclusion Calculation

Each control was assessed prior to the usability testing to indicate which capabilities would be most demanding and to estimate the percentage of users who would not be able to complete the task. The calculations were conducted for the population as a whole (age 16-102) and specifically for the older age group of the participants (age 60-80 years old). Earlier applications of the Exclusion Calculator are discussed in Section 3.3.2.4.

5.2.4.2 Usability Testing

Two groups of participants were asked to perform a task which involved setting both an on and off time and a temperature twice during a weekday and the same at weekends. The metrics evaluated in this study were task performance, time taken and use of instructions. The time taken for the user to either complete the task or ask for the instructions was measured using a stopwatch. Once the instructions were provided, the time the users engaged with the instruction manual was also measured. Task success and use of instructions were recorded for each user.

The controls were presented to participants in a systematic manner to ensure that learning effects from the controls were minimised. This method of presenting the controls in a specified order ensured that each control was presented first, second or third the same number of times.

The researcher observed the task to determine where errors occurred in the programming process and the process was audio-recorded to capture user comments. The end time was determined either by the participants asking to stop the task or by the participants telling the researcher that they had completed the task.

Both groups of participants were given the scenario to set a heating controller to heat the home during specified hours. The participants were given the opportunity to ask for clarification of the instructions. The settings used in the task are detailed in Table 5.1, and at any other occasion, the temperature was to be left at the default setting. These instructions were detailed in written and tabular format and the researcher provided no further help during the task.

Table 5.1 Settings Used in the Task for the Usability Testing

Day	**Time**	**Temperature**
Monday - Friday	7am-9am	19°C
	4pm-11pm	21°C
Saturday and Sunday	7am-9am	19°C
	6pm-10.30pm	21°C

5.2.4.3 Raw NASA Task Load Index

Considering the current limitations in assessing thinking demands using the Exclusion Calculator, an additional method of rating cognitive demands has been used in this study. Using a subjective rating scale rather than task-related or physiological measures is less intrusive to task performance and the user respectively. Users were asked to complete the paper-based rating scales directly after completing the task with each controller. The raw scales were used in this study to simplify the process given the strong correlation between TLX and RTLX found by Byers, Bittner and Hill (1989, see Section 3.3.1.4).

5.2.5 Selection of Devices

Digital programmable thermostats are one of a range of heating controls available to users offering control over both temperature and duration of heating. The decision to focus on digital programmable thermostats is consistent with the industry move from manual to digital interfaces. The controls selected for this study, all digital programmable thermostats, were the Honeywell CMT927, Siemens REV24-RF and Drayton Digistat+3RF. All of the selected controls allow programming for both the weekdays and weekends with three sets of periods per day.

The device interfaces shown in Figures 5.2, 5.3 and 5.4 have the key functions required in completing the task. Each of the controls works in a different manner; the Honeywell control (Figure 5.2) works on an individual day basis, where once one day is programmed, the settings may be copied to other days. In contrast, the Drayton and Siemens controls allow programming blocks of days. The Siemens control (Figure 5.3) requires a slider to be moved across the bottom of the product, demanding a large amount of dexterity from the user. The Drayton control (Figure 5.4) provides functionality that is the same as that of the other controls; however, it has only four buttons for the user to interact with.

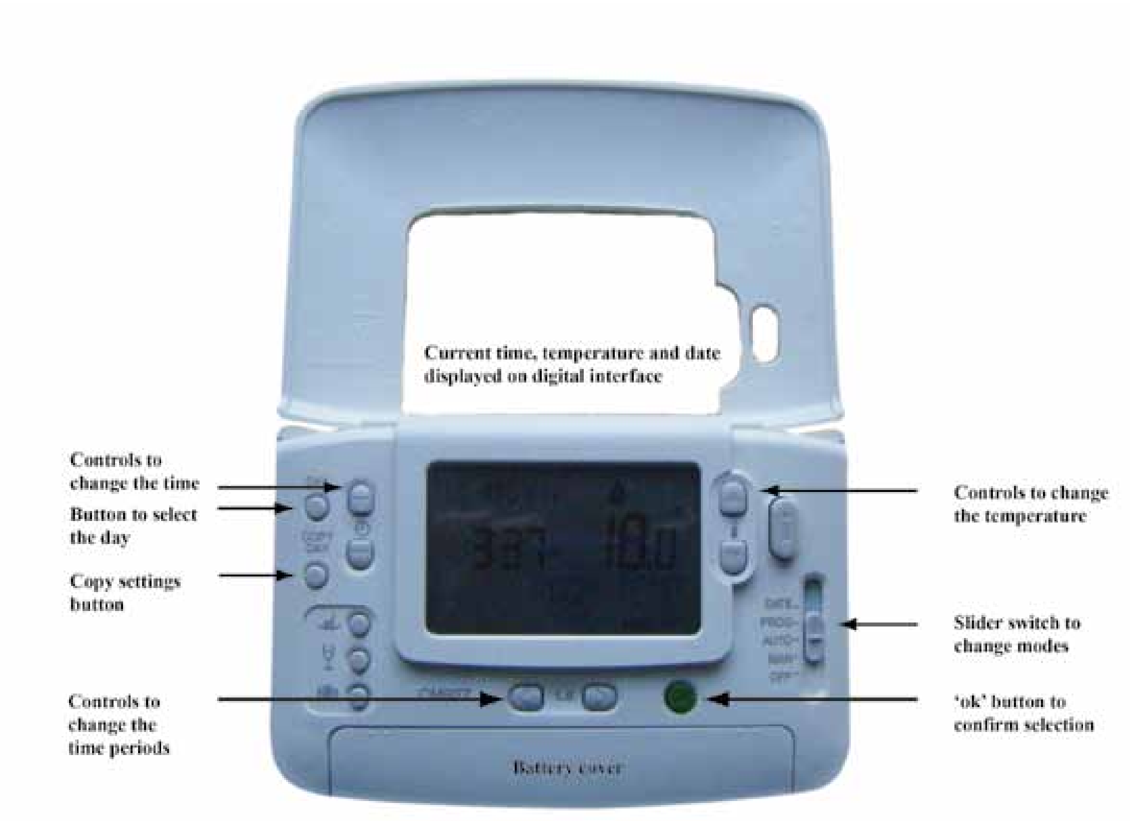


Figure 5.2 Honeywell CM927 Control Interface

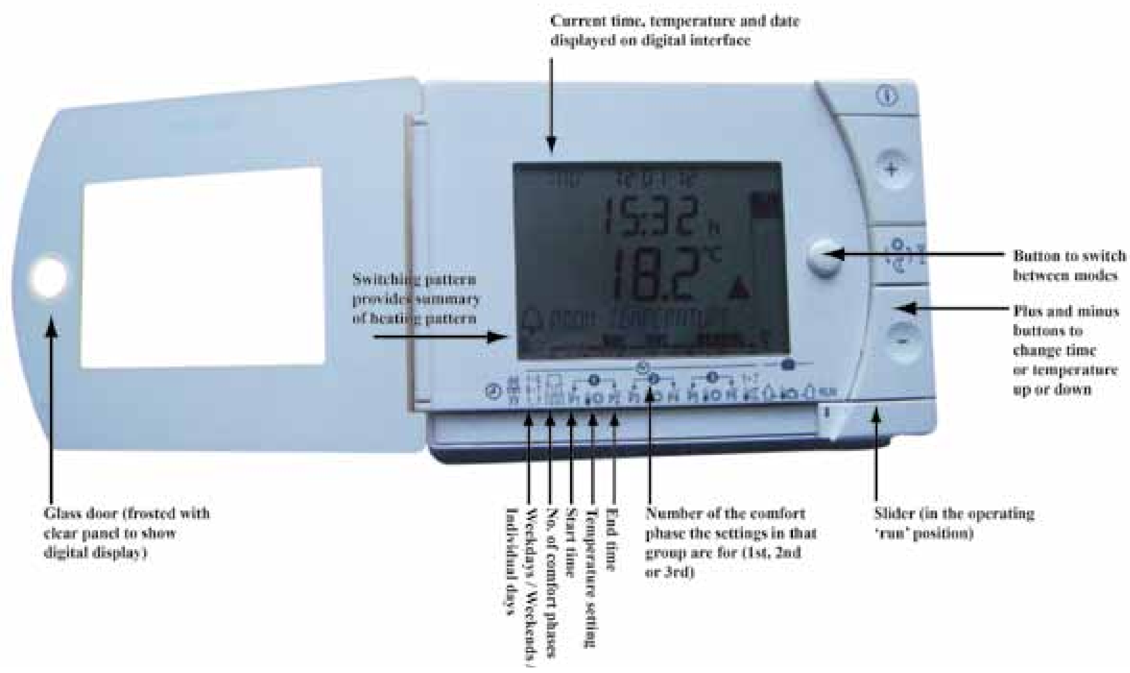


Figure 5.3 Siemens REV24-RF Control Interface

Figure 5.4 Drayton Digistat +3RF Control Interface

5.2.6 Variables

The users' ability to complete the task may have been influenced by prior experience with a digital programmable thermostat. Therefore, prior experience was assessed in the questionnaire before attempting the task. It was found that 5 younger users and 6 older users did have a digital programmable thermostat at home. However, of these 11 people, 4 admitted that they were not the primary users of the controls within their home.

Participants also detailed their prior experience and current usage of computers and mobile telephones. In terms of computer usage, all younger users and 7 of the older users used a computer on a daily basis. Mobile phone usage varied more. Again, all younger users used a mobile phone on a daily basis to make phone calls and send text messages. This compared with 8 of older users who had a mobile phone with only 1 using it on a daily basis. This technical experience may have contributed to the younger users' success in the task.

To minimise learning effects and bias of results, the order in which the users received the controls was varied. The controls were reset to the default programme for each user and the current date and time were preset to the correct values. Testing was held in two meeting rooms that were artificially lit, with appropriate lighting levels.

5.2.7 Statistical Analysis

For the quantitative results, various statistical analyses were conducted; Chi-square tests, one-way repeated-measures analysis of variance (ANOVA), one-tailed t-tests and

2x3 ANOVA for comparison between the NASA TLX measures. These are summarised in Table 5.2 below.

Table 5.2 Statistical Analysis Methods

Statistical Method	Applied To
Chi Squared test	Exclusion Calculation results
One-way repeated measures ANOVA	Task completion time
One-tailed t-test	Instruction usage between groups
2x3 ANOVA	NASA TLX results

A Chi-square test was used to compare the expected frequency of exclusion (based on the exclusion calculation) to the actual frequency of exclusion for each age group. This use of Chi-square is a 'goodness of fit' test, according to Hinton (2008) to establish whether there is a significant difference between the observed and expected frequencies.

Due to the use of multiple heating controls a one way repeated measures ANOVA was selected to analyse the time spent attempting the task for both user groups. This is particularly applicable when using the same participants across different conditions (Hinton, 2008).

One-tailed t-tests were used to establish the difference in the younger user group only between those who were successful in completing the task with and without the instructions. The one-tailed t-test is applicable as a direction is anticipated in this difference, i.e. the participants will take significantly longer to complete the task successfully when using the instructions.

To understand where the interaction occurs between the multiple factors of the RTLX a 2x3 factorial ANOVA is used (age group vs. control type). This method allows comparison between the two user groups and between the three controls tested. The statistical analysis of the RTLX results, reported in Section 5.3.5, was completed using SPSS by Dr Mark Young of Brunel University, a co-author on the associated paper.

5.3 Results Part I - Quantitative Results

The outcomes of this study are presented in the order in which they were assessed. First, the exclusion calculation results are presented and the most demanding capabilities are highlighted. Secondly, task performance is discussed in terms of performance times, success and instruction use. Lastly, insights regarding the perceived workload placed upon the users are described.

5.3.1. Exclusion Calculation Results

Prior to commencing the usability testing, exclusion calculations were conducted on each set of controls. This exclusion is solely for the programming task, which requires no hearing or locomotion capabilities. The calculations were performed for two age ranges, 16–102 years (the maximum available data) and 60–80 years (to represent the older users).

The Drayton control was seen as the least exclusive of the three controls, excluding 7.5% of the population aged 16–102 years and 13.5% of people aged 60–80 years. This is because there is no door to open and only four buttons are available to the users. As a result, the thinking capability is judged the most exclusive for this set of controls.

For the Honeywell control, the result was an overall exclusion of 8.25%, and an increased exclusion of 15.5% for the older user group. Again, the thinking capability was the most exclusive capability for the Honeywell controls, followed by the visual demand.

The Siemens control was viewed as the most exclusive of the three controls, excluding 9.5% of the population aged 16–102 years and 18.2% of people aged 60–80 years. In contrast to the Honeywell and Drayton controls, the most exclusive capability for the Siemens control is dexterity due to the high demands of the slider, followed by the cognitive demands.

5.3.2 Task Performance Results

Overall, older users found the task complex and frustrating. None of the older users completed the task successfully with any of the controls. Therefore, the older participants' results are not shown in Figures 5.5 and 5.6. Younger users had greater task success, with the number of successful younger users, and their use of the instructions, shown in Figure 5.5.

With the Siemens control, 12 of the younger users were successful, 8 without the use of the instructions. This was followed by 10 of the 14 users being successful using the Honeywell control. The Drayton control is the only one of the three controls tested on which the younger users spent longer time than the older users, both with and without the instructions. This is partly to do with the length of time taken by the task for successful completion. However, 5 of the younger users were not successful in completing the task, which was the highest failure rate among the younger users.

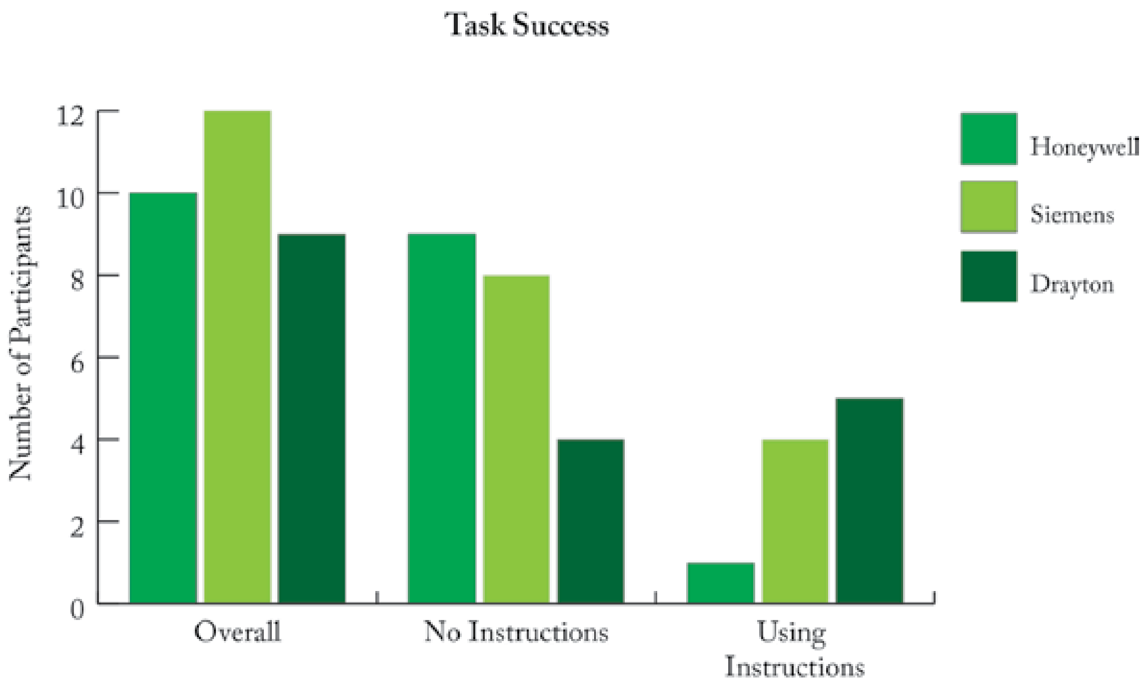


Figure 5.5 Task Success for Younger Users

On average, older users spent 8 minutes and 27 seconds (507 seconds) attempting the task with the instructions before asking to stop the testing. Reasons for the older users asking to stop the testing included severe frustration, users feeling that it would take them too long to complete the task and users thinking that they had successfully completed the task.

Given the stark differences in success rates between older and younger users, separate statistical analysis on task times were conducted. A one-way repeated-measures analysis of variance (ANOVA) using task completion time irrespective of success as the dependent variable suggested that there was no statistical difference between the three controls for either age group (older users: $F(2, 18) = 0.058$, p = n.s.; younger users: $F(2, 26) = 0.095$, p = n.s.). Despite the older users attempting the task for a longer time, on average, there was no statistically significant difference between the times spent using each of the controls. The mean successful task time for the younger users was 7 minutes 26 seconds (446 seconds), a considerable length of time. The successful task times for the younger users and each control are shown in Figure 5.6

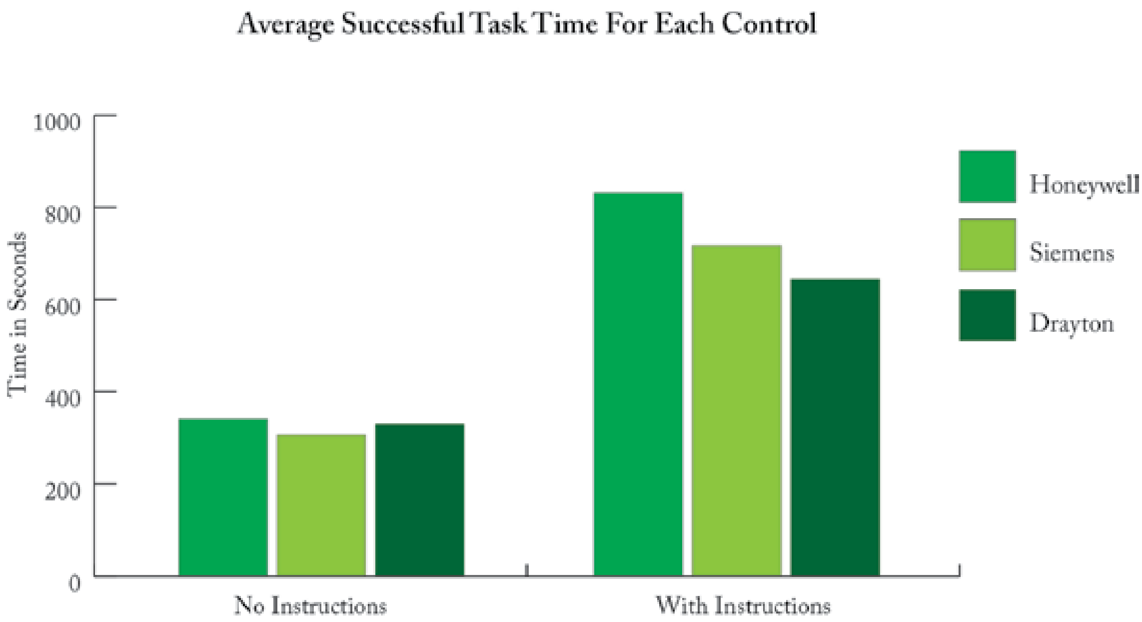


Figure 5.6 Average Successful Task Time

5.3.3 Instruction Usage

Completion of the task successfully using the instructions took the younger users, on average, 12 minutes 11 seconds (731 seconds) compared with 5 minutes 26 seconds (326 seconds) without the need for instructions. A one-tailed t -test showed a significant difference in the task completion time between the younger users who required the instructions to complete the task successfully and those who did not ($t(12) = -5.2$; $p < 0.001$).

The Siemens instructions were particularly problematic for the older users, with 4 of the 9 older users who requested the instructions being too intimidated to attempt the task. This resulted in the average time the older users attempted the task for being shortest with the Siemens control. Primarily, this was because users ended the testing early due to being intimidated by the instructions, making statistical analysis more difficult. The frequency of instruction use by participant, illustrated in Figure 5.7, highlights the fact that only 5 of the 24 users did not request for the instructions. Of these 5 users, 3 completed the tasks successfully, but 1 younger user and the older user did not.

Table 5.3 Frequency of Instruction Use by Participants

Frequency of Instruction Use	Not used	Once	Twice	Three Times	
Younger Users	3	6	4	1	14
Older Users	1	1	6	2	10

5.3.4 Estimated Exclusion vs. Actual Exclusion

The exclusion calculation results and the task success results are compared in Figure 5.8 to make the difference between the two sets of results explicit. It has been assumed that if a user was unable to complete the task successfully, then he or she has been excluded. The test found a significant difference between the estimated and actual exclusion of users from both age groups ($p < 0.05$ as $X^2 = 11.68$ and df = 5). The trend of the estimated exclusion increasing with age has been verified, yet complete exclusion of the older users was not expected.

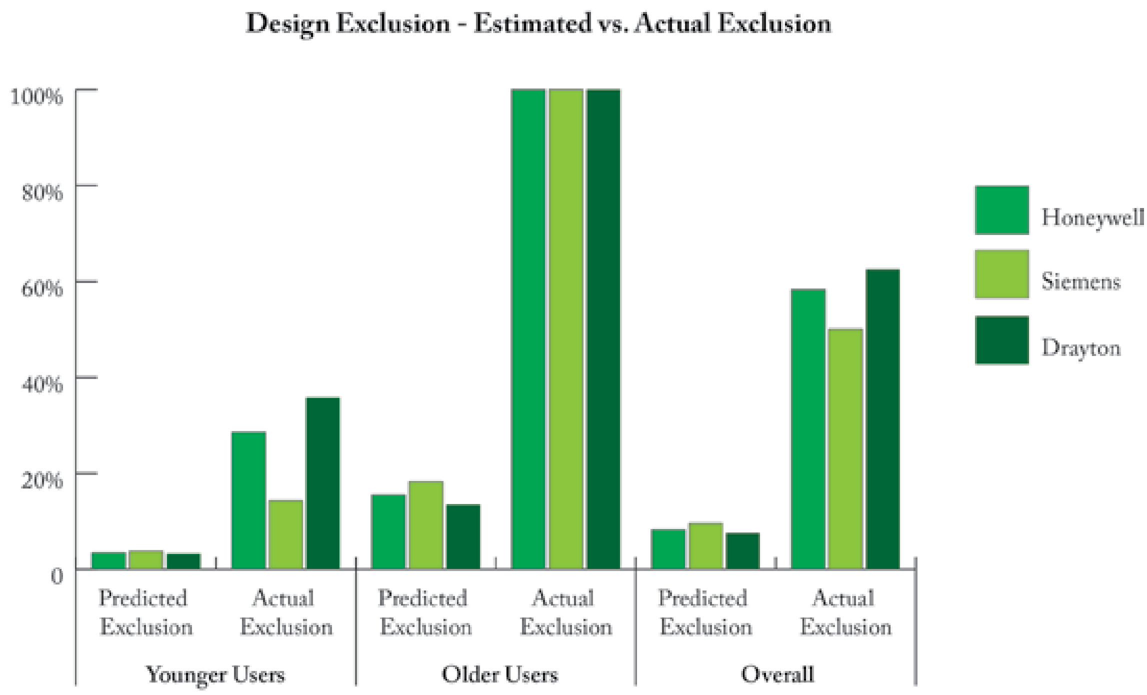


Figure 5.7 Estimated vs. Actual Exclusion

5.3.5 Raw NASA Task Load Index application

A 2 × 3 ANOVA (age group vs. control type) on the overall workload score of the RTLX found a significant main effect for control type ($F(2, 44) = 9.30$; $p < 0.001$) and a marginal significance for age ($F(1, 22) = 3.37$; $p < 0.1$). Overall workload tended to be higher for older participants than the younger group (mean 62.3 vs. 53.5), with the lower rating implying that the controls were easier to use. Pairwise comparisons for control type found that the Honeywell control was rated significantly lower than the Siemens ($p < 0.005$) and the Drayton ($p < 0.005$) controls. There was no difference between the Siemens and Drayton controls. Furthermore, the interaction between age and control type was non-significant.

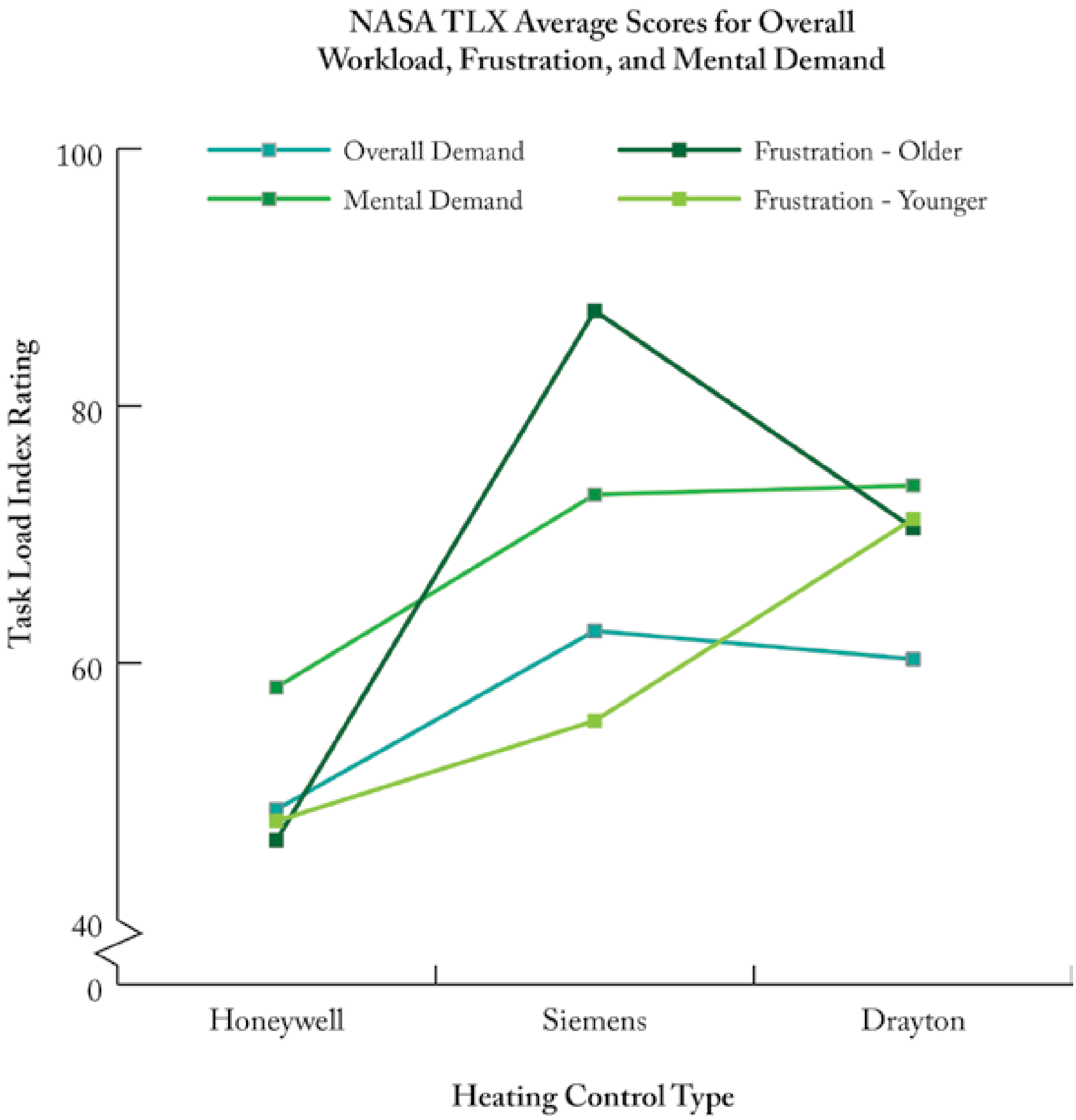


Figure 5.8 NASA TLX Average Scores for Selected Sub-scales

Of the six dimensions rated, all three controls scored highest on frustration level (mean = 66.0), then mental demand (mean = 65.7). This indicates that the main source of loading with the task is perceived to be frustration followed closely by mental demand, shown in Figure 5.9. Thus, similar 2 × 3 ANOVAs were conducted for the frustration and mental demand scores. For frustration, there was a significant main effect of control type ($F(2, 44) = 7.38$; $p < 0.005$) and a significant interaction between age group and control type ($F(2, 44) = 3.42$; $p < 0.05$). There was no main effect for age group.

Pairwise comparisons for control type revealed that the Honeywell control was rated lower than the Siemens ($p < 0.005$) and the Drayton ($p < 0.01$) controls. Post-hoc t-tests revealed the source of the interaction to be a significant difference between young and old groups on the Siemens control ($t(22) = -3.36$; $p < 0.005$).

For the mental demand sub-scale, a significant main effect for control type was revealed ($F(2, 44) = 8.43$; $p < 0.005$). Both the main effect for age and the interaction were non-significant. Pairwise comparisons for control type revealed the Honeywell control to be rated lower than both the Siemens ($p < 0.005$) and the Drayton ($p < 0.005$) controls. Both the overall workload scores and the frustration and mental demand scores were above the high workload threshold of 40 defined by Knapp and Hall discussed earlier (1990, cited in Gawron, 2008).

5.4 Results Part II - Qualitative Results

The discussion centres on the user comments and the usability problems experienced during the testing. Four main usability issues were identified from the user observations and comments. These were: overall system complexity, the lack of a 'Confirm' or 'Enter' button, the complexity of instructions and the use of unfamiliar symbols. Older users specifically commented on the size of the text on the interfaces and in the instruction manuals, which caused them difficulties. This resulted in severe user frustration and some users being unable to complete the task successfully.

Each of the four issues is discussed and supplemented with direct comments from the participants. The section is concluded with an analysis of the user comments to produce tangible design guidance. This guidance aimed to help remove the barriers to use, especially for older users. Implementing such design guidelines may also reduce the cognitive load placed on the user and could enable effective use of the controls.

5.4.1 On/Off Times

Setting the on and off times for a period of heating was problematic for users with each set of controls. The Honeywell and Drayton controls provide six intervals, which can be programmed individually. Users frequently did not understand that the second, fourth and sixth time periods are essentially the finish or off times.

The Drayton control users were forced to use all the six programming slots despite the task only requiring four. The Siemens control used the idea of a 'comfort pattern' similar to the time period concept of the other controls. If the users did not engage or understand this function, they were unable to set the evening settings on the weekend, which had a default of one phase. This led to user confusion and resulted in irrefutable errors in the task for the 2 younger users who were unsuccessful and the 1 older user who did not use the instructions.

Confusion regarding the on/off times can result in accidental heating of the home, consuming a considerable amount of heat energy unbeknown to the user. Five of the users did not turn the temperature down at the end of the heating period when using the Honeywell control. In reality, this would result in the heating system trying to maintain a constant temperature of 19°C-21°C throughout the day and night.

5.4.2 Support from Instruction Manuals

The lack of support from the instruction manual was a particular issue for the Siemens control. The users' reaction to the instructions was predominantly negative with younger users remarking "the instructions are pretty rubbish" and "the instructions just confused me". The older user group also had difficulty with the instructions, saying "You'd need a full day for this. Good thing I haven't got these at home", "I wouldn't even attempt it because that is, this is an instruction nightmare [sic]" and "Those instructions are horrible".

The Siemens instruction manual was particularly daunting, with 4 of the 10 older users being too intimidated by the instructions to attempt the task. When using the Drayton control, one older user remarked "all I want to know is which buttons to press". This indicated that the instructions were providing an overwhelming amount of information.

5.4.3 Number of Interface Buttons

Instruction use with the Drayton control was the highest (15 out of 24 users), which may be attributable to the lack of buttons and support on the interface. One older user said "if I just went into a house and there were no instructions I'd have a big problem with that". When attempting the task, 6 of the older users and 9 of the younger users looked for more controls and buttons. This occurred even when the control was the first used with younger users commenting "are these all the buttons?" and "is that all there is to it?". The minimal use of buttons caused frustration for both user groups and 3 users developed coping strategies by trying to press two buttons together as an 'Enter' function.

The Honeywell control provided an 'Ok' button, which gave users confidence that they had completed an action. The Honeywell interface had an abundance of buttons, which proved to be a distraction to some users. This was particularly true for buttons such as 'Party', 'Holiday' and 'Exception Day' modes. One older user commented that on the interface, "there is too much to read and there are too many little things".

The main usability problems with regard to buttons and controls on the Siemens interface were that users did not initially understand that there was a door or locate the slider. There is little indication of either the door or the slider and neither is labelled on the interface. Half of the older users failed to identify where the slider was. Two participants commented "it refers to a slider but I can't see how to adjust the slider" and "I haven't even figured out which is the slider". This implied that they were aware that they were required to use a slider but could not find it. Without identifying the slider, the user could not programme any settings and, therefore, the controls would be left on the default setting.

5.4.4 Variety of Symbols

Upon opening the door and seeing the Siemens control interface, which is dominated by symbols rather than by buttons (see Figure 5.3), 2 younger users indicated their intimidation. Similarly, older users exclaimed "Nope doesn't mean anything to me" and "I don't think I like this". The use of symbols on the Honeywell interface was also a point of contention; one older user commented, "I can't think what they, what these buttons would be, they don't seem to mean a lot to me" in reference to the symbols. Similarly, 2 younger users questioned what the symbols of the different modes meant.

5.4.5 Analysis of Research Observations

From the audio transcripts and observations throughout the research, themes have been extracted. These themes relate to user capabilities and the issues discussed in detail in Chapter 5. Firstly, the audio transcripts were coded using a priori coding approach, with the user capabilities defined in the Exclusion Calculator as categories. Upon initial analysis these categories were found to be useful at a high-level but too broad to make the analysis tangible. Each capability was subdivided into further categories:

- For vision this was the font and size of text provision and the overall visual look of the control
- For dexterity it was divided into knowing where to press and what would happen when a button was pressed and the physical ability to press the button
- For cognition there was a complexity category and a feedback category, which was primarily comments regarding the lack of system feedback

As the cognitive demands were found to be most exclusive and underestimated in the existing Exclusion Calculator the design principles specifically focus on reducing these demands. A final theme was a lack of feedback from the systems of the settings entered. The frequency of the occurrence of the themes is shown for each of the three controls in Figure 5.10.

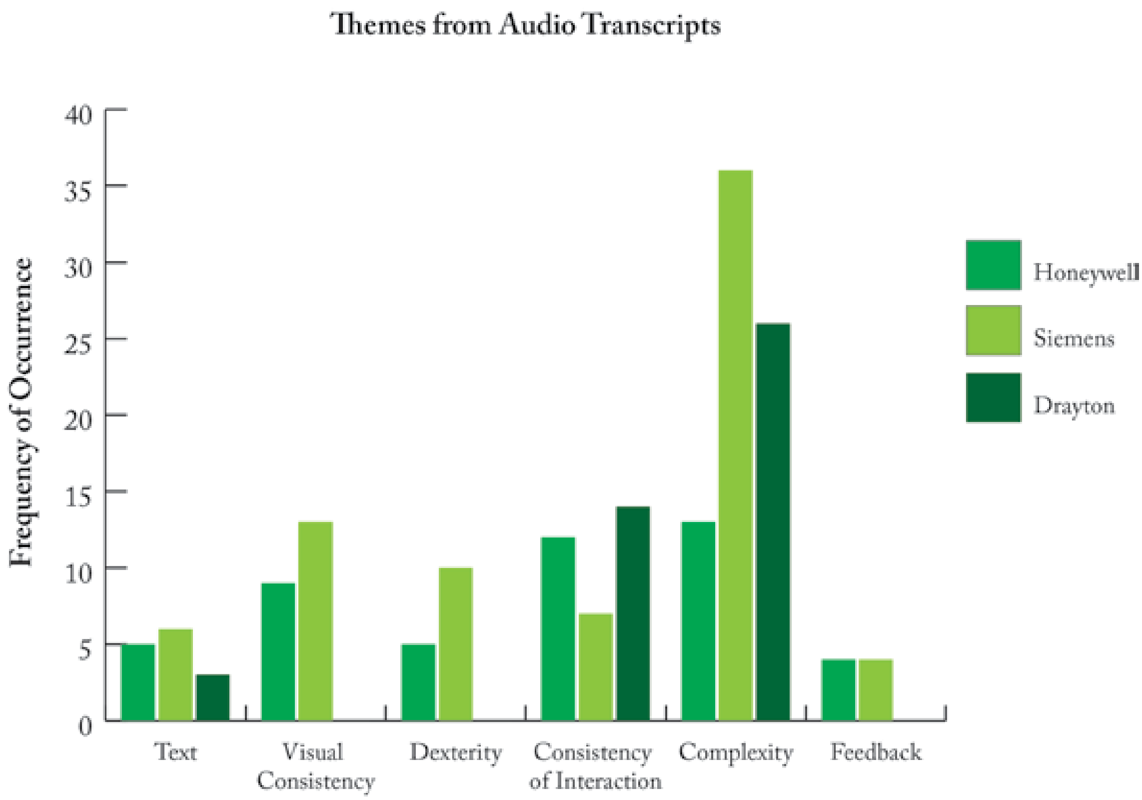


Figure 5.9 Frequency of Theme Occurrence from Transcripts of Observations

In order to reduce the demands placed upon users a set of Inclusive Design Principles for Energy Management Systems, known hereafter as the design principles, have been formulated. These are based upon the user observations and consist of ten points relating to the three main areas of user exclusion: thinking, vision and dexterity. Six of the ten design principles directly are related to the themes elicited from the observation data.

The principles of advice and comparison are drawn from the literature review and could be incorporated into feedback provided by the system. Staats, Harland and Wilke (2004) found comparison particularly useful for people already engaged with energy saving initiatives. Whereas, Schultz et al. (2006) found comparison combined with positive reinforcements helped high consumers reduce consumption and low consumers maintain efficient behaviour. Karjalainen (2010) included advice provision as part of the usability guidelines for room temperature controls in offices; however, it remains unclear as to whether this results in energy savings. Despite none of the current systems having audible feedback, incorporating this may help reduce the visual demand placed on users. Any audio features incorporated should be optional as not to irritate users.

The proposed design principles are:

- Text - consider the size of text, the legibility of fonts and contrast between text and the background to reduce visual demands.
- Visual Consistency - if using symbols or icons try to keep them consistent with existing symbols from other interfaces, as this can reduce the load upon the user.
- Audio - consider including the provision of optional audio feedback, as this could reduce reliance on the users' visual requirements.
- Dexterity - the size of any buttons should be suitable for use by people with limited dexterity. The force used to operate these buttons/controls should not be excessive. In addition, feedback that a button press has been recognised could assist users.
- Consistency of Interaction – using styles of interaction that are familiar to the user such as mobile phones, computers or ATM systems may help reduce cognitive and dexterity loads.
- Complexity - avoid unnecessary complexity of the interface wherever possible.
- Feedback - give the user feedback on the settings programmed, their energy consumption and positive reinforcement of energy reductions achieved. Ensure that any feedback provided is easy to understand, relevant and meaningful to the user.
- Advice - provide the user with some advice to help them change behaviour and nudge them in a more sustainable direction.
- Comparison - where possible relate their energy consumption to a peer group, putting their energy consumption in context. Show the user what good looks like to provide them with a benchmark.
- Metrics - keep the quantity of different numerical units to a minimum as not to intimidate or confuse users.

5.5 Discussion and Further Work

This study indicates that users experienced severe difficulties in programming the heating controls; these difficulties were exacerbated in the older user group. The complete failure of the older user group to complete the task was unexpected. This may in part be due to the complexity of the task itself. Measures were taken to ensure that the task was clearly explained in writing with a summary table of numeric values and the researcher available to answer questions relating to the task. Instead of utilising the full capabilities of the controls, only two heating phases were requested rather than the three available.

Excessive workload was placed upon both user groups, with mental demand and frustration being rated highly. As a direct consequence, many users indicated that they would not choose to use such products. This negative reaction reduces the potential to heat the home efficiently. Moreover, the feeling of dissatisfaction and intimidation among users was clearly apparent when using the controls. Only three of the users managed to complete the task successfully without requiring instructions for any of the controls. The interface should provide users with the necessary support to enable them to use the product as intended.

The use of unfamiliar symbols can increase the cognitive load for users, which can lead to exclusion. This highlights the importance of labelling and text feedback rather than that of symbols as was found in the long-term usability study by Imai et al. (2010). Their study found that, "text can be one of the important visual features associated with function" (pp. 185, 2010) and interfaces may be easier to learn when text feedback is provided (Imai et al., 2010). Freundenthal and Mook (2003) also found that icons were particularly problematic for the older users interacting with a prototype heating control.

Despite the small sample size, this study emphasises the importance of directly involving users in the design of the controls. Although the sample size was small, usability problems became apparent rapidly, especially with the older user group. Moreover the small study sample means that the success rates cannot be extrapolated for the whole population. However, the aim of this study was to understand flaws in the interfaces, and a sufficient number of participants was used to achieve this. The study is also limited by the number of digital programmable thermostats tested, yet the results are a useful contribution to the design of future heating control systems.

The recommendations for further work centre on opportunities for developing more inclusive heating control interfaces. From the usability testing several areas for improvement have been discussed. The following four recommendations are made for the development of any future control interfaces:

1. Providing a summary of the settings programmed available to the users. This may help users identify any mistakes made prior to running the system. Furthermore, providing clear on and off times (rather than time periods or comfort phases) may avoid unintentional and unnecessary periods of heating, again potentially reducing energy consumption.
2. Clear and concise instructions could benefit all users in programming their heating controls. A lack of support led to unsuccessful use of the product during the usability testing, which could result in uncomfortable conditions in reality.

Whether improved instructions could also help users reduce their energy consumption is not clear at this stage.

3. Careful consideration of the number of buttons. Too few buttons led to high frustration and users giving up on the task, whereas too many distracted the users. The provision of a 'Confirm', 'Enter' or 'Ok' button is recommended to allow users to save the settings programmed. The users should not feel intimidated by the number of buttons and symbols on the interface.
4. The use of text labelling to make functions explicit. Text labelling is recommended on future control interfaces, as is the standardisation of symbols across different interfaces. The consistent use of symbols will reduce the time taken to learn a new interface and help users adapt to new products.

5.6 Conclusions

The main cognitive issue for users was found to be the idea of time periods rather than an on/off time. This resulted in controls being unintentionally programmed to heat throughout the day and night. If this part of the process was made explicitly clear, undoubtedly energy savings could be made. In addition, providing a summary of the settings may alert users to any mistakes that they may have made and avoid periods of unintended heating.

The Exclusion Calculator provided valuable insight at the start of the process, making explicit where design exclusion was likely to occur. However, these results again underestimated the exclusion found through usability testing. This study demonstrates that both user groups had difficulties with the task and that these problems were exacerbated among older users.

The RTLX scales indicated both user groups experienced excessive mental workload. The cognitive demands were particularly unreasonable in the case of mental demand and frustration level. Any inclusive control system developed should reduce both the mental demand and frustration level experienced in the use of the system.

In conclusion, improving the usability of these controls will undoubtedly help their effective use and in turn could potentially reduce heat energy consumption. Overall, there was a lack of system transparency and feedback to the users. Increasing the feedback from the interface can improve the experience of using such a product and help the users to programme their control efficiently.

Chapter 6 - The Development Of A More Inclusive Heating Control Interface

Abstract

This chapter aimed to apply the findings of the research thus far in the development of a prototype heating control interface. This prototype has the specific aim of reducing user exclusion. This chapter discusses the development of this novel heating control interface and the results of the associated evaluation. The system developed allows users to programme both time and temperature for the entire week or on a daily basis to be consistent with the functionality of current digital programmable thermostats.

To visualise the reduction in cognitive demands a Hierarchical Task Analysis (HTA) has been completed for the prototype. This can then be compared with the HTA previously conducted of existing controls. The user exclusion is estimated using the Exclusion Calculator, prior to the evaluation with users. The user testing included attempting the programming task used previously to illustrate success rates and the Raw NASA TLX (RTLX) scales were used to assess associated mental workload.

The results tentatively suggest that the user exclusion has been reduced compared to existing controls, particularly amongst the older participants. This is implied from a success rate of 56.3% for the older participants; in an average time of 5 minutes 32 seconds. Low levels of frustration, effort and mental demand were observed in younger participants and in successful older participants. However, frustration levels remained significant amongst unsuccessful older users.

The user observations helped identify areas for further improvements of the prototype heating control interface. The results presented suggest that the cognitive demands of such a system have been reduced, with an observed reduction in design exclusion. It remains unclear as to whether these reductions in capability demands could result in energy savings.

6.1 Introduction

The application of the research findings in the design of a heating control interface is part of the novel research presented in this thesis. The proposed heating control interface aims to illustrate that reducing the cognitive exclusion may make such a system more usable and inclusive. In order to help evaluate whether this exclusion can be reduced a working prototype has been developed. The prototype is an initial proof of principle prototype, which aims to reduce the complexity of the programming task. This is thought to reduce the user exclusion, particularly in relation to the cognitive exclusion.

This study aimed to answer the third research question, "Can the exclusion relating to digital programmable thermostats be reduced?". It also achieved the third research objective - to design and develop an inclusive product or system which allows users to control their heating usage within the home. This chapter reports the development of the prototype, the results of the user testing and discussion of further design improvements. It is believed reducing the cognitive exclusion relating to such systems can reduce the associated heat energy consumption.

The literature widely agreed that when programmed effectively, digital programmable thermostats can save energy (see: Gupta, Intille and Larson, 2009, Bordass and Leaman, 2001, Moon and Han, 2011). Yet, current research suggests the majority of households do not programme their thermostats (see Freundenthal and Mook, 2003, Karjalaninen, 2009, Meier et al., 2011 and Peffer et al., 2011). Improving the usability of such systems and including a wider range of users is thought to have a greater environmental benefit than increased levels of functionality (Shipworth et al., 2010, Peffer et al., 2011, Caird and Roy, 2008).

The reasons for this lack of engagement are partially thought to be the overall usability and complexity of such systems. Peffer et al. (2011) identified a need for further understanding regarding the usability of digital programmable thermostats. However, most usability studies are limited to student participants under 30 years of age (Langdon and Thimbleby, 2010). This study proposes to address the need for improved usability of such controls, with specific effort to include a wider range of participants including older people (age 50-80).

From the previous analysis, the programming of digital programmable thermostats involved 27-32 decision steps to set the heating to come on twice a day for both weekdays and weekends. If the cognitive demands placed upon users could be reduced, and programming process simplified, it is thought greater energy savings could be realised. Ideally, heating controls would be simple to programme to help users achieve comfortable conditions within the home, while at the same time enabling reductions in the environmental impacts of heating demand.

6.2 Materials and Methods

6.2.1 Design

The study design mirrors the design of the study reported in Chapter 5 to allow for tentative comparison between results, particularly with regard to the cognitive aspects assessed in the RTLX scales. The study again follows a multi-strategy design consistent with the previous studies. This study design primarily involves the collection of quantitative data. The Exclusion Calculator served as a basis for the quantitative data, followed by the quantifiable usability metrics of task success and time taken. User comments and observations were noted during the testing and provided a small amount of qualitative data.

A between-group design aimed to reduce factors such as user fatigue and learning effects of repeated tasks, however it is more difficult to get statistically significant results (Lazar, Feng and Hochheiser, 2010). The study was designed for two sets of participants to perform the same task using the prototype to allow comparison between the two groups.

6.2.2 Participants

Two groups of participants were recruited for the study: younger users (20-35 years) old and older users (50-80 years old). The participants for the full user testing were 15 participants aged 23-35 (mean = 27.9 years, male = 8, female = 7) and 16 participants aged 52-78 (mean = 68.6 years, male = 7, female = 9). Older participants were recruited through the Brunel Older People Research Group, including some who took part in the previous study. This prior experience of similar products was not thought to have influenced the task performance, as all participants were previously unsuccessful. Of the participants, 12 older users and 5 younger users said they currently had a digital programmable thermostat at home. Participants gave their informed consent to the study and received no payment or reward for taking part. The study was approved by the School of Engineering and Design Ethics Committee on the 26th October 2011.

6.2.3 Testing Procedure

The study procedure was divided into two sections the development of the prototype and the user based evaluation. Prior to completing, the user testing an Exclusion Calculation and HTA were conducted for the new system. This may allow tentative comparisons to the previous studies. The programming task was kept consistent with the previous study, which involved setting the control for two heating periods for both weekdays and weekends.

6.2.3.1 Initial User Testing

During the development phase paper prototypes were tested with 6 participants aged 23-35 (male = 4, female = 2). Due to the prior experience of interacting with the paper prototype, these participants were excluded from the latter user testing. All six participants could control the temperature and duration of the heating in their homes and had interacted with their heating system within the last year. Importantly, these participants were considered lay users of the system as none of them worked within fields related this research.

Using the paper prototypes, participants were asked to envisage that the screen represented a touch screen or a webpage. They were then asked to touch the screen where they would expect to click a button to simulate the user interaction. The participants were asked to complete three example tasks and were encouraged to talk aloud during the process. Depending where on the interface was 'pressed' the participant was provided with the next paper screen of the interface. Once the tasks were completed, participants were invited to give feedback on the experience. The tasks the participants were asked to complete were:

1. You just got into the house and you are feeling a bit cold. Can you turn on the system for a short amount of time?
2. You want to set your heating so it is on in the morning when you get up for work and on in the evening when you come home from work. At the same time you don't want to spend too much money or waste energy heating when you aren't at home. Can you set your heating for the weekdays to come on between 06:00 and 08:00 at 20°C and in the evening between 18:00 and 22:00 at 21°C?
3. You are trying to manage your energy spending, can you show me how you would use any features to try to help you understand the way you are using your energy?

6.2.3.2 Full User Testing

The final system testing ran on a laptop but it was explained that it could run on a variety of platforms to suit the users' requirements, i.e. on a laptop, desktop, smart phone, device with a touch screen or a more traditional box on the wall. After gaining the participants' informed consent, information regarding prior usage of digital thermostats, computers and mobile phones was gathered. Lastly, a paper-based technical self-confidence scale was completed by each participant prior to attempting the tasks. This is similar to the affinity to technology scale used by Wolters et al. (2010).

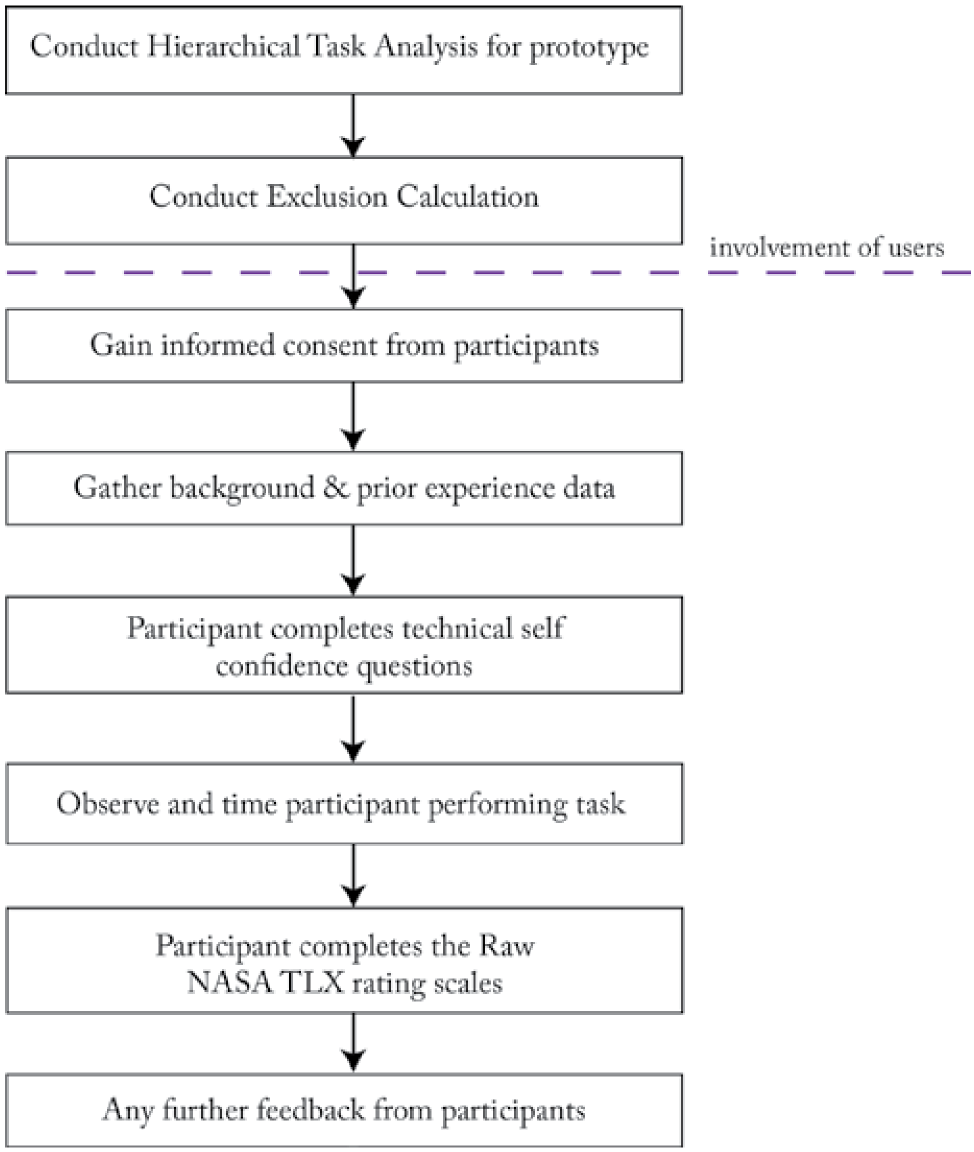


Figure 6.1 Procedure Diagram

Both sets of participants were then given the three tasks used in the paper prototyping stage. The second task involved programming the control and was timed individually. It was noted whether the participants were successful, used the help features, and any points of confusion for the user. The testing was audio recorded and participants were encouraged to give feedback both during and post task. The RTLX scales were then completed by participants after all three tasks had been attempted.

Figure 6.2 User Testing Set-up

6.2.4 Application of Methods

Prior to involving users, two methods were used to assess the demands expected to be placed on the participants; an Exclusion Calculation and a HTA. These methods are discussed in detail in Chapter 3 and the use of these methods is consistent with the previous two studies (Chapters 4 and 5). Upon completion of the testing, the participants were asked to complete the RTLX scales.

The usability testing of the interactive prototype involved three tasks consistent with those discussed in Section 6.2.3.1. As a warm up task the participants were asked to turn on the system to run for a short amount of time, i.e. utilise the boost function. The second task was to programme the prototype control to the settings shown in Table 6.1. To ensure consistency, and allow tentative comparisons to be made, the main task was kept consistent with the previous chapter. A final task asked users to illustrate how they might try to understand their energy consumption from the home screen, i.e. using the feedback features.

Table 6.1 Settings Used in the Usability Testing

Day	Time (12 hour clock)	Time (24 hour clock)	Temperature
Monday - Friday	7am-9am	07:00-09:00	19°C
	4pm-11pm	16:00-23:00	21°C
Saturday and Sunday	7am-9am	07:00-09:00	19°C
	6pm-10.30pm	18:00-22:30	21°C

6.2.5 Variables

Participants were asked to detail whether they had a digital programmable thermostat, whether they had control over both time and temperature through another means, if they had interacted with the system in the previous 12 months and if they were financially responsible for heating their homes. Of the participants, 5 of younger users and 12 of the older users had a digital programmable thermostat at home.

Prior experience and current usage of computers and mobile telephones by participants was also gathered prior to attempting the task. To reduce the impact of variety in computer usage, participants were made aware in the invitation to participate that the prototype was based on a laptop. Participants were informed they would be asked to complete three tasks using the prototype. To minimise learning effects and bias of results, the prototype was reset to a common starting point with no settings programmed.

In terms of computer usage, only one older participant did not use a computer at all and 13 used a computer on a daily basis. Mobile phone usage varied more. All younger users used a mobile phone on a daily basis to make phone calls and send text messages. Although all of the older participants had a mobile phone, only 8 used it on a daily basis and 6 participants used it only to make calls. This technical experience may have contributed to success in the task.

6.2.6 Statistical Analysis

For the quantitative results, various statistical analyses were used to establish significance. The statistical analysis is reported in conjunction with the user testing results (Section 6.4). Observed user exclusion was compared to predicted exclusion from the calculation and was evaluated based on frequency using Chi-square tests. This compared the expected frequency of exclusion to the actual frequency of exclusion observed.

Independent t-tests were used to compare successful task completion times between the older and younger user groups, where parametric data was available. Mann-Whitney U Tests were used as a non-parametric alternative to independent T-tests. Non-parametric tests were used due to the small sample sizes and the non-normal distribution of results.

Mann-Whitney U Tests were used to determine whether there was a significant difference between the successful task completion times and the age of the participants. The RTLX scores were also evaluated using a Mann-Whitney U Test to determine whether the differences between the RTLX ratings of the two user groups were significant. Correlations were evaluated using Pearson's product-moment correlation coefficient for parametric variables.

6.3 Development of the Design Intervention

Due to the industrial nature of this research, the outcome was expected to be a product to be manufactured under license by the sponsor organisation, Buro Happold. Several process models were considered to develop the design intervention from the compendium of design process models How Do You Design? (Dubberly, 2005). Two of the models cited by Dubberly were seriously considered; Pugh's Product Development Process (1990) and Nigel Cross' Four Stage Design Process (2000). Pugh (1990) suggests a detailed four-stage process from specification through to manufacture. Whereas, Cross (2000) suggests a simple iterative process of exploration, generation, evaluation and communication, with less of a focus on a manufactured outcomes.

The seven stage New Product Development Process from Ulrich and Eppinger (2004; see Figure 6.3) was selected as the most appropriate design process for this project. This was due to the on-going testing and prototyping cycles of the process. This gave scope for the findings of the user testing to be fed back into the design of the intervention at each stage of the process.

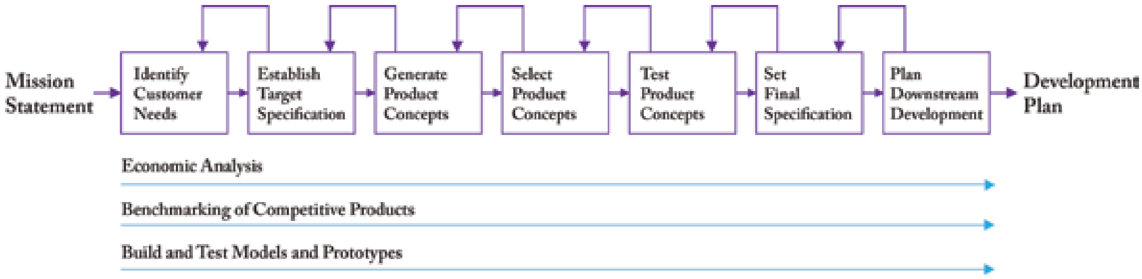


Figure 6.3 New Product Development Process from Ulrich and Eppinger (2004)

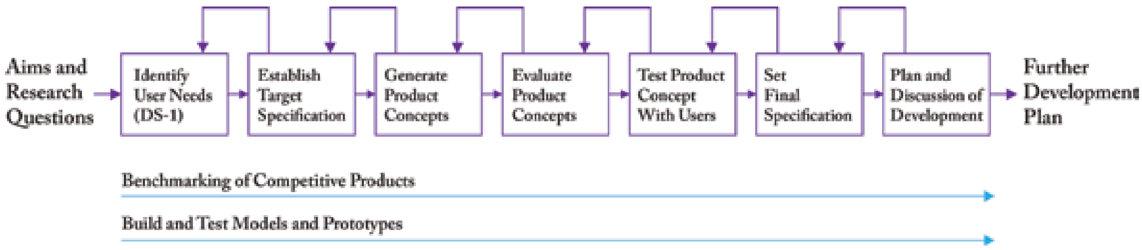


Figure 6.4 Adaptation of the New Product Development Process from Ulrich and Eppinger (2004) with a focus on user testing

Figure 6.4 shows the adaptation of the Ulrich and Eppinger's (2004) process for application in this research. The application of the design process was front-loaded identify the customer needs through the descriptive studies in Chapters 4 and 5. From the research stage the specification in Appendix 6 was developed. Concepts were then generated considering the inclusive design principles for energy management systems proposed in Chapter 5 (page 151).

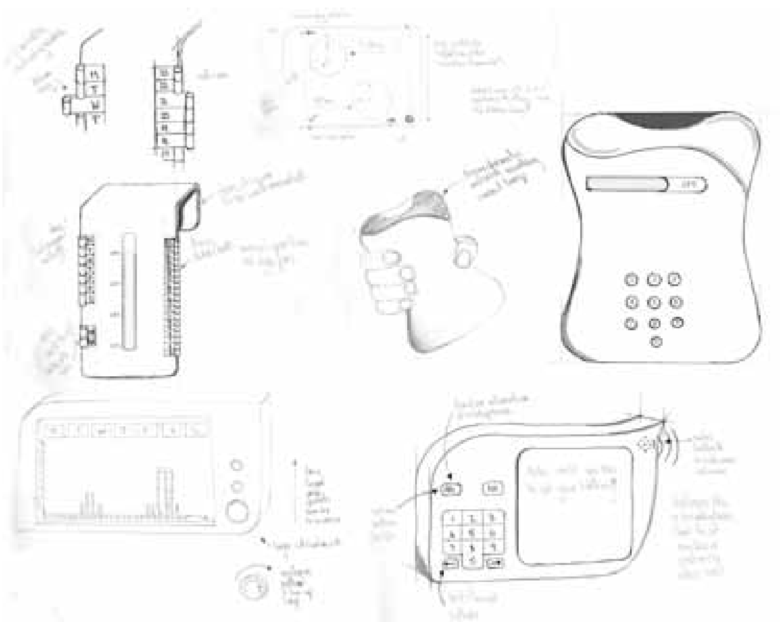


Figure 6.5 Concept Generation Sketches

The eight concepts, a selection of which, are shown in Figure 6.5, were then evaluated using a weighted criteria matrix. The criteria used were, with the relative weighting out of 5 shown in brackets:

- Estimation of cost (5)
- Level of functionality (5)
- Ease of manufacture (3)
- Aesthetic quality (3)
- Accessibility (5)
- Feedback on current energy consumption (5)
- Consistent use of symbols and styles of interaction (3)
- Number of metrics used (1)
- Advice provided to reduce energy consumption (1)
- Level of overall complexity (5)

The selection of concept for further development was based upon the overall score of each concept, then refined by the scores within the highly weighted criteria. This lead to the selection of an application concept that could operate over a range of platforms, rather than a manufactured physical object. This was deemed most appropriate and flexible to provide feedback to users, to allow a variety of accessible text formats and had the benefit of low manufacture costs. The development of an interface is not only flexible from a technological perspective but also adaptable for a wide range of people. This is appropriate where a single design solution cannot accommodate all users and is consistent with the principles of inclusive design, which underpin this research.

From the selected concept both paper prototypes and a proof-of-principle prototype were developed and tested with users. The testing of these prototypes is reported in this chapter. The findings of this user based testing fed into further requirements of the design specification. The future development and further work to improve the prototype is discussed in Chapters 8 and 9 of this thesis. This section continues with a description of the final prototype development before reporting the results of the user testing.

6.3.1 Task Clarification

The current user exclusion relating to digital programmable thermostats is investigated in Chapters 4 and 5 of this thesis. These studies found that the cognitive demands of digital programmable thermostats are a significant barrier to their effective use, especially by older people. In order to clarify the essential requirements of the design intervention, several key factors have been defined. In order to illustrate how these key factors have been met, success criteria were also defined. The key factors and the methods used to evaluate each key factor are described in Table 6.2.

Table 6.2 Key Factors of the Design Intervention

Key Factor	**Success Criteria**	**Measured/Evaluated Using**
Reduce user exclusion, especially amongst older users, relating to digital programmable thermostats	Overall exclusion less than 7.5% for users 16-102 years old and less than 13.5% for users 60-80 years old	Exclusion Calculation
	Successful programming of the heating profile using the new system	Task Success Rates (improvement compares to Chapter 5 results)
Reduce cognitive demands placed upon the user, compared to existing controls	Reduced number of decision steps in the programming task (less than 27 decisions)	Hierarchical Task Analysis
Improve usability of such controls to enable successful programming	User is able to programme the profile used in the usability testing	Task Success Rates
	This is achieved in a timely manner, approximately five minutes	Task Performance Time
Reduce frustration and mental demand placed on users	Mean frustration less than 66.0 and mean mental demand less than 65.7 (RTLX Scores from previous study)	Raw NASA Task Load Index
Provide same level of control as existing digital programmable thermostats	Comparable level of control to existing systems	Actual Support Realisation

6.3.2 Intended Support

The intended support is best described in Figure 6.6, which illustrates the ideal, complete system. The resources of the research project are insufficient to realise the entire range of intended functionality. Therefore the actual support satisfies only the core functionality of the intended support. Blessing and Chakrabarti argue, "the contribution of the design research is unlikely to be detailed in the technology used but most likely on the new functions and concepts for the support" (pp. 164, 2009). However, it is important to qualify what the intended support would consist of at this stage. A full and detailed product design specification can be found in Appendix 6. This specification has been developed in accordance with BS 7373-1:2001(British Standards Institute, 2001).

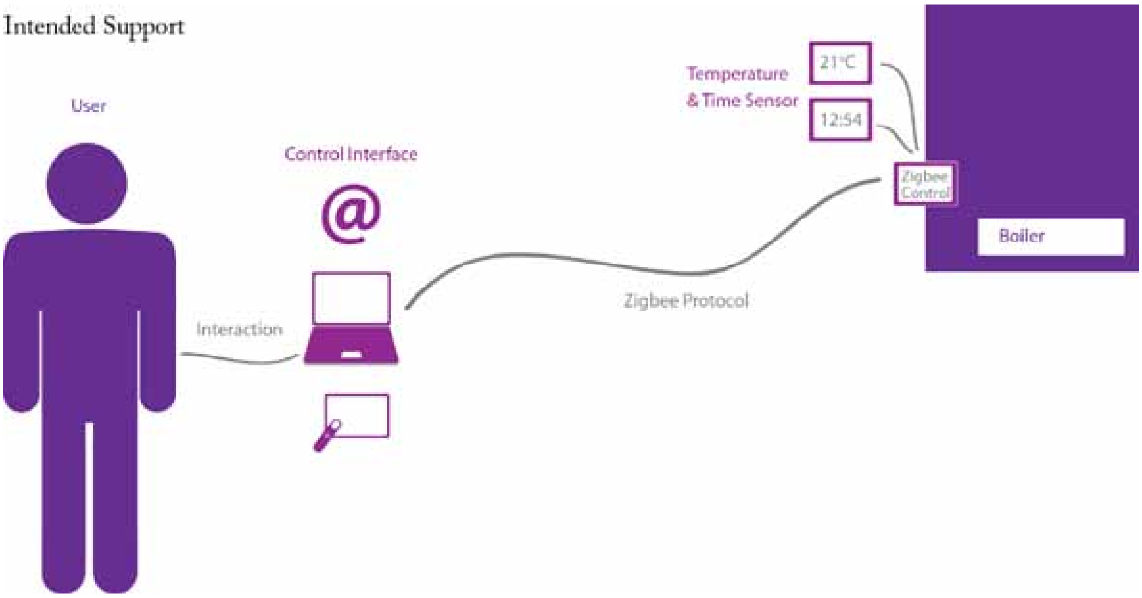


Figure 6.6 Diagram of Intended Support

It is proposed that further development would link the interface to a boiler control over a ZigBee wireless protocol within the home. Such ZigBee enabled boiler controls are currently available as a ready-made component. These components turn the system on and off dependent on a signal from the interface. Furthermore, with the smart meter rollout there will be an increased number of wireless protocols within the home with the ability to connect a range of devices to the internet.

A separate temperature sensor within the home would still be required to signal when the room temperature had reached desired levels. An embedded clock would also be required so the system could become active at specific times. However, this research focuses on the user interaction with the heating control interface, shown on the left hand side of the diagram; the rest of the intended support forms the future work section of this research.

6.3.3 Actual Support

The actual support developed takes the form of a software interface that can operate on a laptop, desktop or tablet computer. The prototype interface had comparable core functionality to a digital programmable thermostat. It allows the user to enter settings controlling both the temperature and duration of the heating period. The interface provides proof of principle for the evaluation phase, however, any settings entered do not control a heating system.

The prototype was developed to a working prototype stage to allow simulation of the interface and appropriate user testing. Adobe Illustrator was used to develop static low-fidelity representations of the control, which were tested as paper prototypes. The prototype was developed further using Adobe Flash, Flash Catalyst and Flash Builder to add interactivity to the system. This interactivity simulates how the user would engage with the system through either a touch screen interface in the home, a web interface or a smart device interface.

An adequate level of functionality is provided by the design intervention to assess the key factors, described previously in Table 6.2, and to conduct the subsequent user evaluation. The evaluation focuses on assessing the demands placed upon users and the usability of the prototype system. There are four main screens (or states) that the user can interact with using the buttons on the screen. The four screens are the home screen (shown in Figure 6.7), a general help screen, an enter settings screen (shown in Figure 6.8) and a summary screen.

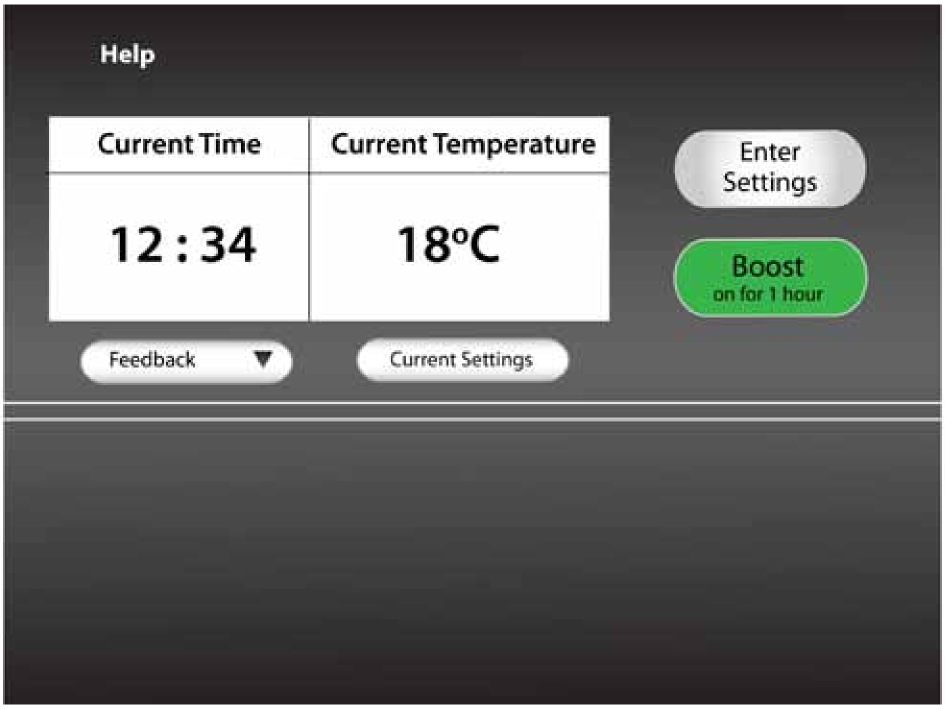


Figure 6.7 Screen Shots of Prototype Home Screen

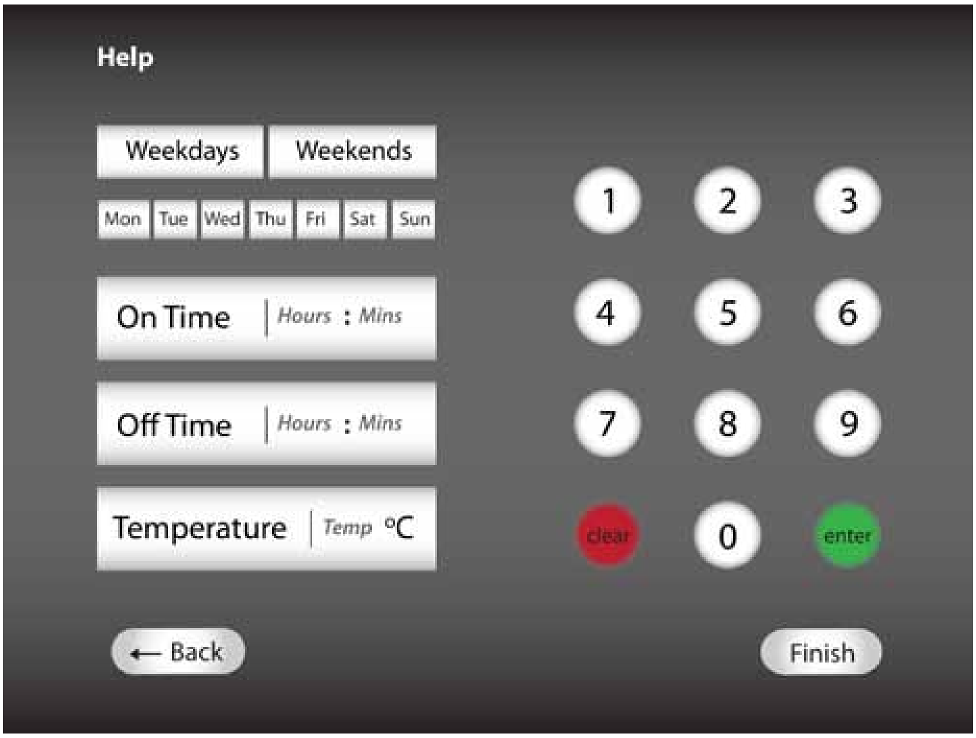


Figure 6.8 Screen Shots of Prototype Enter Settings Screen

6.3.4 Summary of Design Changes

During the development of the prototype interface the design principles proposed in Chapter 5 were considered throughout. The application of each principle in the prototype development is discussed subsequently:

- Text - The font and size of text was carefully considered and the level of contrast between the text and the background is high.
- Visual consistency - The use of symbols was limited to degrees Celsius and all buttons have text-based labels.
- Metrics - The number of metrics used by the system was kept to a minimum of time and temperature.
- Audio - Currently there is no audio provision, however, future development may include the summary of settings being audible, as well as visual.
- Dexterity - The size of the buttons was made as large as possible, providing a large target area and helping to reduce the dexterity requirements placed on the user.
- Style of interaction - This was based on a keypad in order to be consistent with

other numerical based tasks, which users may be familiar.

- Feedback - This was provided in the form of the summary screen and additional provision was made for feedback relating to heat energy consumption, consistent with smart meter rollout.
- Complexity - By reducing the number of unique decisions required of the user, the overall complexity was reduced. This is shown in the HTA in Section 6.4.1.
- Advice and comparison - Currently the system does not provide any advice or comparison to inspire changes in behaviour. This was deemed outside the core functionality of the system, however could be incorporated in further development.

The specific design changes implemented in the prototype interface aim to reduce the cognitive demands placed upon the user. These changes are:

1. The use of clear, concise language labelling the buttons and not symbols
2. Providing 'Help' in context of use, to better support the user during interaction with the interface
3. Specific on times and off times, to reduce confusion surrounding 'set points' as previously observed
4. The use of a keypad to enter numerical settings, as opposed to arrows or plus/minus buttons
5. Provision of a summary screen to add transparency and feedback to the system

None of these design changes are revolutionary, yet the combination of changes shown in Figure 6.9 is thought to reduce user exclusion significantly. This combination of changes is intended as the novel contribution of this interface. The changes also involve the implementation of three of the principles of universal design flexibility in use, being simple and intuitive to use and perceptible information.

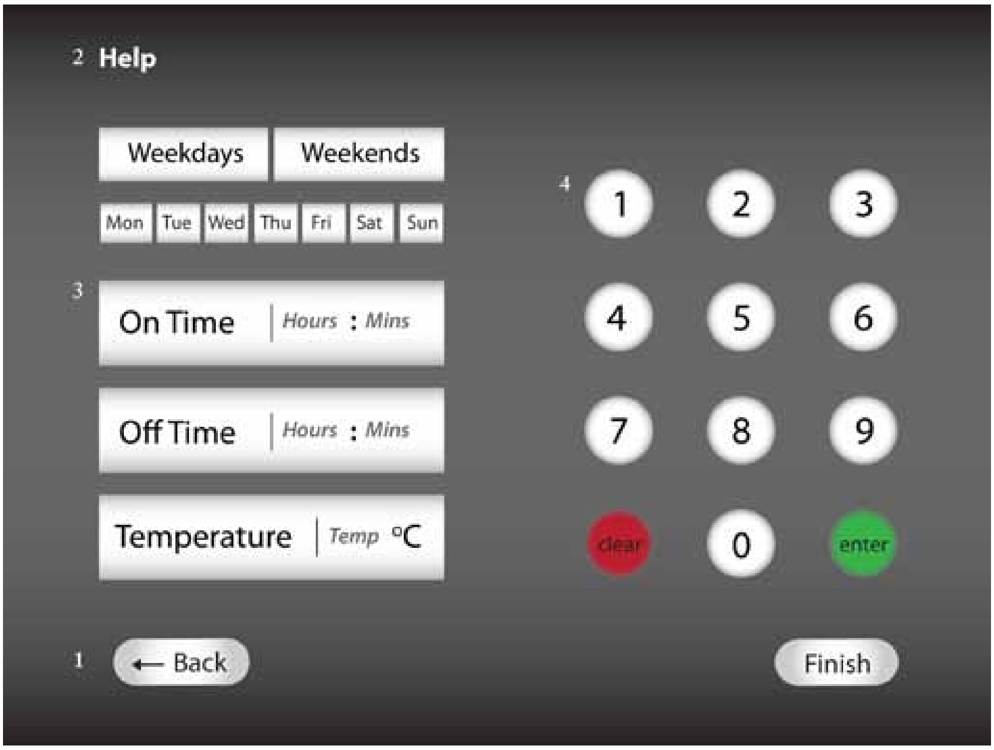


Figure 6.9 Illustration of Design Changes (numbers 1-4)

6.3.5 Initial User Testing Results

Prior to the development of the full working prototype, low-fidelity paper prototypes were tested with 6 participants. These paper prototypes consisted of variations on three main screens; the home screen, settings screen and summary screen (as shown in Figure 6.10).

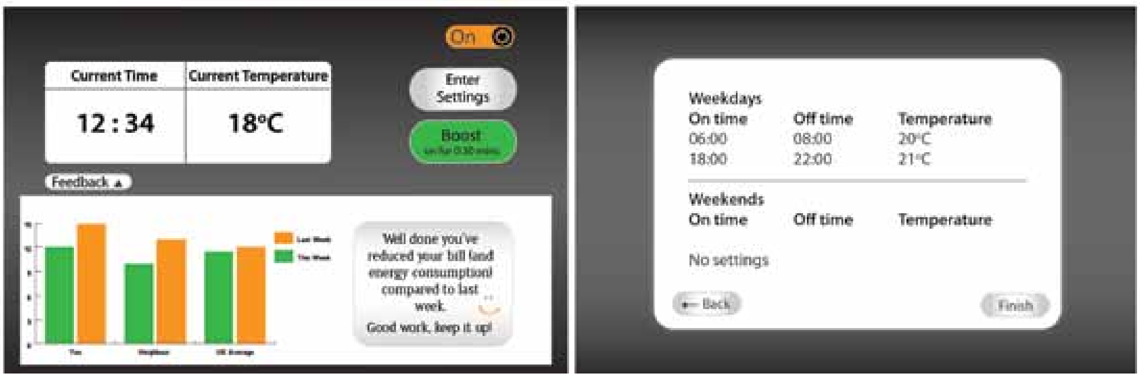


Figure 6.10 Paper Prototypes

The use of paper prototypes was helpful in identifying high-level usability problems at an early stage in the design process. Four usability issues became apparent during the initial testing as areas for the following improvements to the final interactive prototype:

1. Providing a help button on all of the screens available to the user
2. Adding a link to the current settings summary on the home screen
3. Removing the on/off switch, which was deemed redundant
4. Clarification of the interaction between saving a setting and moving to the next setting

In the final prototype, the help button appeared on all screens and provided help relating specifically to the screen that the user was interacting. The on/off switch was removed, however the provision of an 'Out of House' button was considered to help reduce energy. This would only turn the system on to protect the piping of the heating system when the temperature dropped below a given value, such as 5°C or 7°C.

To clarify the saving setting interaction the labelling of the buttons was modified. 'Enter' now saves one complete setting; an error message would be displayed if the user attempted to submit an incomplete setting. The 'Finish' button completes the programming process rather than 'Ok' used previously. The 'Ok' button now features as a confirmation button on the summary screen.

Despite only a small number of participants taking part, common points of confusion were easily identified. The results helped refine the interface to ensure that the final prototype worked efficiently and intuitively.

6.4 User Testing Results

The user testing aims to evaluate how effective the prototype was in fulfilling its core functionality, to reduce the user exclusion and cognitive demands of the programming task. This section discusses the results of this evaluation including the results of the HTA, exclusion calculation, usability testing and the Raw TLX assessment.

6.4.1 Hierarchical Task Analysis

The HTA, shown in Figure 6.8, clarifies the tasks required to programme the prototype and helps identify where errors may occur in the process. The HTA, shown in Figure 6.11, shows the 17 overall decision tasks, which must be completed to achieve the goal of programming the control. In terms of errors, the HTA identified there may be confusion over whether the 'Enter' button is pressed after each time or temperature or only once all fields are complete. This was a specific point of interest in the user observation stage of the evaluation.

In comparison to the HTAs conducted previously the number of decision steps has been reduced by between 10 and 15 decisions depending on the control assessed. Furthermore, of these 17 decision steps in the central plan only 8 are unique decisions. The other 9 are a repetition of the same 3 tasks; setting the on time, the off time and the temperature (four times in total). Further reductions in the cognitive load are expected through the simplification of the individual sub-task plans, which are sequential in nature, i.e. "Do 1 then 2" or "Do 1, 2 or 3". The only sub-task with an associated decision is the final one, "Reviewing the Summary Screen", where the user must decide either to change the settings or accept them as shown.

The HTA has been colour coded to give a visual representation of the main capabilities required to complete the task or subtask, shown in Figure 6.12. Locating the interface within the home has been excluded from this analysis, as it is designed to operate across a range of platforms not at a fixed location.

6.4.2 Exclusion Calculation

From the HTA it is apparent that the main capabilities involved in the task are thinking, dexterity and vision. Minimal reach and stretch may be involved in moving the hand and arm to press buttons or move a mouse depending on the platform the interface is being viewed. There are no locomotion or hearing requirements of the system. For the purpose of this Exclusion Calculation the prototype is assessed based upon use on a laptop.

The calculations were performed for two age ranges: 16–102 years (the default and maximum available data) and 60–80 years (to represent the older user group). To improve the objectivity of the assessment the analysis was performed by Jonathan Fox, an Access Consultant at Buro Happold who was not involved in the prototype development. The extent of the capability required was noted during the assessment and is shown in Table 6.3 to enable repetition.

Figure 6.11 Hierarchical Task Analysis of the Heating Control Prototype

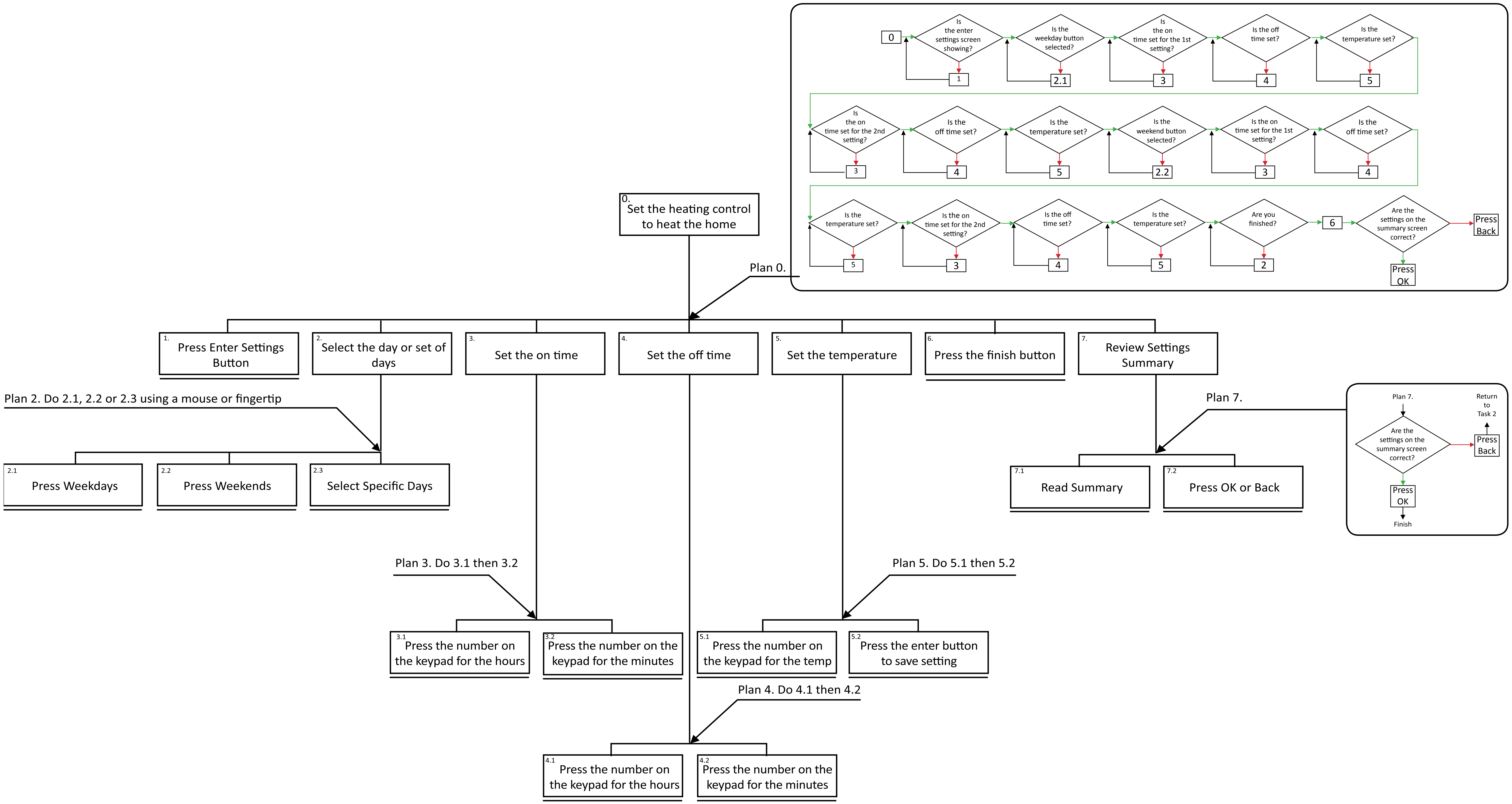


Figure 6.12 Hierarchical Task Analysis of the Heating Control Prototype, Colour Coded by Main Capability Demand

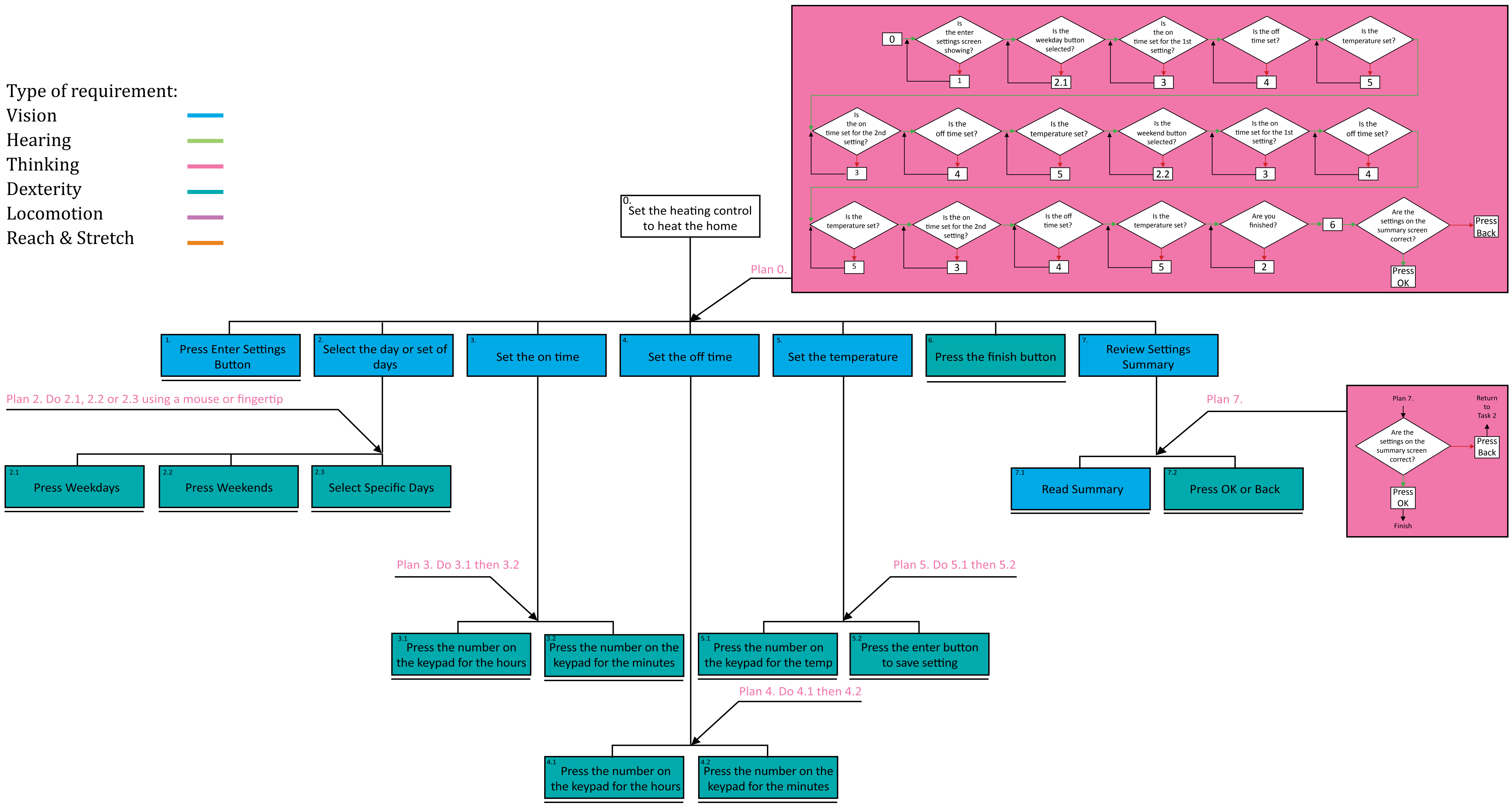


Table 6.3 Evaluating the Type of Demands of the System

Capability	**Type of Demand**	**Level of Demand**	**Reason for Choice**
Vision	Reading text at various distances	Read ordinary newsprint (3/3)	Text on the interface was judged to require considerable visual acuity
Hearing	None	None	The system has no audio feedback
Thinking	Think clearly without muddling thoughts. Do something without forgetting what the task was while in the middle of it. Remember a message and pass it on correctly. Read a short newspaper article. Remember to turn things off, such as fires cookers or taps	5 out of 13 options selected (5/13)	The thought process primarily completing a short task These phrases were judged most relevant to the scales available
Dexterity	Performing fine-finger manipulation with one hand	Turning a page (1/3)	Turning a page equivalent to using a mouse
Reach and Stretch	Reaching one arm out briefly.	Reach one arm out in front (briefly) (1/3)	Interface requires user to use a mouse or to hold a phone in front of them
Locomotion	None	None	The interface would be in flexible locations such as web-based or phone-based

The exclusion calculation results give an overall exclusion of 7.4% for users aged 16-102 years old and 13.1% for users 60-80 years old. This was 0.1% and 0.4% less compared with the previous calculations. This gives an indication of the levels of exclusion, which could be expected during the user testing. The most demanding capabilities were thinking and vision, whereas dexterity requirements had been reduced.

Table 6.4 Calculated Design Exclusion for Both Age Ranges

Capability requirement	Number of people excluded aged 16-102	Percentage of population aged 16-102	Number of people excluded aged 60-80	Percentage of population aged 60-80
Vision	1 525 000	3.4%	629 000	4.3%
Hearing	0	0%	0	0%
Thinking	2 165 000	4.8%	719 000	7.5%
Dexterity	456 000	1%	176 000	1.9%
Reach and Stretch	47 000	0.1%	27 000	0.3%
Locomotion	0	0%	0	0%
Total Exclusion*	3 359 000	7.4%	1 247 000	13.1%

*Total adjusted by calculator to account for overlap between disabilities

6.4.3 Task Performance Results

During the user testing three metrics were assessed: task success (and accuracy), time taken to complete the task and use of help features. This section reports the results of these metrics measured during the user testing, prior to reporting the RTLX scores.

6.4.3.1 Task Success

The definition of successful task completion was based on the process illustrated in the HTA. If one of the steps in the HTA was not completed then the task was judged unsuccessful. For example, if the user did not press the 'Finish' button to complete the task this would be unsuccessful. Regarding accuracy in the task, one numeric user error in the time or temperature setting for the task would be acceptable, however more than one would result in task failure.

Similarly, the task was deemed successful if the participants programmed individual days (such as Mon-Fri then Sat and Sun) or the Weekdays/Weekend option as either is correct. It was judged therefore that if the user missed a step in the HTA or made more than one accuracy error the user was excluded by the product.

Overall, 23 of the 31 participants (74.2%) were successful in the programming task. Of these, 19 participants (61.3%) were completely accurate in completing the task (shown in Figure 6.13). Four successful participants made one minor input error, for example inputting 21°C instead of 20°C for the weekend morning temperature.

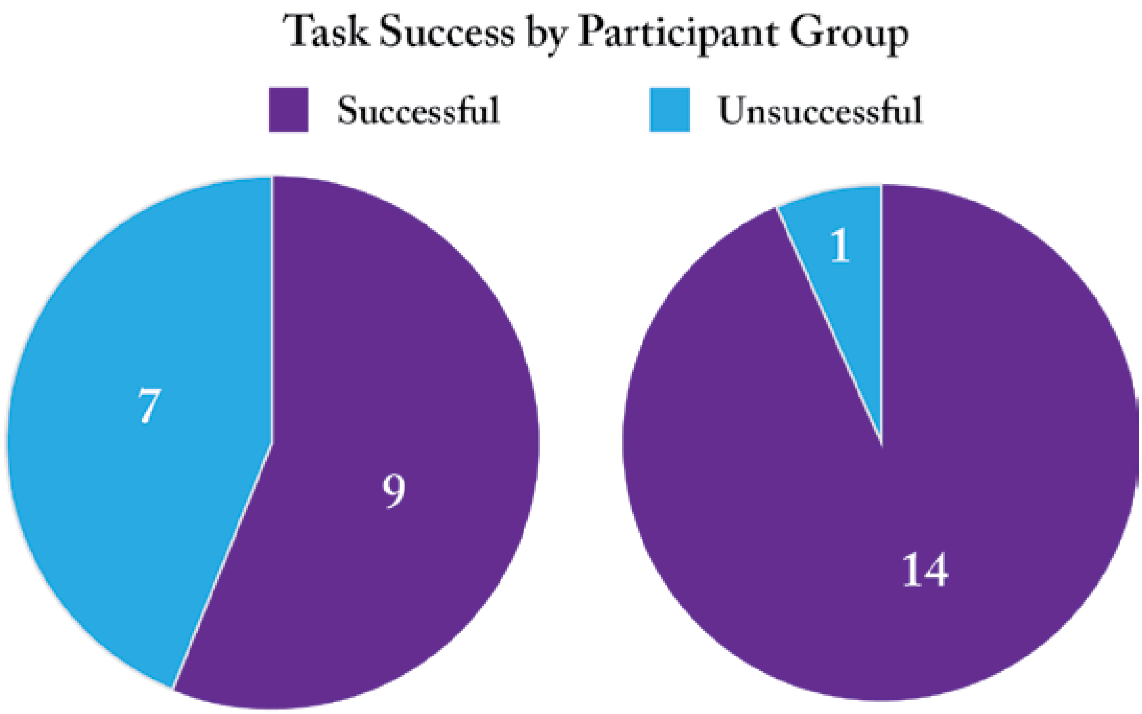


Figure 6.13 Successful Participants by Age

In terms of task success, 9 of the 16 older users were able to programme the prototype for two heating periods on the weekdays and two on the weekends. This gave a success rate of 56.3% for the older participants. Despite the improved success rate, a Chi-square goodness-of-fit test discerned there was still a significant difference between the observed and expected exclusion of the older age group ($p < 0.01$ as $X^2 = 13.204$ and $df = 1$).

Only 1 of the 15 younger users did not complete the task successfully. This was due to the participant not saving the weekend evening setting and entering an incorrect temperature earlier in the task. This gave a success rate of 93.3% for the younger participants. Hence, there was no significant difference between the younger users excluded and estimated exclusion for the general population ($p < 0.971$ as $X^2 = 0.001$ and $df = 1$).

Of the 14 younger participants that were successful, 7 were male and 7 were female. In contrast, women in the older user group had greater success in the programming task than the men. Of the successful older participants, 3 were male and 6 were female. A Chi-square test for independence was not possible due to the frequency of success being less than 5 for older male participants. However, it is unlikely the difference between older male and older female participants' task success would have statistical significance.

6.4.3.2 Task Performance Time

For the older participants the average successful task time was 5 minutes 32 seconds (332 seconds; shown in Figure 6.14). The fastest successful task time was 2 minutes 19 seconds (139 seconds) ranging up to 9 minutes 51 seconds (591 seconds) for the slowest successful task time.

A Mann-Whitney U Test revealed there was no significant difference between the successful task times of older male and female participants (U=3.0, z=—1.55, p=0.121, r=-0.052). However, there was a strong, positive correlation between the participants' age and the time taken to complete the programming task successfully (r=0.687, n=23, p<0.01). This correlation is significant at the 0.01 level (two-tailed).

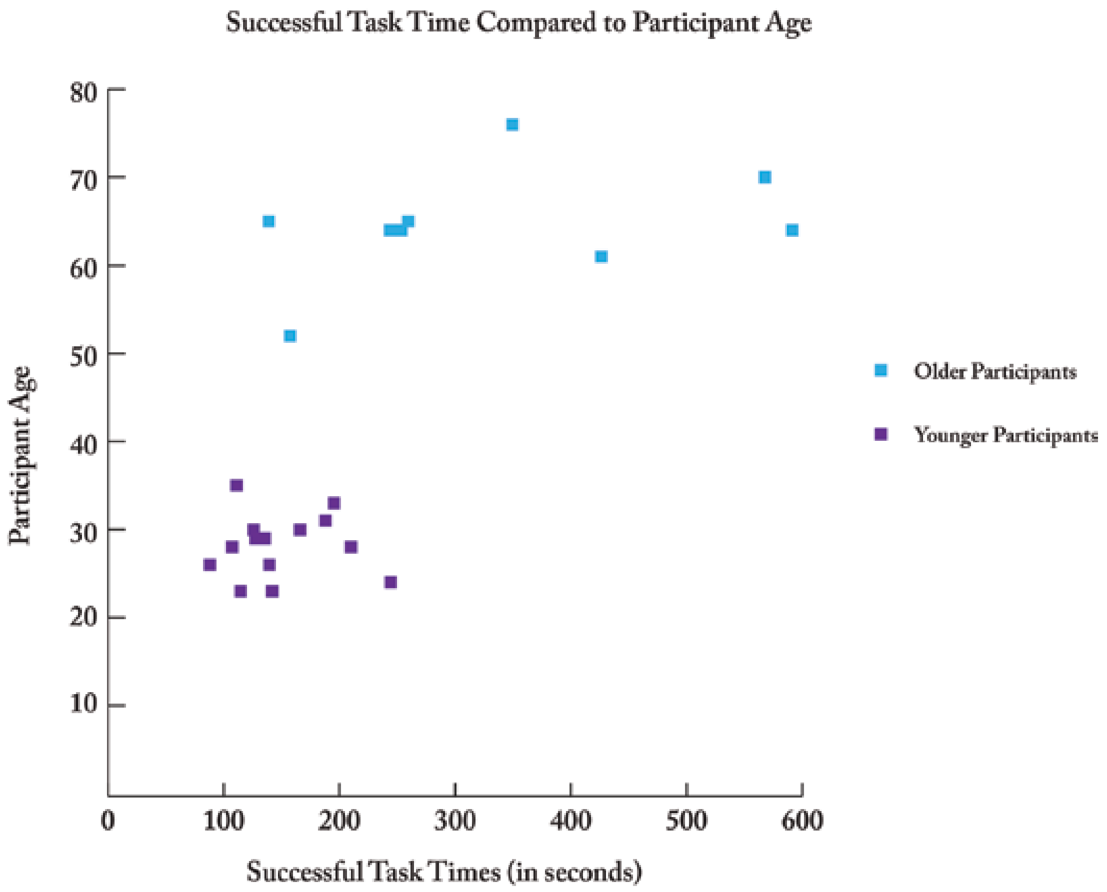


Figure 6.14 Scatter Plot of Ages of Successful Task Times

The successful younger users were significantly quicker than the older users at completing the task, with average successful task time 2 minutes 30 seconds (150 seconds). An independent t-test was conducted to compare the successful task times for older and younger participants. This revealed a significant difference in successful task times for older users ($M=331.9$, $SD=165.4$) and younger users ($M= 149.5$, $SD=44.8$; $t(8.76) = 3.231$, $p=0.011$, two-tailed).

6.4.3.3 Use of Help Features

No instruction manual was provided with the prototype as it was thought that the interface should be designed so that it is intuitive enough to use without instructions. Furthermore, the instruction manuals of existing products were found to be a point of confusion during the previous testing. A help function was provided on the final prototype, shown in Figure 6.15, to explain what each feature did at the point of interaction, putting the instructions in context. However, only one of the unsuccessful older users looked at the help function when they found the task difficult.

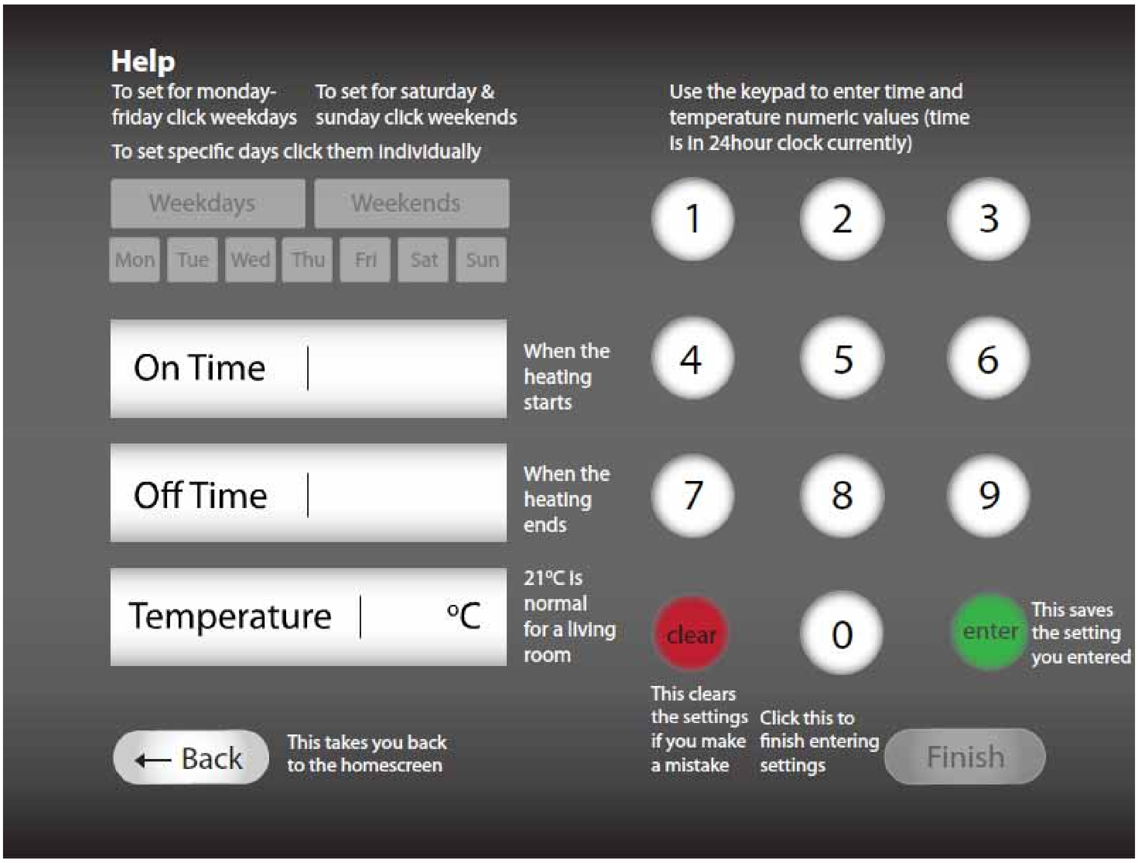


Figure 6.15 Help Displayed in Context on Screen

It is possible that the help section did not appear like a button and went unnoticed by some users. One user commented it may be more obvious at the bottom of the screen and another said she would only look for help had the system been unresponsive. When shown the help feature upon successful completion of the task one participant commented, "The instruction there is so clear that had I gone to that page first I would have had no doubt about what I was to do". The same participant also commented that having the help in context was useful, as they would not use an instruction manual.

Again, only one younger user used the help feature. The participant said the help feature was not initially obvious as a button but that when pressed it was useful. With regard to the fact that the help was in context the participant commented, "It was nice how [the instructions] all came up and did everything in one go. Normally help, it just takes too much time to read through".

6.4.3.4 NASA TLX application

Overall workload tended to be higher for older participants than the younger group (mean 36.1 vs. 21.7), with the lower rating implying a lower level of demand. The scales that were rated highest amongst the older users were mental demand (mean = 47.5, younger users mean = 34.0), followed by frustration (mean = 41.6, younger users mean = 20.6) and effort level (mean = 41.5, younger users mean = 26.8; all shown in Figure 6.16). Although the average older users' mental demand, frustration and effort scores were above the high workload threshold of 40 (defined by Knapp and Hall, 1990, cited in Gawron 2008), all were below the half way mark of 50. In terms of perceived performance, older participants rated their performance higher than previous testing with an average score of 44.7. This reduced further to 35.0 for successful older participants (with 100 being poor perceived performance). Similarly, younger users perceived their performance as successful with an average score of 17.9.

For the frustration and effort levels, significant differences were found between the older and younger users. A Mann-Whitney U Test revealed a significant difference in the frustration levels of older participants (Md=34.4, n=16) and younger participants at the $p<0.05$ level (Md=13.5, n=15; U=68.5, z=-2.039, p=0.041, r=-0.366). Similarly, significance at the 0.05 level was also revealed between the effort levels of older participants (Md=34.4) and younger participants (Md=15.6; U=69.0, z=-2.024, p=0.043, r=-0.364). However, there was no significance between the mental demand scores of the older and younger participants. This implies that older participants found the task required significantly more effort and caused significantly more frustration than amongst the younger participants.

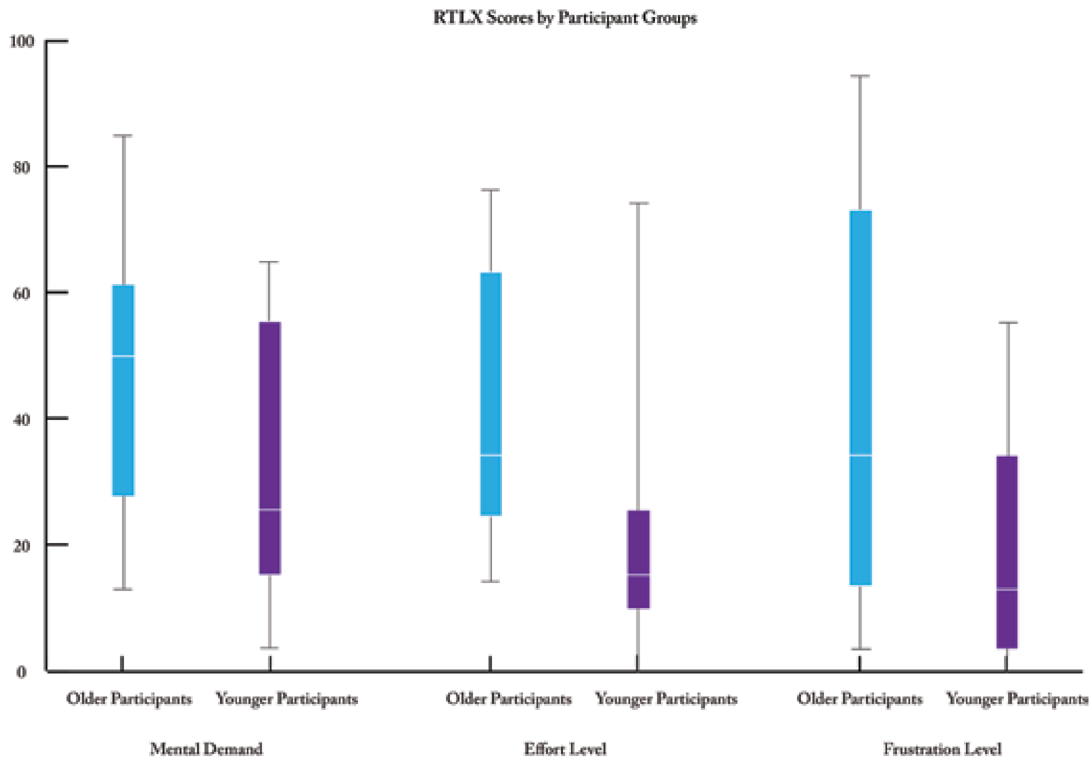


Figure 6.16 TLX Scores by Participants

6.4.5 Observations

During the testing participants were observed to identify points of confusion and areas for further improvement. There were five main observations, which may translate into design improvements to reduce user exclusion further. The first of these was the observation that many participants clicked either the text box or the label relating to the text field they were attempting to enter values. This was observed for 9 of 16 older participants and all of the younger participants. Highlighting the active field using colour or a flashing cursor may help the user understand where an input is expected.

Secondly, this may reduce an error observed in 6 of the older participants who did not understand, at least initially, that the minutes field for the on and off times was required. This was despite 'Mins' being displayed as a prompt in the text field as an indicator. Younger users did not appear to have this issue although one asked as to whether the clock was 12 or 24 hour.

When fields such as this were not completed and the participant attempted to enter the setting an error message "Not all fields have been completed" was displayed. Error messages such as this were observed to have little impact on the behaviour of the participants. More specific feedback, both visual and text based, should be incorporated to help users identify where errors had been made.

The main observation for the younger participant group was uncertainty as to whether a setting had been stored once 'Enter' was pressed. 'Enter' saved the setting and cleared the screen ready for the next setting to be input. The clearing of the screen led to 7 of the younger participants questioning whether this had been stored or deleted. Providing confirmation that the setting had been saved would improve user confidence during the programming task.

Lastly, the 'Clear' button was a source of frustration for 4 older participants and 3 of the younger participants. Rather than clear one character or field it cleared the entire setting. This was due to the researcher's limited ability to programme such a level of functionality. Ideally, the 'Clear' button would delete one character or field at a time. This would make the system more tolerant to user errors and reduce the associated user frustration.

6.5 Discussion and Further Work

This discussion focuses on the comparison of results between the two user groups and the implications of these results on reducing design exclusion. Interesting observations regarding participants' technical self-confidence scores are also reported. These support the fact that the prototype being based on web platform or touch screen on a wall was not seen as a barrier to use amongst older participants. Limitations of the study are recognised and further areas for design development are considered.

6.5.1 Reductions in Design Exclusion

Despite the considerable design effort, the calculated exclusion was only reduced by a minimal amount. The HTA illustrates that the cognitive demand has been reduced and the plans have been simplified to help reduce cognitive exclusion. However, this is not reflected in the Exclusion Calculation results. This highlights both the subjective nature of the calculator and the limitations of the cognitive scales currently available. Nevertheless, older users were successful in completing the programming task using the prototype. By implication, the results indicate that the user exclusion has been reduced. The success of 56.3% of older participants is encouraging evidence to support the argument that inclusive design can help reduce the cognitive exclusion relating to digital programmable thermostats.

The time taken for the older participants to complete the task successfully was on average 5 minutes 32 seconds, more than double the average successful task time of the younger participants (2 minutes 30 seconds). Interestingly, this was quicker than the average successful task time for the younger users (7 minutes 26 seconds) in the previous study using the same task settings. Furthermore, the successful completion of the task is thought to be more important than speed of completion in indicating a reduction in user exclusion.

The cognitive demands were lower than previously recorded, with overall mean RTLX scores being below the low demand threshold of 40. Amongst older participants, the scores varied largely depending on whether the participant was successful or not, as shown in Figure 6.17. Those that were successful rated the demands low on average; mean mental demand was 40.9, mean effort 33.8 and mean frustration 26.3. This suggests that cognitive exclusion has been reduced for the programming task, at least amongst successful participants.

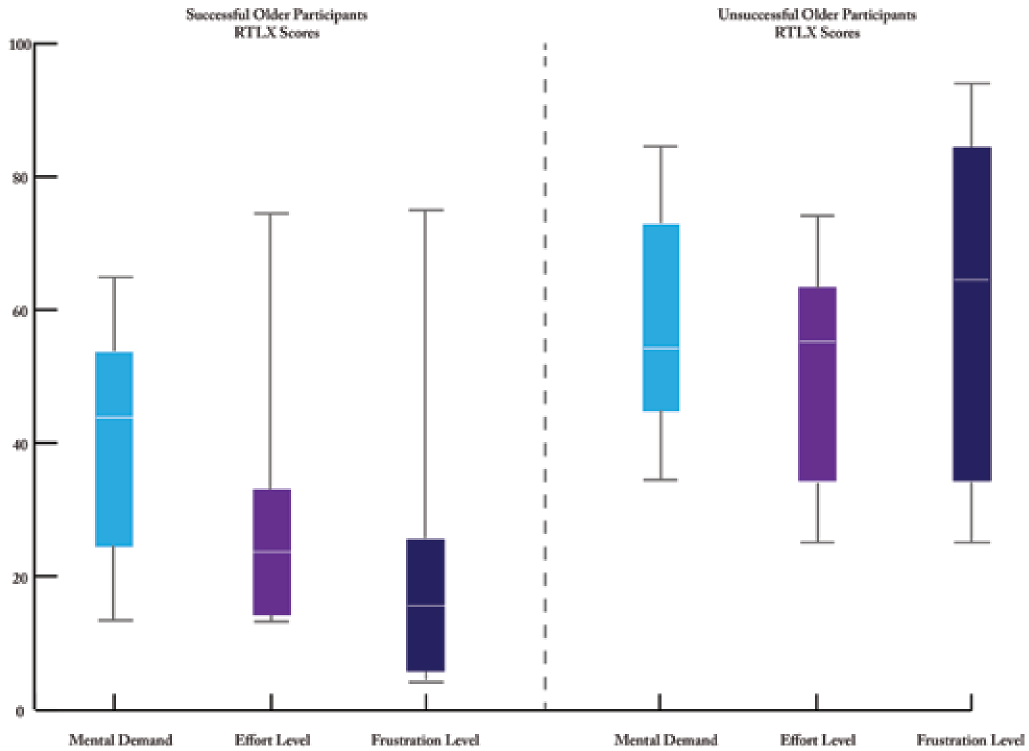


Figure 6.17 RTLX Scores for Successful vs. Unsuccessful Older Participants

However, unsuccessful participants rated the system higher with mean frustration highest (61.3). Task success was found to have a large and significant effect on frustration levels for older participants, shown in Figure 6.14. A Mann Whitney U Test revealed a significant difference in the frustration levels of unsuccessful older participants (Md=64.6, n=7) and successful older participants (Md=15.6, n=9; U=9.5, z=-2.33, p=0.02, r=-0.58). Task success was not found to influence mental demand (mean= 56.0) or effort levels (mean= 51.5) significantly amongst the unsuccessful older participants.

6.5.2 Technical Self-Confidence

Technical self-confidence data was gathered prior to attempting the task using the prototype. Interestingly, older users who rated themselves as most technically self-confident were not successful with the task. Participants that rated themselves less confident had greater success, with 3 of the 4 participants that rated their technical self-confidence less than 50% successful with the task. These participants also performed quicker with an average task time of 3 minutes 40 seconds compared with 6 minutes 28 seconds for users with technical self-confidence scores above 50%.

Overall, there was a negative correlation between age and technical self-confidence, with self-confidence decreasing with age ($r = -0.229$, $n = 31$ and $p=0.215$). This negative correlation was small and did not reach levels of statistical significance. Of the unsuccessful older participants, 6 out of 7 rated their self-confidence highly (above 60%). Participants with a high technical self-confidence appeared to be less patient and got frustrated quickly. Highly confident older people were also less tolerant of error messages. Only the participant with the lowest technical self-confidence score of 22% was also unsuccessful.

6.5.3 Study Limitations

The main limitation of the study was the concept nature of the prototype and the small sample size of the study. The small study sample and between-group study design makes it more difficult to get statistically significant results. Hence, the study results cannot be generalised. Further work would be required to test the final prototype in a larger number of homes and with older people living independently.

A further limitation of the study is ability of the researcher to programme more advanced functionality to the prototype. Ideally, error messages would be displayed in relation to specific errors or incomplete fields. However, the researcher was only able to indicate in a generic message that a field was incomplete or an error had been made and not specifically where the error lay.

Additionally it was anticipated that participants would use either individual day buttons or groups of days and not a combination of the two, which was observed. The prototype was unable to provide a summary screen that contained a mixture of the two settings. For example, if the participant entered settings for ‘Mon-Fri’ then ‘Weekends’ only the weekend settings were shown in the summary screen.

6.5.4 Further Work

Further development of the prototype is based upon the user observations. Improvements to the system error handling would help reduce user frustration, with specific information regarding where a value was required. Similarly if the 'Finish' button was greyed out when there were no settings entered this may reduce confusion surrounding how to enter a setting. This could then become active when suitable settings had been entered.

One observation discussed was that most participants clicked into the text input boxes to ensure they were active. Other participants were observed clicking the words 'On Time', 'Off Time' and 'Temperature' or the surrounding boxes before entering the value in an attempt to ensure the value went to the correct field. Showing the user a flashing cursor in the active text input field or highlighting the area where a value is expected may help support the user further.

A summary of the programmed settings is provided at the end of the process and several participants found this useful. As mentioned previously, the prototype should be developed to cope with a mixture of individual and groups of days in the summary screen. Furthermore, being able to edit an individual setting via the summary screen to cope with changes to schedule without having to re-programme the control could improve user satisfaction with the system.

Additionally, if a particularly long time were set for the heating to be on or at a particularly high temperature the user would be warned in the summary screen. This may form a 'nudge' towards more energy efficient behaviour at the point of control, which could enable energy savings. Furthermore, this system may incorporate information on energy consumption data consistent with the requirements of the UK smart meter rollout. This requires both heat and electricity energy consumption feedback in households by 2020. Integrating these design changes in the development of the actual support could improve task success rates, reduce user exclusion further and enable energy savings.

6.6 Conclusions

The main aim of this study was to reduce the user exclusion, in particular the cognitive exclusion, relating to programming a digital thermostat. The results tentatively suggest that the user exclusion has been reduced due to the increased task success rates of the older participants. The prototype is also judged nominally more inclusive according to the Exclusion Calculation results.

The improvements in the programming task success rates of older participants allows the tentative conclusion that the prototype heating control is more inclusive than existing digital programmable thermostats. The improvements in task success rates and reductions in successful task times observed for both groups of participants further this argument.

The reduction in cognitive demands of the prototype interface are notable, with mental demand and frustration scores being low amongst younger participants and successful older participants. The lack of significance between the mental demand of the younger and older participants further supports the argument that cognitive demands have been reduced.

Although the results may not be generalised due to the small study sample, the need for future testing is recognised. Similarly, the areas of improvement noted should be addressed prior to any further testing. This may help reduce the significant levels of frustration still observed in unsuccessful older participants. The study results support the argument that the cognitive exclusion relating to digital programmable thermostats may be reduced through a more inclusive design solution. The combination of results from the HTA, Exclusion Calculation and user testing strengthen this argument.

Preferably, such a heating control interface would help reduce incidences of heating the home when the occupants are not present or during the night, as was observed in Chapter 5. Reducing or eliminating such incidences of unnecessary heating could have a significant environment impact, the scale of which requires further investigation.

Chapter 7 - Estimating The Impact On Heat Energy Consumption Of User Interaction With Heating Controls

Abstract

From the observations of users in the previous research, it became clear many people struggled to use digital programmable thermostats. Without being able to programme their controls, people are unlikely to save energy and may even consume more energy as a result. One key observation was that some users did not reduce heating temperature at the end of the heating period. This may result in accidental heating throughout the day and/or night, unbeknown to the users. The remaining research is to estimate the scale of the energy savings achievable through improved user interface design.

This chapter aims to assess the energy impact of this particular user error in two case studies in the south-east of England. It also compares the energy impact of a variety of possible heating profiles on the two case studies modelled. The use of the model from the Elmswell 'Clay Field' development (Elmswell) allowed the model to use real-world data measured in-situ to improve its accuracy. The results from the Elmswell model have also been compared to the real-world thermostat settings and heat energy consumption of the dwellings on that site. The use of the Retrofit House model allowed for comparison with a larger, older and less efficient building type.

The modelled results indicate an increase in heat demand of between 14.5-15.6% annually. This is achieved when comparing the programming error to the energy consumption of the successful programming of the profile from the user testing. These results showed that users who successfully programmed the heating control could consume less energy, than the default settings of the Honeywell, Drayton and Salus controllers in both case studies. The results help suggest the scale of any energy savings possible by eliminating the user programming error. Further work would be necessary to establish the scale of energy savings an improved control system could achieve in reality.

7.1 Introduction

The objective of this study was to quantify the potential energy savings of the system developed. The study evaluated the energy consumption associated with one user programming error previously identified. This aimed to answer the fourth research question of "Does this user exclusion have an effect on the associated heat energy consumption?". The study compared the impact of a variety of possible heating profiles on the associated heat energy consumption of two domestic buildings in the UK. These two buildings are modelled in Integrated Environment Solutions' (IES) Virtual Environment 6.4.0.8. Both house models represent end of terrace, family homes; measured data has been used to define values of model variables, such as air tightness measured on site, wherever possible. The two buildings modelled represent common building types within the existing UK housing portfolio. End of terraces represent 10.1% and semi-detached homes 30% of the English housing stock. However, further evaluation of other building types may be required and should include mid-terrace housing, detached properties and flats. The process can be repeated to add the evaluation where building models are available.

The Elmswell development (discussed in Chapter 4) is a social housing development built to high standards and awarded BRE's EcoHomes Excellent certification. The site consists of 26 homes in Suffolk in the south-east of the UK. The Elmswell model was a two-bed, end of terrace house designed to be particularly well insulated and therefore should not require excessive heating. Furthermore using the Elmswell house allows for an increased level of robustness in the model, as measured data can be used to demonstrate its accuracy. In particular, this enables realistic values to be used for the insulation properties of the building fabric and hence greater accuracy in the assessment of the home's ability to retain heat. Similarly the Retrofit House is part of a social housing development in the south east of the country, albeit part of a much larger development built in the 1960's. Due to the similarities of the weather between London and Suffolk the same weather data was used to evaluate the two models, as were the heating profiles used.

From the earlier user testing of controls (Chapter 5), it was observed that setting the on and off times for a period of heating was problematic for users. This confusion surrounding on/off times could have a negative impact on energy consumption and could result in accidental heating throughout the day and/or night, unbeknown to the users. Two of three controls tested previously provided six intervals that can be programmed individually. Users frequently did not understand that the second, fourth and sixth time periods are essentially the finish or off times, where the temperature should be reduced. Five of the users did not turn the temperature down at this point when using the Honeywell control (approximately 20% of the sample). This resulted in the controls being programmed to heating throughout the day at 19°C and through the night at 21°C unintentionally.

The results from the modelling have been compared to the real-world thermostat settings and heat energy consumption available from the site at Elmswell. The results presented in this study help suggest the scale of any energy savings possible by eliminating this particular user error. As a result, this could provide an estimate of the environmental impact and improve the design of future control systems. Removing this potential error or providing the user with feedback to avoid this scenario could enable more efficient use of heating controls. However, further evaluation would be needed with the system implemented in homes to validate any of the modelled results.

7.2 Materials and Methodology

IES is a powerful software package that allows for the control of specific variables, which can influence the environmental performance of buildings. Once the geometry is created, the same building model can be used to evaluate the impact of solar irradiation, natural daylighting, natural ventilation and HVAC strategies amongst others.

IES was selected as the most appropriate software in attempting to evaluate the success of the intervention in a modelled scenario. IES is an industry standard software used for the detailed modelling of a variety of environmental parameters not solely energy performance. ECOTECT is a possible alternative to IES however, it is not used within the sponsor organisation to the same extent.

The energy modelling completed in this research used the combination of a detailed existing building model and the ApacheSim energy modelling plug-in. This enabled the researcher to assess the energy performance of the building, using realistic building parameters. This can then be compared to actual energy monitoring data of the building post-occupancy.

7.2.1 Design

This study uses two house models to estimate the scale of the energy saving associated with improvements in the usability of control systems. Both models have considered six possible heating scenarios, which are listed below and shown in Figures 7.1 and 7.2:

- The default settings of the controls tested in Chapter 5 (the Honeywell, Siemens and Drayton controls)
- The default settings of the controls installed at the Elmswell development, evaluated in Chapter 4 (the Salus control)
- The settings the participants were asked to programme as the example heating profile in Chapter 5 (Task Settings)
- The settings of the profile when the controls were not turned down at the end of the heating period (i.e. when the controls were left on through the day and night, labelled 'Misuse')

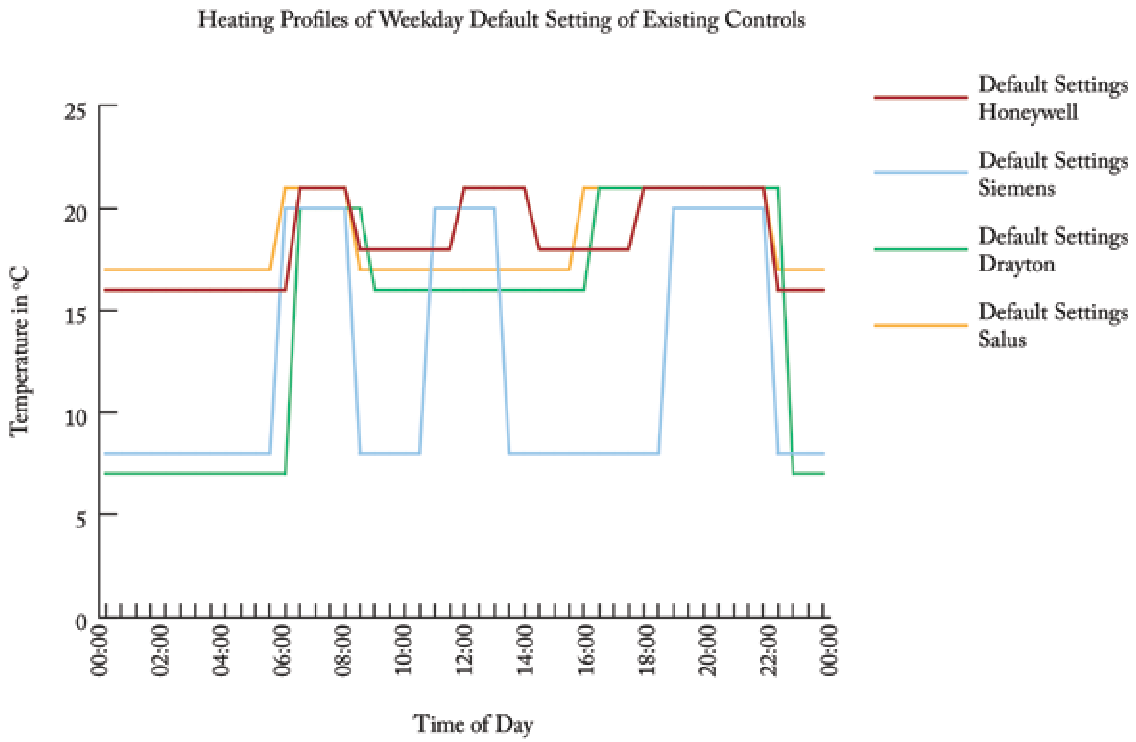


Figure 7.1 Heating Profiles for the Weekday Defaults of the Existing Controls

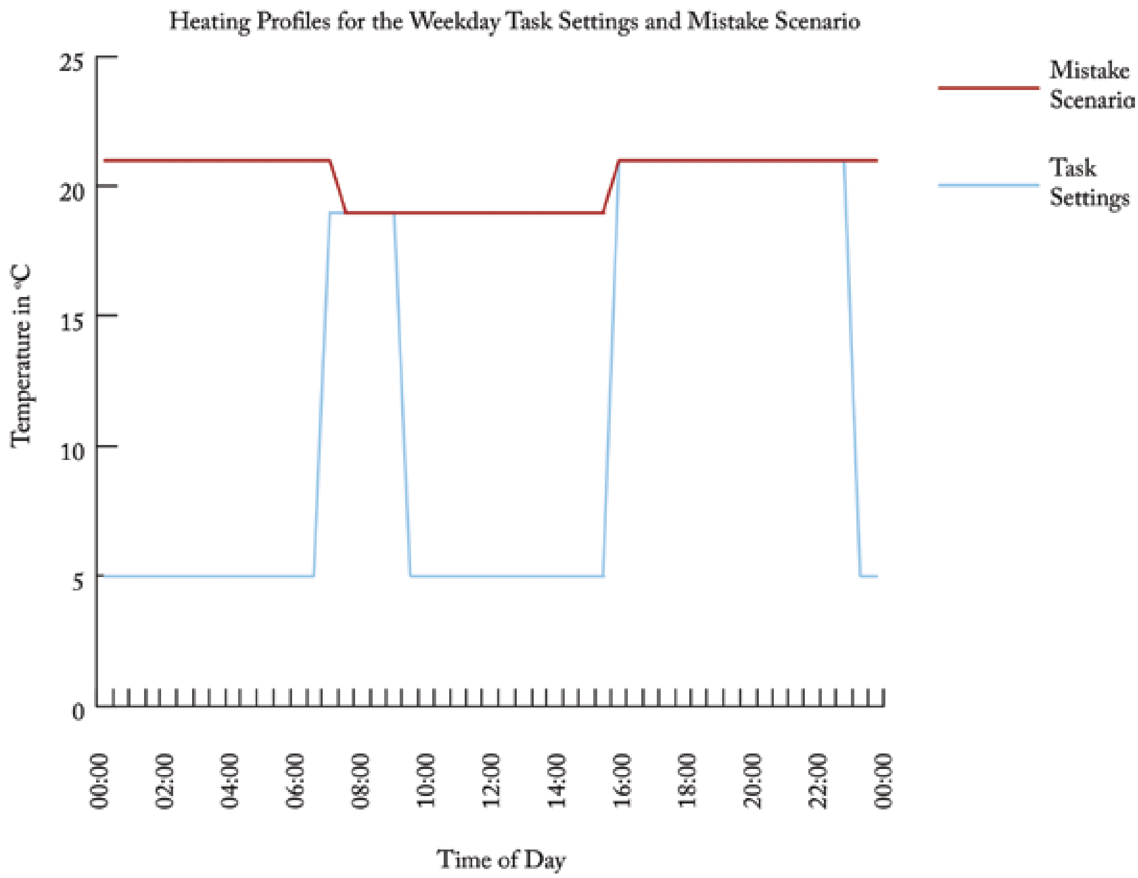


Figure 7.2 Heating Profiles for the Weekday Task Setting and Mistake Scenario

Using existing houses as the basis for the modelling allowed the development of accurate and realistic models, which is vital to elicit valid energy consumption results. Furthermore, using the model of the home at the Elmswell development will enable a basic comparison with actual consumption data. This was collected during a previous post-occupancy evaluation by Gill (2010).

7.2.2 Procedure

The study procedure consists of five parts. The first aspect is to create the model geometry, which already existed for these two buildings. Secondly, the variables, discussed subsequently, are defined within the model.

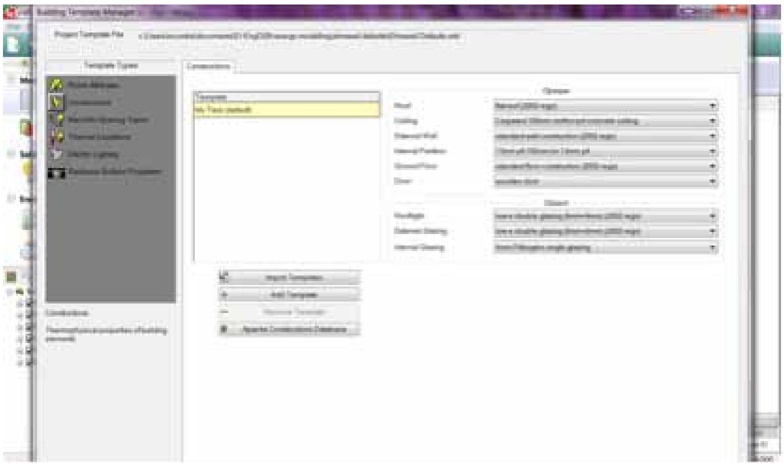


Figure 7.3 Screen Shot of Variables Defined Within IES

The main aspect of the work lies in defining the occupancy and heating profiles for the model. The weekly heating profile is made up of a weekday and weekend profile repeated for the associated number of days. Once the energy profiles were created, multiple building types can be evaluated using the same profiles.

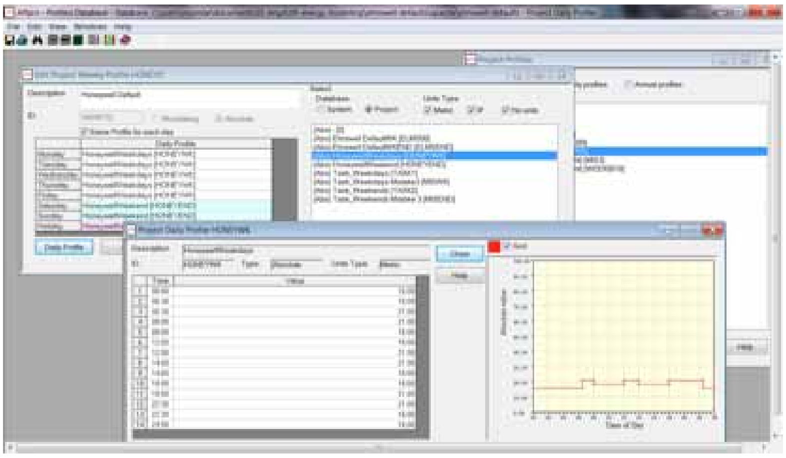


Figure 7.4 Screen Shot of one of the Profiles Created Within IES

When the heating profiles have been set up within IES, the parameters of the existing models are defined to be consistent with the measured data for the site where available. Each heating profile is simulated for both dwellings using the ApacheSim plug-in for IES. This runs for an entire year to establish the annual energy consumption for each heating profile in kilowatt-hours (kWh).

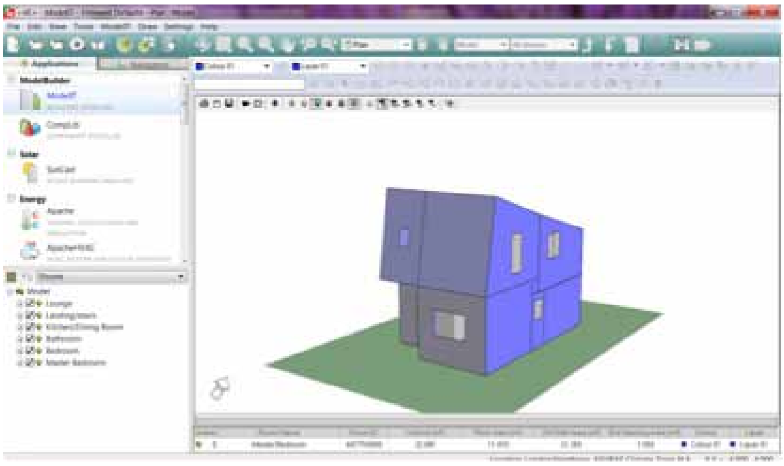


Figure 7.5 Screen Shot of the Elmswell Building Model Within IES

7.2.3 Variables

The parameters in the model represent the actual building where the U-values have been measured in-situ. As such, the property has an internal floor area of 69.1m^2 and a glazed area of 11.7m^2. The building has an external wall to glazing ratio of 9.8:1. In terms of floor area, this is consistent with the average size of a two-bedroom house from the CABE Dwelling Size Survey (Scott Wilson, 2010). The walls have a U-value of 0.25 W/m^{2}K performing better than the target U-value of 0.35 W/m^{2}K specified in the Building Regulations (Office of the Deputy Prime Minister, 2010). Similarly, the windows have a U-value of 1.4 W/m^{2}K, with 2.2W/m^{2}K the requirement of the building regulations. The roof U-value was set at 0.19 W/m^{2}K, which is significant as up to 25% of heat loss is through the roof of the home.

Occupancy is based on 25m^2 per person giving occupancy of 2.58 people per household, close to the average occupancy of 2.36 (Office of National Statistics, 2001). It was assumed the house is unoccupied for the majority of the daytime when residents are at work. Air infiltration is kept constant at 0.168ach, as was measured on site post-construction. The heating system delivery efficiency was kept consistent at 89%, which is comparable to an efficient boiler.

The Retrofit House property was larger with a floor area of 154.2m^2 with 4 bedrooms and a garage. The garage floor area was discounted however, as this would not be conditioned, leaving the remaining living area (including circulation) space of 119.8m^2. The building has an external wall to glazing ratio of 8.2:1. The U-values of the walls was set to be 0.35 W/m^{2}K consistent with the 2002 building regulations as no measured data was available. The windows have a less efficient U-value than those at Elmswell of 1.98 W/m^{2}K but still within the 2002 building regulation requirements.

Occupancy of the Retrofit House is again based on 25m^2 per person, giving occupancy of 4.49 people per household, which is considerably above the national average. It was assumed the house is unoccupied for the majority of the daytime when residents are at work or school. Air infiltration is set to a constant, default value of 0.250ach as again no measured onsite data was available.

Table 7.1. Summary of Variables and Performance Characteristics for the IES Models

Variables	**Elmswell House**	**Retrofit House**
Air tightness (ach)	0.168	0.25
U-value – Walls (W/m^{2}K)	0.25	0.35
U-value – Windows (W/ m^{2}K)	1.355	1.98
U-value – Roof (W/m^{2}K)	0.1899	0.1899
Internal gains – Lighting (W/ m^2)	12	12
Internal gains – People (W/person)	90	90

7.3 Results Part I - Modelled Results

Both dwelling models show that the scenario with the observed user error previously identified resulted in the largest annual energy consumption, as detailed in Table 7.2. The energy consumption of default heating profiles of the controls occurs in the same order for both case studies. For three of the controls (Honeywell, Drayton and Salus) the default setting consumption is greater than if the task profile was programmed successfully. This indicates that leaving the controls on the default settings is not necessarily the most energy efficient solution. This may be in part due to the high default daytime setbacks of the Honeywell and Salus controls, of 18°C and 17°C respectively. Incidentally, 18°C is considered a desirable temperature for occupied rooms other than living rooms in CIBSE Guide A (1999).

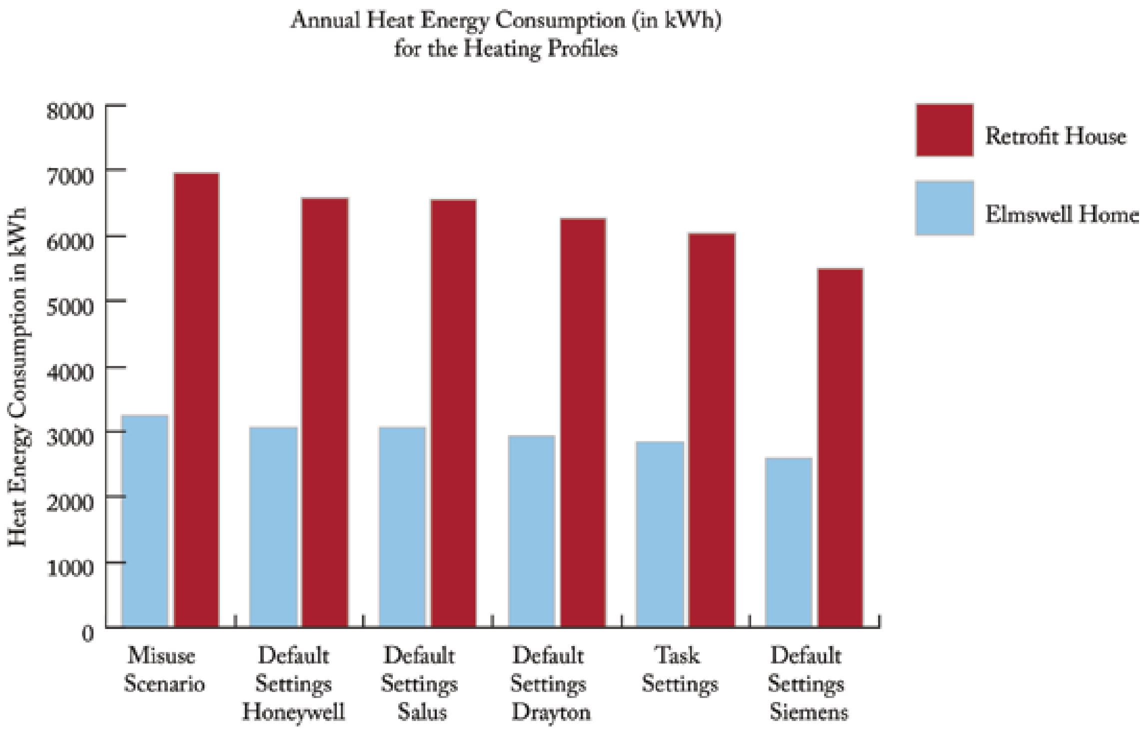


Figure 7.6 Annual Energy Consumption of Both Homes for Each Scenario

Table 7.2 Annual Energy Consumption in kWh and the Default Temperatures of the Controls

	Retrofit House (119.8 m²)	**Elmswell House (69.1m²)**	**Default Setback Temperature of Control**
Misuse Scenario	6956.7	3250.6	N/A
Default Settings - Honeywell	6572.2	3072.7	18°C
Default Settings - Salus	6557.6	3069.7	17°C
Default Settings - Drayton	6262.7	2940.4	7°C
Task Settings	6048.4	2839.3	5°C
Default Settings - Siemens	5496.4	2596.6	8°C

7.3.1 Elmswell Results

Firstly, the energy consumption of the default settings of the heating controls was compared to the task settings. These settings can then be compared to establish annual energy consumed in each scenario. Only the default settings of the Siemens control were more efficient than the task settings, this was due to an automatic set back temperature of 8°C and short heating durations. The Honeywell, Drayton and Salus controls consumed more energy annually than the task settings, shown in Figure 7.7 (where the Salus control represents the actual heating control installed at the development).

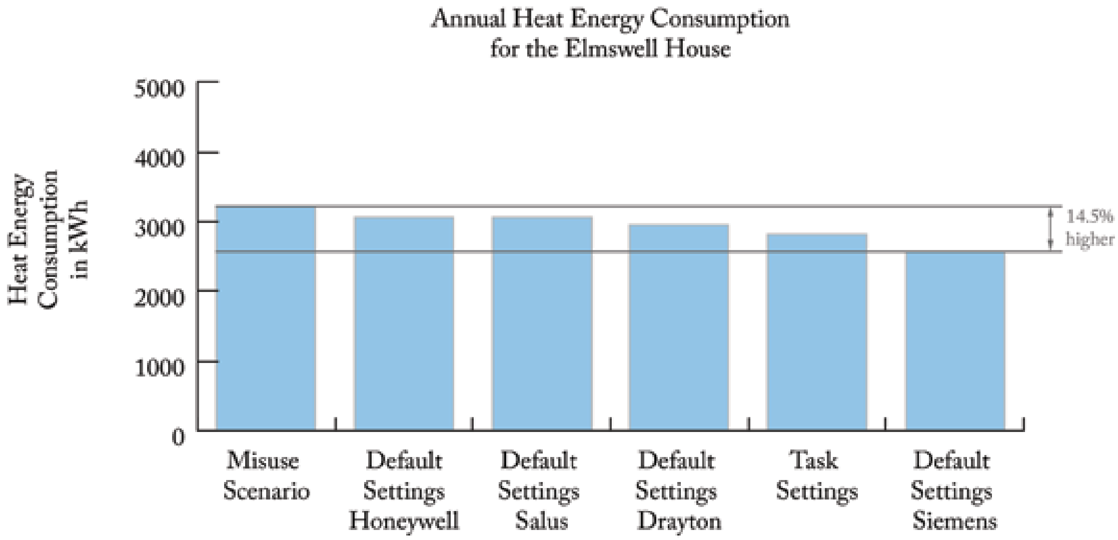


Figure 7.7 Annual Energy Consumption of the Heating Profile - Elmswell

The second point of interest to research was modelling the excess energy consumption of the user error observed. By accidentally programming the controls to heat through the day and the night, energy consumption was found to be 411.3 kWh higher annually than if the user completed the task successfully. This user error could theoretically result in an increase of 14.5% in heat energy consumption and the production of an extra 81.4kg of CO_2 emissions annually per household (carbon factor for natural gas = 0.198).

7.3.2 Retrofit House

In this scenario, the annual savings associated with achieving the task versus the misuse scenario was 908.3kWh, with an extra 179.8kg of CO_2 emissions produced annually. This illustrates that the energy consumption of the misuse scenario is 15% higher than if the user programmed the task settings successfully.

The Retrofit House consumption was higher primarily due to the increased volume to be conditioned. The building envelope performance did have some impact as shown in the per metre square (m^2) comparison in Table 7.3. Comparing the consumption per m^2 of the Retrofit House to the home at Elmswell there is an increase of approximately 10kWh/m^2 in consumption.

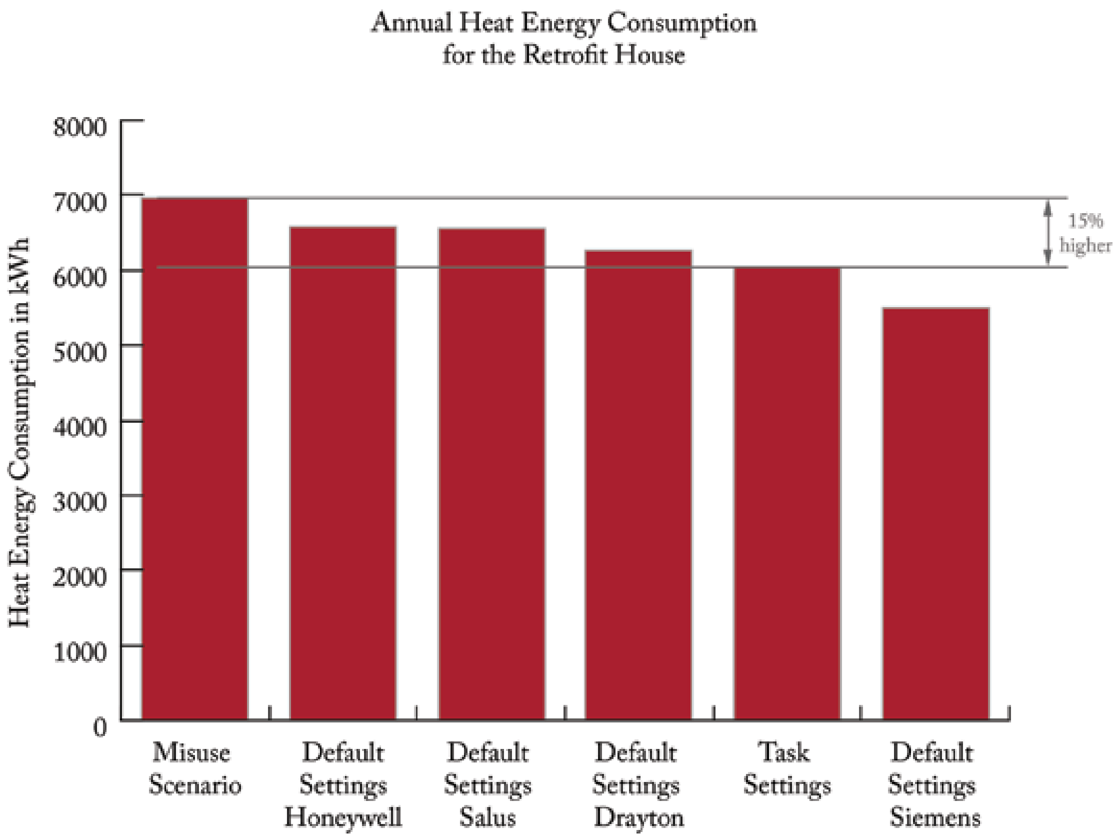


Figure 7.8 Annual Energy Consumption of the Heating Profile - The Retrofit House

Despite the differences in the building parameters used, the scale of the savings potentially achievable is consistent with the results from the Elmswell model. The reduction in energy consumption between the misuse and task scenarios was 15.0%, comparable to the 14.5% reduction from the Elmswell model.

Table 7.3 Comparing Consumption per m^2 Between Models

	Elmswell Consumption kWh per m^2	**Retrofit Consumption kWh per m^2 (0.25ach)**	**Retrofit Consumption kWh per m^2 (0.5ach)**
Misuse Scenario	47.0	58.1	64.4
Default Settings - Honeywell	44.5	54.9	-
Default Settings - Salus	44.4	54.7	-
Default Settings - Drayton	42.6	52.3	-
Task Settings	41.1	50.5	-
Default Settings - Siemens	37.6	45.9	55.7

To examine whether the same scale of savings would be seen in a less efficient model, the rate of air infiltration was increased from 0.25ach to 0.33ach and the simulation run again. This found that despite the consumption per m^2 increasing, the scale of the savings between the misuse and task scenarios remained similar, if slightly increased, at 15.6%.

7.4 Results Part II - Comparison with Real World Data Elmswell

To put the modelled results in context the recorded thermostat settings from the eleven houses studied at Elmswell were analysed. The initial modelling results suggest that the defaults of the controls available to users at the Elmswell development consume a comparable amount of energy annually to the default settings of the Honeywell control. It is unlikely that the default setting will be used outside of the test conditions and in the initial study at the Elmswell development; only one of the eleven houses used the default settings of the controls. The thermostat settings recorded during the initial study in Chapter 4 indicated that five of the eleven surveyed heated their homes at 20˚C or above after 23.00 hours. This was considered to be heating through the night, similar to the user error of not turning down the heating at the end of the heating period observed in Chapter 5.

As is consistent with the modelling of the misuse scenario, the real world data indicates that the houses heated during the night had higher annual heat energy consumption. The data shown in Figure 7.9 shows actual on-site energy consumption for heating and hot water. Observed performance from the Elmswell development correlates with results obtained from the modelling. In particular, the night-time heating impact can be used to verify the simulation results in part. Occupants who were observed to maintain high temperatures through the night appear predominantly at the right hand side of the graph, shown as red bars of Figure 7.9. However, it should be noted that of the results seen at Elmswell it is not possible to assume usability issues are solely responsible for night-time heating. Other factors such as working patterns and personal preference must be taken into account.

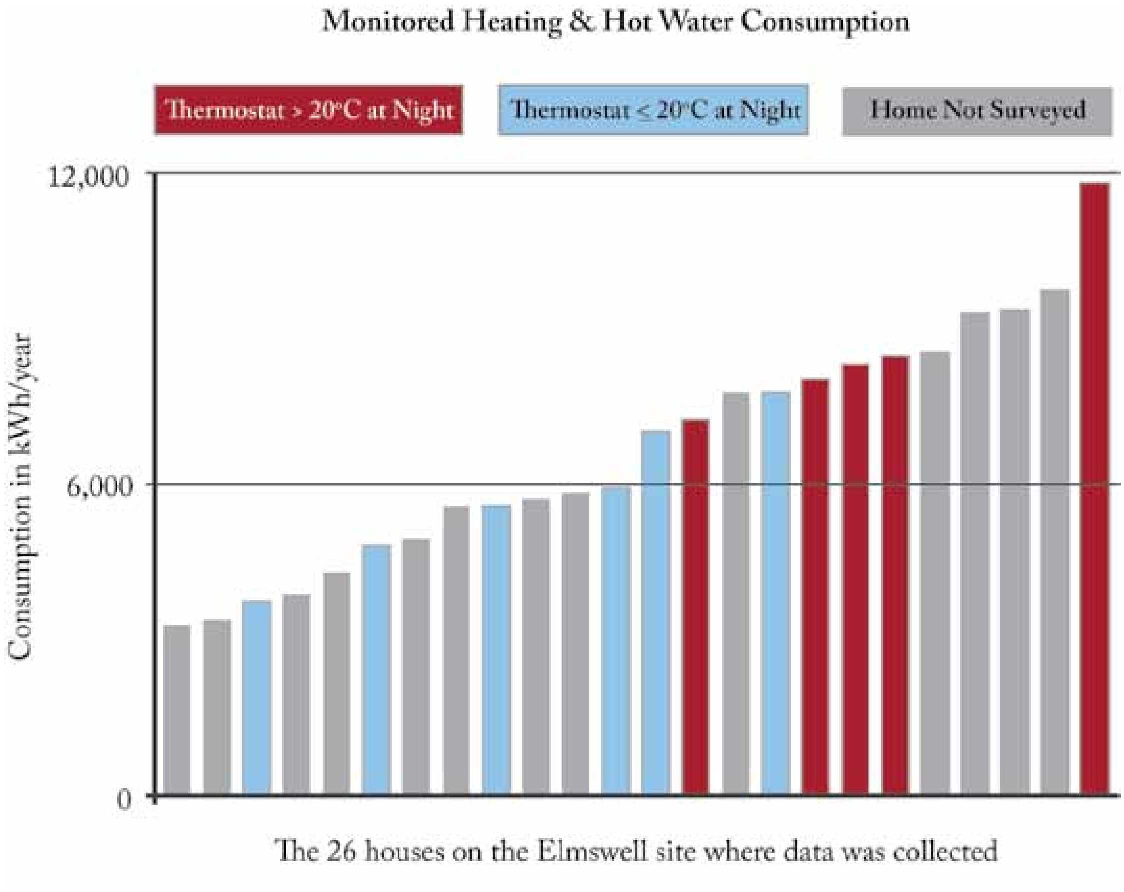


Figure 7.9 Actual Heating and Hot Water Energy Consumption of the Homes (Zack Gill, personal communication 2011)

7.5 Discussion

The energy modelling demonstrates that the user error observed could result in increased energy consumption of approximately 15% annually. Relating the energy modelling to the thermostat settings recorded at the Elmswell development indicates that the issues observed in the user testing translate to real-world behaviours. The error was observed in 20% of the sample in Chapter 5 and 45% of participants at Elmswell. If this problem occurred nationwide that would equate to between 5.5 and 11.9 million households. Although these numbers are large they are comparable with the findings of Wilhite et al. (1996) and Linden, Carlsson-Kanyama and Eriksson (2006), which found less than 50% of Norwegian households and 38% of Swedish households respectively did not reduce the temperature through the night. The estimated energy savings therefore could become more significant if scaled up from one housing developing to multiple households across the UK.

7.6 Conclusions

The actual energy consumption of the Elmswell development goes some way towards verifying that the houses that heated through the night consumed more energy. The real-world validation of the results is limited to the behaviour observed in the 24 participants of the user testing and again at the 11 dwellings surveyed on site. Therefore, the conclusions can only be tentative due to the small sample sizes of the validation group.

Future work should examine whether the improved control system does enable reductions in energy consumption. In support of this, further development of the prototype would be required and in-situ testing performed in a larger number of homes. The type of building, fabric efficiency, occupancy and local climate may influence the scale of the savings achievable.

The comparison of consumption per m^2 illustrates the impact of building fabric performance is potentially not as large as first thought. There does not appear to be a significant relationship between the fabric efficiency and the scale of savings estimated. Hence, the impact of improved controls is likely to be comparable across a range of dwelling types, irrespective of their efficiency.

The fact that savings could be made at the Elmswell 'Clay Fields' development, in such particularly well insulated homes, through proper programming of controls is encouraging. The default settings in any future control system should be carefully selected as the default set back temperature has been shown to have a considerable impact on the associated energy consumption. The verification of the modelled results adds credibility to the observed behaviours in the user testing. If periods of unintentional heating could be eliminated through the improved design of controls then the energy savings made could be in the region of 15% annually.

Chapter 8 - Discussion

This chapter compares the research findings of the studies presented in this thesis with the findings of the literature review and discusses whether the research questions outlined in Chapter 3 have been answered. This section expands upon the results and conclusions of Chapters 5 and 6 specifically. It also aims to develop and discuss the argument that reductions in user exclusion may also enable energy savings. Achieving energy savings will require not only well-designed, inclusive products but also changes in user behaviour. The discussion concludes with consideration of the ethical implications of the research.

8.1 What is the Scale of and Reason For User Exclusion Relating to Digital Programmable Thermostats?

The first and second research questions are closely linked in their scope and are discussed jointly in this section. The first research question relates to the scale of user exclusion regarding digital programmable thermostats. This is answered through the application of the Exclusion Calculator and the comparison of this to the results from user testing in Chapters 4 and 5. The second research question aimed to understand the reasons for user exclusion, especially the cognitive barriers to use of digital programmable thermostats. Barriers to the effective use of such products were identified in the literature review and the user testing reported in Chapter 5.

8.1.1 Scale of User Exclusion

The scale of the user exclusion, associated with digital programmable thermostats, was investigated in Chapter 4 and 5. These studies used four example controls of similar functionality. The Exclusion Calculator was used to give an estimate of the user exclusion based on the capability demands of the UK population. These results were then compared to the user observations both in home (Chapter 4) and laboratory settings (Chapter 5).

The results of this research suggested that the Exclusion Calculator underestimated the actual exclusion observed, in relation to all four controls assessed (shown in Table

8.1). For younger people, the observed exclusion was up to 4.75 times higher than the estimated exclusion.

The trend of increased exclusion for older users, identified by the Exclusion Calculator, was confirmed in Chapter 5 of this research. A Chi-square test found a significant difference between the estimated and actual exclusion of users from both age groups ($p < 0.05$ as $X^2 = 11.68$ and $df = 5$). The observed exclusion was significantly higher for older people than was expected. The limitation of these results is the small sample sizes of the observed groups. Nevertheless the scale of overall user exclusion observed was still deemed excessive.

Table 8.1 Comparison of the Scale of Estimated Exclusion and Actual Observed Exclusion

Heating Control	**Estimated Exclusion (Younger users 24-45 years old)**	**Observed Exclusion (Younger users 24-45 years old)**	**Estimated Exclusion (Older users 52-78 years old)**	**Observed Exclusion (Older users 52-78 years old)**
Salus	9.5%	66.6%	-	-
Honeywell	8.25%	28.6%	15.5%	100%
Siemens	9.5%	14.3%	18.2%	100%
Drayton	7.5%	35.7%	13.5%	100%

8.1.2 Reasons for User Exclusion

From the research work presented in this thesis it has become clear that the Exclusion Calculator underestimated the design exclusion relating to both heating controls and the prototype system. This is particularly relevant for the assessment of cognitive demands, which is recognised as a particular weakness of the Exclusion Calculator (Waller, Langdon and Clarkson, 2009; Cardoso and Clarkson, 2012). The findings of this research further support the idea that the cognitive aspects of the calculator demand further consideration.

The literature reviewed in Chapter 2 highlighted certain usability problems for older people using heating controls and smart home interfaces. Etchell et al. (2004) and Caird and Roy (2008) agreed that visual demands placed on older people by existing controls were problematic, primarily due to small text sizes and buttons. Similarly, this research found older people had difficulty with small fonts and symbols when using existing controls. Hence, a conscious effort was made to ensure that the fonts used in the prototype were large and high colour contrast combinations were used between the font and the background.

Regarding the use of symbols, both Imai et al. (2010) and Freundenthal and Mook (2003) found the use of symbols was confusing for older users. The results from Chapter 5 corroborate this and highlight that the use of numerous symbols may intimidate older users. This led to the use of text only to label buttons in the development of the prototype heating control interface.

The final usability issue raised in the literature was the complexity of existing systems as a barrier to effective usage (Meier et al., 2011). This research concurs with Meier et al. (2011) that existing controls are particularly complex. The detailed task analysis reported in Chapters 4 and 5 of this research illustrate the complexity of programming existing controls. A significant reduction in this complexity has been achieved in the prototype heating control interface. This was done by reducing the number of steps in the programming task and simplifying the sub-tasks to reduce complexity further.

While the literature demonstrated that existing heating controls suffered from the above-mentioned usability problems, Chapter 5 identified three further issues:

- The instruction manual not supporting users sufficiently
- Confusion surrounding the end of a heating period
- The number of buttons available to the user

The development of the prototype interface considered not only the issues identified in the literature review but also the issues identified through the user observations. Addressing the combination of these issues has resulted in improved usability and reduced user exclusion.

8.2 Can The Exclusion Relating to Digital Programmable Thermostats be Reduced?

The third research question was to understand whether the user exclusion identified in Chapters 4 and 5 could be reduced through the design and development of a more inclusive heating control interface. Chapter 6 addressed this question directly in the development of the proof-of-principle prototype. The results presented in Chapter 6 are largely positive and suggest reductions in the user exclusion have been achieved.

The significance of the results lies in the comparison between these results and the results of earlier testing of existing digital programmable thermostats. The studies, which constitute Chapters 5 and 6, were kept as similar as possible in terms of methodology and approach, to allow the provisional comparison of the results.

However, the studies are by no means identical. The largest differences between the two studies are the participants who took part and the presentation of the prototype on a laptop compared with a standalone product. A concentrated effort was made to ensure the style of interaction was similar to using a finger to press a button, as with a touchscreen interface, by users interacting with the prototype using only a mouse. Despite the differences, this comparison shows improvements have been made in all performance metrics measured, especially for older users.

8.2.1 Reductions in User Exclusion

Younger users had success rates of between 64.3 - 85.7% programming existing digital programmable thermostats for two settings on weekdays and weekends. The success rate was dependent on the control being assessed in Chapter 5. Success rates completing the same task using the prototype system were found to be higher at 93.3%. This implies that user exclusion was reduced somewhat for the younger participants.

More significantly, none of the older participants could complete the task using the existing controls. Whereas, a success rate of 56.3% was achieved using the prototype system. This large increase in older participants' success implies that a wider range of users can be included by reducing the cognitive demands of the system. Despite a large increase in success rates for older people a significant percentage of the older participants were still excluded from using the prototype. Further design improvements could refine the participants and further reduce this exclusion.

8.2.2 Usability Improvements

Compared to the performance metrics of Neilsen's (1993) framework the usability of the prototype system can be verified as:

- Learnable - it was easy for the users to learn without the need for instructions
- Efficient - both user groups were able to achieve their goal quicker
- Memorable - the process to enter a setting was easy to remember and repeat
- Few Errors - low error rates were observed, with only 4 of the 23 successful participants making accuracy errors
- Satisfaction - improved perceived performance in the RTLX scales

With regard to efficiency, the time taken, older participants who were successful completed the task in an average time of 5 minutes 32 seconds. This is quicker than the average successful task time of 7 minutes 26 seconds for the younger participants using the existing controls in Chapter 5. Similarly, there was a large reduction in successful task time for younger participants from a mean of 7 minutes 26 seconds to 2 minutes 30 seconds. Despite this improvement, the difference in successful task completion time between the older and younger participants is still significant. The most important performance metric is the increased success of older participants.

The difference in task time for younger participants using instructions of the existing controls was significantly longer compared to those who completed the task successfully without the instructions (mean 12 minutes 11 seconds vs. 5 minutes 26 seconds). This significance was not found in the prototype testing, where help was provided in the context of the interface rather than a separate manual. This lack of significance may be partially attributed to the fact only one younger participant required the help feature. The usability factors of learnability and memorability were not formally examined in this work. However, the absence of instruction use by the majority of participants implies the system was intuitive enough for participants to interact without instructions.

While user satisfaction is highly subjective, improvements can be tentatively verified with successful participants rating their performance highly when completing the RTLX scales post-test. This was observed in both participant groups rating their performance higher using the prototype than when using the existing controls. Older participants rated their performance with an average score of 44.7, which reduced further to 35.0 for those who were successful (with 100 being poor perceived performance). Similarly, younger users perceived their performance as highly successful with an average score of 17.9.

These observed improvements suggest the prototype system is more usable than existing systems previously evaluated. Hence, one of the research aims has been achieved - to develop a novel heating control interface, which is both more inclusive and helps reduce energy consumption. However, the social acceptability of the prototype and acceptability of cost, reliability and perceived utility still require further examination.

8.3 Does User Exclusion Have an Effect on the Associated Heat Energy Consumption?

The fourth research question was to understand the effect of reduced user exclusion on the associated heat energy consumption. The results reported in Chapter 7 began to answer this question, however further work is required in this area (see Section 9.6.1). Reductions in heat energy consumption of 14.5-15.6% were simulated, however the savings achievable in reality may differ from these results.

From the literature review, a gap was identified that energy savings could be made through improved usability and encouraging night-time setbacks of heating controls. Moon and Han (2011) identified that the largest reductions in energy consumption were correlated to reduced night-time setback temperature. The energy modelling presented in Chapter 7 of this thesis corroborates these findings.

Despite this being most efficient behaviour it is in the minority in Norway and Sweden. The findings of this research are consistent with the existing research as 45.5% of the homes at Elmswell did not use night-time setbacks. This was compared to <50% in Norway (Wilhite et al., 1996) and 38% in Sweden (Linden, Carlsson-Kanyama and Eriksson, 2006). However, the data from this research must be interpreted with caution because of the small sample size and only one location.

Yet, there is an opportunity for 45.5% of the occupants at this specific site to save energy by reducing their heating temperature during the night. It is worth noting that the energy savings would be dependent on the thermal efficiency of the building fabric and the differential between the inside and outside temperatures. The buildings at this site are highly efficient and therefore should retain their heat well. It is worth noting at other sites if the outside temperature was particularly low the system may have to work harder to achieve the desired internal temperature, consuming a greater amount of energy.

8.3.1 Increasing Frequency of User Interactions

In the literature, there is a recognised lack of interaction with thermostats in the homes. In the USA, 89% of respondents rarely or never programmed the thermostat (Meier et al., 2011) and in Finland 60% of households did not interact with their thermostat regularly (Karjalaninen, 2009). Many of the older participants, who took part in the study in Chapter 5, commented they would not choose to use the controls tested.

Importantly, a correlation between increased interactions with energy management systems resulting in greater energy savings has been verified by Jain, Taylor and Peschiera (2012). Extrapolating this to heating controls, it could be possible that increased user interaction with heating controls would result in energy savings. However, this is assuming the interaction with the controls is effective.

In the study reported in Chapter 6, greater numbers of both older and younger participants experienced successful interactions with the prototype system. This positive experience may provide users with a greater sense of perceived control. Based on the Theory of Planned Behaviour this increase in perceived behavioural control could directly influence the performance of the behaviour (Azjen, 1991). By enabling people to programme their controls effectively, it is expected that energy savings of up to 15% annually could be achieved.

8.3.2 Improvements in Design Support of Future Energy Management Interfaces

In the existing research there appeared to be a need for up-to-date guidelines for the design of such interfaces. Freundenthal and Mook (2003) suggested that the available interface design guidelines were somewhat outdated and this may result in usability issues. Karjalainen (2010) addressed this gap with a set of new and similar usability guidelines for office thermostats. However, these guidelines did not have an inclusive or domestic product focus. Hence, there is a gap in current research for inclusive design guidelines within the context of domestic energy management systems.

To support designers in implementing an inclusive design process in this context, a set of design principles have been suggested in Chapter 5. The principles aimed to address the areas of cognitive exclusion and to make the finding of this research tangible for designers. Furthermore, the development of the design principles could help disseminate the findings of this research beyond the sponsor organisation.

These design principles are based upon the research findings and have been generalised for applications beyond heating control interfaces, such as in-home energy displays. The number of controls and feedback interfaces within homes are increasing. Hence, there is an opportunity for inclusive design to enable a greater number of successful user interactions with such products. Insufficient consideration of users in the design of these products may limit the energy savings achievable.

8.4 Ethical Considerations

There are some considerable ethical concerns surrounding control of the domestic environment, as thermal comfort is highly subjective. Particularly with regard to older people's environments, as they can be more sensitive and vulnerable to the cold. The trend of increased automation raises similar ethical concerns to Persuasive Technology (see Section 2.9.2). Automating systems or forcing users to reduce their heat energy consumption may affect occupant comfort negatively. This would be unethical if the occupant was unable to override such a system.

This raises a further research question; do people want to reduce their energy consumption? Although this is outside the current scope of the research, anecdotal evidence in this research suggested that users are more concerned with the cost of their energy rather than the impact of their consumption. Additionally, if controls were made more usable, would consumption actually increase? Providing easy interaction may lead to increased interaction and an increased number, or duration, of heating periods. Rebound effects may also be observed, where energy savings made in this area may be offset by less efficient behaviours elsewhere.

It is impossible to guarantee correct use of the system or energy efficient user behavior, however this does not mean it should not be attempted. It is possible that this research could enable a wider range of users to reduce their energy consumption. Yet the research does not attempt to constrain user behaviour, as this is felt to be unethical. Whether users choose to behave in an energy efficient manner is outside the scope of this research but this does not mean it should not be encouraged.

Chapter 9 - Conclusions

This chapter concludes this thesis bringing together the previous chapters, which constitute the research work of this EngD. The chapter demonstrates how the research aims and objectives were met and presents overall conclusions. Additionally, the limitations of the work are acknowledged and recommendations for future work are made.

9.1 Fulfilling the Research Aims and Objectives

The purpose of this research was to identify where there were opportunities for an inclusive design approach to reduce energy consumption in the domestic environment. Traditionally the sole objective of inclusive design is to ensure the widest range of users can interact successfully with a product, building or service. This research challenges the existing paradigm by applying an inclusive approach with the explicit aim to reduce both user exclusion and energy consumption.

This thesis has focused on one specific environmental technology, domestic heating controls, which could enable energy savings to be made by occupants within the home. It also aimed to address the need for further usability studies called for in the literature. The core objective however, was to develop an alternative heating control interface, which is both more inclusive and helps reduce energy consumption. For a detailed explanation of the research objectives and how these have been met by this research see Table 9.1.

Table 9.1 Research Objectives and Evidence to Support Fulfilment

Research Objective	**Evidence for Fulfilment**	**Related Chapter of Thesis**
To understand the scale of user exclusion relating to digital programmable thermostats	The scale of exclusion is estimated using the Exclusion Calculator	Chapter 4
	The pilot study showed 66% of people were unable to programme their heating controls	Chapter 4
	Increased user exclusion trend verified amongst older users, yet significantly different between estimations and observations	Chapter 5
To understand the reasons for user exclusion relating to these products, especially amongst older users	Initial observations of usability issues	Chapter 4
	Detailed observations of 24 users attempting a task with 3 types of controls	Chapter 5
	Qualitative user comments gave insight into problematic parts of the programming process	Chapter 5
To investigate the validity of existing tools for quantification of user exclusion in a real-world setting	Comparison of the Exclusion Calculator results to real-world observations in their own homes	Chapter 4

Table 9.1 Research Objectives and Evidence to Support Fulfilment (continued)

Research Objective	Evidence for Fulfilment	Related Chapter of Thesis
To design and develop an inclusive product or system which allows users to control their heating usage within the home	A proof of principle prototype was developed and the associated user testing reported	Chapter 6
	Improved task success rates, in both younger and older participants	Chapter 6
	Reduction in mental demand and frustration levels associated with use of the prototype	Chapter 6
To quantify the potential energy savings of any such system developed	Energy modelling of impacts of user errors compared to achieving the task successfully	Chapter 7
	Savings estimated to be in the region of 14.5%-15.6% annually	Chapter 7

9.2 Overall Conclusions

The core objective of this project was to design, develop and test a novel product, which was both inclusive and sustainable. The emphasis of this research was to reduce the heat energy consumption of domestic buildings, primarily through improvements in the user interaction with heating controls. The research studies documented contribute towards verifying the overall research hypothesis that more inclusive heating control systems could enable reductions in domestic heat energy consumption. The new interface developed proved the principle that those users who were previously excluded from using existing heating controls can be included in the programming of such controls.

This research found there was large user exclusion, particularly amongst older people, associated with current advanced digital programmable thermostats. In addition, the cognitive demands of such products were significantly underestimated in the Exclusion Calculator. Reducing the cognitive demands and simplifying the programming process was shown to reduce user exclusion and make systems more usable, especially for older participants.

It was observed that the large cognitive demands of these products resulted in user errors in the programming process. Such errors in this process may result in excessive and unintentional heat energy consumption. Eliminating one particular user programming error could result in heat energy savings in the region of 14-15% annually.

Such errors were observed from the thermostat settings recorded in 5 of the 11 households at a particular site (see Appendix 2). The energy modelling highlighted that the default settings of the controls can have a large impact on energy consumption and these should be selected with care. With further development, the implementation of the prototype heating control interface in homes may help reduce unnecessary periods of heating. This could make a significant contribution to reducing the CO_2 emissions associated with domestic heat energy consumption.

The field of user behaviour within the built environment is attracting more interest, as more people realise the large energy impact of the interactions between the building and the occupant. Therefore, employing an inclusive design approach to improving such interactions may enable energy savings to be achieved by a wider range of people.

9.3 Contributions of the Research

The first contribution to knowledge of this research is the real-world application and validation of the Exclusion Calculator in relation to digital programmable thermostats installed at an environmentally efficient residential development. The study presented in Chapter 4 was one of the first published attempts to validate the Exclusion Calculator in a real-world setting.

The second contribution to knowledge is the detailed understanding of usability issues relating to digital programmable thermostats, especially for older people. This research responded to calls from the literature, which stated the need for further exploration of usability issues regarding existing heating controls. Furthermore, it responded to Langdon and Thimbley's (2010) call for greater diversity amongst participants in such studies. Published in the Journal of Engineering Design, the results reported in Chapter 5 were the first usability study considering the cognitive demands placed on older participants when programming digital programmable thermostats. Hence, the research contributes a greater understanding of the scale of and reasons for user exclusion relating to digital programmable thermostats.

The third contribution to knowledge is in the design, development and initial testing of a novel heating control interface. This heating control interface provides a proof of principle prototype, which reduces the capability demands placed upon users. It is a response to the findings of the first two studies and is inclusive due to the consideration of cognitive demands. These demands were reduced through a series of design changes, reported in Section 6.3.4. The user based testing, documented in Chapter 6, demonstrated increased usability and user satisfaction amongst older participants using the prototype. Additionally, the possible energy savings associated with reducing user errors in the programming task have been quantified in Chapter 7. The research contributes the conclusion that a tentative link may exist between a more inclusive heating control and energy savings in the region of 15% annually.

Additionally, some aspects of the methodology used to complete this research have also contributed to knowledge in a novel way. The design Exclusion Audit process (see Section 3.3.2.4) has been extended in this research to help account for the lack of sensitivity in rating the cognitive demands within the Exclusion Calculator. The task analysis element of the Exclusion Audit has been formalised using the Hierarchical Task Analysis (HTA). To relate the stages of the task more directly to user capabilities the HTA has then been colour coded to help visualise the capabilities that may be most exclusive (prior to conducting the Exclusion Calculation). This is the first novel aspect of the methodology.

The second related to assessing the cognitive demands of products. Upon conducting the exclusion calculation and user testing, the mental workload placed upon participants was assessed using the Raw NASA Task Load Index (RTLX) scales. This research includes the first published attempt to assess the mental workload, through the application of the RTLX scales in the context of inclusive design research. The use of the RTLX scales has proved useful to understand the cognitive demands, an area where the existing means of assessment are not sufficient.

9.4 Limitations of the Research

This research has provided a deeper understanding of usability issues of domestic heating controls and interesting insight into how this may affect domestic energy consumption. However, as with any research project there have been limitations, which should be acknowledged at this stage. Three main limitations of the research are discussed in this section including; sample sizes, development of design guidance and limitations of the researchers programming knowledge to develop the design intervention further.

9.4.1 Sample Sizes

The first limitation of this research is the small study sample sizes used. These ranged from 10-16 users per participant group. Having the resources of only one researcher limited this research to small sample sizes to make the research manageable. Although an acceptable number of participants were used to complete usability testing, the sample sizes were relatively small. This limits the research findings to specific developments or populations and also limits the wider generalisation of the research findings.

Time constraints also limited the length of the user testing sessions to avoid fatigue in participants. Ideally, a follow up focus group would be conducted to address ideas of social acceptability, cost expectations, compatibility issues and any other concerns of the participants. Availability of testing sites was also problematic in the evaluation phase, despite having an industrial sponsor.

9.4.2 Development of Design Guidance

Due to time constraints, the development of the design principles, proposed in Chapter 5, was limited. Further work is required into the utility of such principles within either the sponsor organisation or the wider design industry. Within the sponsor organisation the design principles have been incorporated into a wider tool development guideline document (see Section 9.5.2). This aimed to ensure in-house tools developed are both inclusive and usable for the intended audience. However, the implementation of the guidelines has not been tested. The testing of the principles ideally would include their industrial application and feedback from designers implementing them.

9.4.3 Development and Testing of Interventions

Possibly the greatest limitation of all was the researcher's limited programming ability to develop the prototype. This took considerably longer than was initially expected, due to the time taken to learn new software. Yet, working within these constraints, the functionality of the prototype was developed to satisfy the core requirements, to allow sufficient user testing. The user experience of the prototype could be improved with greater programming knowledge. This would have allowed better error handling of the prototype system, increased system feedback and testing on a wider range of platforms. This combined with the small samples sizes and study site availablity, somewhat limited the researcher's ability to test the prototype in context.

9.5 Implications of this Research

The results presented in this thesis are significant in two respects. Firstly, this research suggests a link between more inclusive heating controls and potential energy savings. The main implication of this is that energy savings could be achieved in the region of 14 -15% of domestic heat energy consumption annually through inclusive interface design. Reducing heat energy consumption up to 15% per household could make a substantial contribution towards reducing the associated CO_2 emissions. This could in turn contribute towards achieving the national CO_2 emission reduction targets set out in the Climate Change Act (2008). Furthermore, if it is possible for an inclusive redesign of the digital programmable thermostat to save energy it is expected that this approach could enable energy savings in the operational phase of other products.

Secondly, if energy savings may be achieved in two domestic buildings it is implied that other homes could benefit from a more inclusive system. With 7.7 million households including people over 60 years old (Department of Communities and Local Government, 2009b), there is a significant market for such inclusive products. The inclusion of older users increases the potential for energy savings to be achieved across a larger range of households. This is significant with the UK population ageing and the increased number of people living independently for longer.

Furthermore, 6.5 million homes could benefit from upgrades in their heating controls and 13.4 million boilers could be upgraded in the UK (Department of Communities and Local Government, 2009a). Implementing an inclusive control system when upgrading the heating system could help apply such a system at scale. This could significantly help toward reducing the heat consumption of the UK housing stock. Further evaluation of the scale of the energy savings achievable is required prior to this (discussed in Section 9.6.1).

9.5.1 Developments in the Market

This research focused on simplifying, and enabling users to programme their controls, as from the literature this was found to result in the largest energy savings. In contrast to this, developments in the commercial market have taken the route of further automation to ensure the home manages itself in an energy efficient manner. It is well documented in the literature that there is a link between levels of control and occupant satisfaction within buildings (see the work of Bordass and Leaman, 2001). Hence, this research has focused on involving users with the control of their homes. Engaging users in the control of their homes could enable greater and more sustained energy savings.

The market for advanced and internet enabled domestic thermostats is much more developed and competitive now than when the research commenced. One of the core objectives of this research was to develop a product for manufacture under license from the sponsor organisation. Therefore, commercial market developments will influence future developments of the prototype system, especially with a partner organisation. Three notable competitive products are the Ecobee, Nest and Wattbox heating controls, which have similar functionality. The first two heating controls mentioned are currently only available in the USA, whereas Wattbox has been developed in the UK.

Ecobee is an internet-enabled thermostat that reports average energy savings of 26% per household yet still requires the user to enter a programme (ecobee, 2012). It also controls the heating system via a ZigBee wireless protocol as was proposed in this research (see Section 6.3.2). Nest is aimed at the top end of the market retailing in North American markets for $249 and savings are reported up to 20% (Nest Labs, 2012). The system relies on user interaction for the first week until it has 'learnt' your schedule, then there is no further need to interact with the thermostat and feedback is provided through a web-based interface (ibid.). Wattbox is another optimised system, without the need for user involvement, which learns user preference through temperature control alone (Wattbox, 2011). However, despite Wattbox being bought in September 2011 by AlertMe, an electrical energy monitoring company looking to expand into the heating control market, the product is not yet commercially available.

This increased automation eliminates the need for ad-hoc interaction with the product as is often required currently; it is unclear how variations to the schedule are managed. One concern with the automation of the home occurs when occupants move house and have relied previously on an automated system. The concern is that they will become reliant on the automated system and consume excessive energy when they do not have such a system. It is thought that it is unlikely that people will take their thermostat with them when they move, as they would not take the rest of the heating system from the home.

Although the programming process is recognised as far from ideal (by both this study and Freundenthal and Mook, 2003), this research argues against the automation and further exclusion of users from control of the domestic environment. Thus, by engaging users with their controls, educating people about their consumption, providing feedback to people on this consumption it is believed that conscious decisions may be made to save energy. This approach is more appropriately aligned with the inclusive design focus of this research.

9.5.2 Implications for the Sponsor Organisation

For Buro Happold, the sponsor organisation, the research has five main implications:

1. Currently, the building design process is a linear process, yet this research has applied the Design Research Methodology, which is cyclical. The learning from this research methodology could benefit the sponsor organisation by showing the benefits of, and encouraging a more cyclical design process. This could lead to new service offerings within the current Post-occupancy Evaluation provision, in terms of illustrating how to engage building occupants and reduce in-use carbon emissions. This helps building services engineers move towards engaging occupants, rather than trying to control the impacts of occupant behaviour through increased automation.
2. As a company Buro Happold are expanding their business offering into high level consultancy by providing a client supporting role, as well as design consultancy. If the impacts of building occupants and occupant engagement can be established with quantifiable benefits, then this would support the emerging carbon management service being developed by Buro Happold. Such a service could be offered to existing clients and well as aiding relationships with new clients. Buro Happold has a wealth of previous projects, both residential and commercial, where such a service could be applied and developed.
3. Further implications for the Sustainability group within Buro Happold included the development of the heating profiles in IES and design guidance for in-house tool development. The IES profiles used in this research model a range of realistic heating scenarios and default settings. This could provide improvements in the estimation of in-use energy consumption of residential buildings, by providing a range which consumption should be within, rather than an absolute value.
4. The design principles discussed in Chapter 5 have been adapted to provide guidance for the development of consistent, usable and inclusive in-house tools. There is currently a drive to develop in-house tools to communicate with clients and architects and aid their understanding complex engineering concepts. Considering the design principles developed by this research when developing such tools may improve the end user experience.

5. The last implication of the research has been the design and implementation of a whole office energy monitoring system in the London office of Buro Happold. The system monitors electrical energy consumption for two office buildings. This is sub-divided into small power, lighting and air conditioning consumption by floor. The system also monitors core office functions separately, such as consumption of the canteen, print room, servers and lifts, in both buildings. In an attempt to involve the employees in energy saving initiatives an energy feedback interface was developed to display the office's consumption in an interesting and engaging manner. Work to assess the energy impact of the feedback interface is currently ongoing within the sponsor organisation.

9.6 Recommendations for Further Work

This research explores a new area for inclusive design research, which focused on enabling users to reduce the environmental impacts of products, buildings or services. This research examined one specific case where an inclusive design approach can have an environmental benefit. However it is expected there will be more areas where such an approach can be applied. For example two such areas are; the controls of air conditioning units and the in-home displays of electricity monitors. Both scenarios involve direct user interaction with potentially large areas of energy consumption.

This research has focused solely on the UK context yet there is an opportunity to achieve these savings across other countries where heat energy is a dominant factor in consumption. Further research may also include development of the research beyond the domestic market. Specific areas of interest would be North America, Scandinavia, Northern Europe and Japan. There is another opportunity for further development of this research in the non-domestic sector, particularly office buildings.

Research opportunities for further work have been grouped into four themes discussed subsequently. The areas considered pertinent in developing this research further are; validation of estimated energy savings, commercial development of the prototype system, development of the design principles and opportunities to encourage behaviour change.

9.6.1 Validation of Estimated Energy Savings

The main recommendation for further work lies in the testing of the design intervention developed to validate the energy savings estimated in this work. A longitudinal study in homes over an entire heating season would be required to validate the scale of energy savings achievable. This would require significant investment in the development of the prototype beyond the interface to link it to a standard gas boiler. This includes the development of the ZigBee protocol over which the interface would communicate with the boiler. An appropriate manufacturing partner would be required to develop such a protocol within a reasonable period of time.

Ideally, differences in housing type and building efficiency would be kept to a minimum, yet controlling such parameters in real-world research is difficult. Differences in household size, tenure and make up would be as similar as possible to allow for comparison in energy consumption. The recruitment of participants and availability of trial sites has been a noteworthy limitation of this research project.

Any such trial would also require a baseline of consumption data which should be gathered prior to installing the prototype system, preferably through meter readings. Using previous bills to give a consumption baseline is a further option however there may be issues with availability of bills and estimates of consumption. The energy consumption would be compared to the expected consumption from the energy modelling to establish any savings achieved.

9.6.2 Commercial Development of the Prototype System

During the prototype evaluation, in Chapter 6, a number of suggestions for improvement to the usability of the interface prototype were made. The further development of the interface should address the usability issues and points of user confusion identified. The commercial development of the system would extend the prototype towards the goal of the interface being able to control a domestic boiler wirelessly, as described in the intended support (see 6.3.2).

The further development of the system would be dependent on both the realisation of the intended support and the results of said prototype testing trialled in homes, as described previously. The further development of the intended system is somewhat constrained by the limited programming and technical knowledge of the researcher. To address this significant limitation the sponsor organisation is keen to collaborate with a controls manufacturer, who is better placed to extend the system functionality.

9.6.3 Further Development of the Design Principles

The proposed Inclusive Design Principles for Energy Management Systems are another area of potential future research. While they have been applied within the context of this research, future development could involve the testing by application in the design of other energy management systems. This would involve designers of such systems using the principles and providing their feedback. This feedback would then influence the development of an online resource or toolkit for designers. This would focus on reducing capability demands of interfaces to reduce the associated energy consumption. Such development may enable energy savings across a wider variety of user interfaces through which domestic energy consumption is controlled and influenced.

It is thought that the application of the design principles would help reduce the high levels of user exclusion found in the use of current heating controls. The application of the principles may have the double dividend of reduced user exclusion and associated energy consumption. Further work on the design principles should include their presentation as a meaningful and usable resource for designers. The design principles could be converted into a simple, colourful, interactive website to engage and encourage designers to apply them. The design principles contribute to the existing body of human-computer interaction guidelines yet are novel in their categorisation by capability demands of users. However, there is little substitute for involving users directly in any inclusive design process. Further application and testing will be required to validate both the usefulness and acceptability of the design principles.

9.6.4 Opportunities to Encourage Behaviour Change

A further gap in current literature exists regarding the application and evaluation of Design for Sustainable Behaviour strategies in practice. There is an opportunity in the future development of the prototype to apply strategies, which enable the user to change their behaviour. By definition this research is not only inclusive design research but also Design with Intent (Lockton, Harrison and Stanton, 2010), as it has the expressed aim of reducing domestic heat energy consumption. This was not formally recognised at the outset of the research, however, has become apparent over the course of the research.

In order to achieve the energy savings estimated in Chapter 7, changes in behaviour from dwelling occupants may be required. The savings estimated in Chapter 7 are equivalent to the more established savings associated with direct or continuous feedback from in-home energy displays (see Section 2.10.2). The potential savings of 14 -15% annually on heat energy consumption may be sustained by providing feedback on consumption through the same interface.

There is an opportunity for the research to test the energy savings achievable when behaviour steers are introduced. For example, if a software update was applied half way through any longitudinal study, savings could be compared against the new baseline of improved control usability. Features, which may encourage changes in behaviour, may include; feedback on participants heat consumption, comparison with other participants consumption and 'nudges' when a particularly high temperature or long duration of heating is observed.

Any interventions implemented would aim to provide feedback to engage users and to steer their behaviour towards greater energy efficiency. For example, in the summary screen if a particularly high temperature was set or the heating continued late into the night the user could be warned. This could provide an indication to users that they will consume a large amount of energy prior to doing so. The implementation of any such intervention should be done after the scale of energy savings relating to the improved controls have been established.

The combination of the behavioural steers, feedback at the point of control and an easily programmable system may result in greater savings than improvements in usability alone. Introducing these features across a series of updates could also allow comparison of the energy impact of different features or combinations of features. One consideration with the introduction of any such features would be not to overwhelm the user. Therefore, the clarity, relevance and volume of information provided on the interface are of critical importance.

9.7 Concluding Remarks

This research aimed to understand how inclusive design may contribute to reducing energy consumption. It has achieved this aim through the design, development and testing of a prototype heating control interface. This proof-of-prototype was designed for use within the domestic environment, in a manner which includes a wider range of users and may enable energy savings.

This is one of the contributions to knowledge proposed by this thesis. Two further contributions to knowledge have been presented in this thesis: the real-world application and validation of the Exclusion Calculator in relation to digital programmable thermostats and the detailed understanding of usability issues relating to digital programmable thermostats, especially their impact on older people.

In summary, this work focused on applying an inclusive design approach in a novel manner to achieve reductions in energy consumption. It has demonstrated the feasibility of this in one specific situation, domestic heating controls. Future work will focus on the further development of the heating control prototype and applying such an approach in other contexts to achieve energy savings.

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Appendices

1. Journal Publications
2. Thermostat Settings Recorded at the Elmswell Development
3. User Testing Evaluation Forms from Descriptive Study I (Chapter 5)
4. Hierarchical Task Analysis for Existing Heating Controls (Chapter 5)
5. User Testing Data from Descriptive Study I (Chapter 5)
6. Product Design Specification Developed for Prescriptive Study
7. User Testing Evaluation Forms from Descriptive Study II (Chapter 6)
8. User Testing Data from Descriptive Study II (Chapter 6)
9. Heating Profiles Developed for Energy Modelling (Chapter 7)

Appendix 1 - Journal Publications

Appendix 1, containing two journal articles published by Nicola Combe, has been removed from this thesis due to publisher copyright restrictions.

Appendix 2 - Thermostat Settings Recorded At The Elmswell Development

Chapter 4 Residents Thermostat Settings

Default Settings

Day	**Time**	**Temperature**
Monday-Friday	6am	21^oC
	8am	17^oC
	4pm	21^oC
	6pm	21^oC
	10pm	17^oC
Saturday & Sunday	6am	21^oC
	8am	21^oC
	4pm	21^oC
	6pm	21^oC
	10pm	17^oC

Household 1 - Participant 1

Day	**Time**	**Temperature**
Monday-Friday	3am	21^oC
	3am	20^oC
	11pm	21^oC
	11pm	21^oC
	11pm	20^oC
Saturday & Sunday	6am	21^oC
	8am	21^oC
	4pm	21^oC
	6pm	21^oC
	10pm	17^oC

Household 2 - Participant 3

Day	**Time**	**Temperature**
Monday-Friday	6am	21.5^oC
	11am	19^oC
	5pm	23^oC
	8.10pm	22^oC
	3am	21.5^oC
Saturday & Sunday	3am	23^oC
	6am	25^oC
	9am	23^oC
	7pm	24.5^oC
	9pm	24^oC

Household 3 - Participant 3

Day	Time	Temperature
Monday-Friday	6am	23^{o}C
	8am	23^{o}C
	10am	20^{o}C
	6pm	23^{o}C
	10pm	20^{o}C
Saturday & Sunday	7am	23^{o}C
	9am	20^{o}C
	3pm	23^{o}C
	6pm	23^{o}C
	10pm	20^{o}C

Household 4 - Participant 4

Day	Time	Temperature
Monday-Friday	7am	21.5^{o}C
	9am	21^{o}C
	3.50pm	21^{o}C
	7.30pm	22^{o}C
	11pm	20.5^{o}C
Saturday & Sunday	8.30am	21.5^{o}C
	10.30am	21.5^{o}C
	3pm	20^{o}C
	8pm	22^{o}C
	11.30pm	20^{o}C

Household 5 - Participant 5

Day	Time	Temperature
Monday-Friday	6am	21^{o}C
	8am	17^{o}C
	4pm	21^{o}C
	6pm	21^{o}C
	10pm	17^{o}C
Saturday & Sunday	6am	21^{o}C
	8am	21^{o}C
	4pm	21^{o}C
	6pm	21^{o}C
	10pm	17^{o}C

*identical to default settings

Household 6 - Participant 6

Day	Time	Temperature
Monday-Friday	6am	22^{o}C
	8am	21^{o}C
	4pm	21^{o}C
	6pm	22^{o}C
	12am	17^{o}C
Saturday & Sunday	6am	21^{o}C
	8am	21^{o}C
	4pm	21^{o}C
	6pm	21^{o}C
	12am	17^{o}C

Household 7 - Participant 7 & 8

Day	Time	Temperature
Monday-Friday	6pm	23^{o}C
	10pm	22^{o}C
	3.30pm	23.5^{o}C
	6.30pm	22^{o}C
	10.50pm	23^{o}C
Saturday & Sunday	6am	22^{o}C
	11.30am	21^{o}C
	3.40pm	21^{o}C
	6pm	21^{o}C
	10pm	22.5^{o}C

Household 8 - Participant 9

Day	Time	Temperature
Monday-Friday	5.30am	22^{o}C
	7am	15^{o}C
	5am	22^{o}C
	9pm	15^{o}C
	10.50pm	15^{o}C
Saturday & Sunday	5.30am	22.5^{o}C
	7am	20^{o}C
	4.50pm	22^{o}C
	9pm	15^{o}C
	10pm	15^{o}C

Household 9 - Participant 10

Day	Time	Temperature
Monday-Friday	5am	21^{o}C
	8am	21^{o}C
	11am	20^{o}C
	3pm	21^{o}C
	11pm	19^{o}C
Saturday & Sunday	6am	21^{o}C
	8am	21^{o}C
	4pm	21^{o}C
	6pm	21^{o}C
	10pm	17^{o}C

Household 10 - Participant 11

Day	Time	Temperature
Monday-Friday	4.30am	22^{o}C
	8am	18^{o}C
	3pm	22^{o}C
	6pm	22^{o}C
	10pm	18^{o}C
Saturday & Sunday	5.30am	21^{o}C
	8am	21^{o}C
	3pm	22^{o}C
	6pm	22^{o}C
	10pm	18^{o}C

Household 11 - Participant 12

Day	Time	Temperature
Monday-Friday	7.50am	17^{o}C
	2pm	17^{o}C
	4pm	17^{o}C
	6pm	17^{o}C
	10pm	17^{o}C
Saturday & Sunday	6am	17^{o}C
	8am	17^{o}C
	4pm	17^{o}C
	6pm	17.5^{o}C
	10pm	17^{o}C

Results

8 participants unsuccessful

Average time not complete

0 min 48 sec
1 min 49 sec
1 min 51 sec
2 min 26 sec
2 min 15 sec
1 min 38 sec
7 min 57 sec
2 min 19 sec
Total 21 min and 3 sec

Average unsuccessful time 2 min and 38 sec

Average time completed

1 min 32 sec
1 min 29 sec
2 min 07 sec
1 min 07 sec

Total time 6 min and 15 sec

Average succesful time 1 min and 34 sec

Appendix 3 - User Testing Evaluation Forms from Descriptive Study I (Chapter 5)

Informed Consent Form

I freely give my consent to take part in this study. I am a consenting adult over 18 years old and if I have any disability that will require adjustments to be made to the survey I will make the researcher aware of these prior to the study. I have received both verbal and written explanation of the study, and have also been given the opportunity to ask for clarification and/or further details should I wish.

I understand that I have the right to withdraw from the study at any time. My data will be stored securely and, suitably anonymised; my name will never be referred to. The data may be published in part, but that I have the right to ask for my data to be removed should I so wish.

Thank you for your time.

Signed Date

If you have any questions please call Nicola Combe (020 7927 9700 ext 5180) or email Nicola.Combe@BuroHappold.com
This study has been approved by the School of Engineering & Design Research Ethics Committee of Brunel University.

Information Sheet About You And Your Heating Use

Background Questions

Name (please print) ____

Age ____

Sex Female/Male

Level of education GCSE equivalent/A-Level equivalent/Degree/Professional Qualifications

Profession ____

Your Heating Use

Do you have a digital programmable thermostat in your home? Yes/No

If no, please move on to the rating section

If yes, who programmes it? Myself/Someone else/Both

If you, how many times have you programmed the thermostat in the past year?

Monthly/Quarterly/Once or twice a year/Never

If someone else, who (and what is your relationship) ______________________________

Why does someone else programme it? ____

____

Please rate the following statements about your heating use:

	Strongly Disagree		Neutral		Strongly Agree
I know how to change the thermostat settings in the house	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
I know how to change the radiator valve settings throughout the house...	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Reducing my heating from its current usage will reduce my comfort.........	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
I believe it is difficult to use my heating controls	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
When the house is unoccupied I try to ensure the heating is switched off	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Saving money on my heating bills is important to me	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Saving energy and carbon is important to me..	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
I have optimised my heating settings for the way that I use my house.......	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

If you answered agree or strongly agree to the statements regarding saving money and energy can you please detail some of the reasons why?

....

....

....

....

If you have any questions please call Nicola Combe (020 7927 9700 ext 5180) or email Nicola.Combe@BuroHappold.com
This study has been approved by the School of Engineering & Design Research Ethics Committee of Brunel University.

Information Sheet About You And Your Technology Use

Your Technology Use

Do you use a computer? Yes/No

If yes, how long have you used a computer? _______ Years

How frequently do you use it?

Daily/2-3 times a week/Once a week/Once a month/Less frequently

Do you use a mobile phone? To make phone calls/To send text messages/Both

How frequently do you use it?

Daily/2-3 times a week/Once a week/Once a month/Less frequently

---

Please rate the following statements about your technology use:

Statement	Strongly Disagree 1	2	Neutral 3	4	Strongly Agree 5
I successfully cope with technical problems	☐	☐	☐	☐	☐
Even if problems occur, I continue working on technical problems	☐	☐	☐	☐	☐
I really enjoy solving technical problems	☐	☐	☐	☐	☐
Up to now I managed to solve most of the technical problems, and I am not afraid of technical problems in future	☐	☐	☐	☐	☐
I feel uncomfortable and helpless about using technical devices	☐	☐	☐	☐	☐
Technical devices are often not transparent and difficult to handle	☐	☐	☐	☐	☐
When I solve a technical problem successfully, it mostly happens by chance	☐	☐	☐	☐	☐
Most technical problems are too complicated for me to deal with	☐	☐	☐	☐	☐

If you would like to make any further comments or suggestions regarding heating controls and their use please use the rest of this sheet to do so.

____

____

____

____

____

____

____

____

If you have any questions please call Nicola Combe (020 7927 9700 ext 5180) or email Nicola.Combe@BuroHappold.com
This study has been approved by the School of Engineering & Design Research Ethics Committee of Brunel University.

The Task

This task explores how easy heating controls are to programme.

You are asked to programme three types of heating controls so that during the week they heat the home in the morning between 7am and 9am to 19°C and in the evening between 4pm and 11pm to 21°C.

At the weekend the temperature should be 19°C from 7am to 9am and between 6pm and 10.30pm in the evening it should 21°C.

At any other occasion the temperature should be left at the default setting.

The settings of this heating profile are shown in the table below:

Day	Time	Temperature
Monday - Friday	7am - 9am	19°C
	4pm - 11pm	21°C
Saturday & Sunday	7am - 9am	19°C
	6pm - 10.30pm	21°C

Initially the manufacturers' instructions will not be provided. However, please feel free to ask for these at any point and they can be made available to you.

The researcher can not provide any further assistance until you indicate you wish to stop the task. Please indicate when you are finished, wish to stop or want to move on the next set of controls.

If you have any questions please call Nicola Combe (020 7927 9700 ext 5180) or email Nicola.Combe@BuroHappold.com
This study has been approved by the School of Engineering & Design Research Ethics Committee of Brunel University.

Workload Assessment - Drayton Controls

Please put an X on each scale where you feel it is appropriate:

Mental Demand
How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Low **High**

Physical Demand
How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low **High**

Temporal Demand
How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely, or rapid and frantic?

Low **High**

Performance
How successful do you think you were in accomplishing the goals of the task set by the researcher? How satisfied were you with your performance in accomplishing these goals?

Low **High**

Effort
How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low **High**

Frustration Level
How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Low **High**

If you have any questions please call Nicola Combe (020 7927 9700 ext 5180) or email Nicola.Combe@BuroHappold.com
This study has been approved by the School of Engineering & Design Research Ethics Committee of Brunel University.

Workload Assessment - Honeywell Controls

Please put an X on each scale where you feel it is appropriate:

Mental Demand

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Low **High**

Physical Demand

How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low **High**

Temporal Demand

How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely, or rapid and frantic?

Low **High**

Performance

How successful do you think you were in accomplishing the goals of the task set by the researcher? How satisfied were you with your performance in accomplishing these goals?

Low **High**

Effort

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low **High**

Frustration Level

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Low **High**

If you have any questions please call Nicola Combe (020 7927 9700 ext 5180) or email Nicola.Combe@BuroHappold.com
This study has been approved by the School of Engineering & Design Research Ethics Committee of Brunel University.

Workload Assessment - Siemens Controls

Please put an X on each scale where you feel it is appropriate:

Mental Demand
How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Low **High**

Physical Demand
How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low **High**

Temporal Demand
How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely, or rapid and frantic?

Low **High**

Performance
How successful do you think you were in accomplishing the goals of the task set by the researcher? How satisfied were you with your performance in accomplishing these goals?

Low **High**

Effort
How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low **High**

Frustration Level
How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Low **High**

If you have any questions please call Nicola Combe (020 7927 9700 ext 5180) or email Nicola.Combe@BuroHappold.com
This study has been approved by the School of Engineering & Design Research Ethics Committee of Brunel University.

Appendix 4 - User Testing Data from Descriptive Study I (Chapter 5)

General Survey Data

Number	Group	Sex	Age	Level of Education	Profession	Consent
1	Younger	Male	27	Degree	Access Consultant	Yes
2	Younger	Male	40	Degree	Management/Access Consultant	Yes
3	Younger	Female	25	Degree	Façade Engineer	Yes
4	Younger	Female	25	Degree	Engineer	Yes
5	Younger	Male	28	Degree	Engineer	Yes
6	Younger	Female	32	Degree	Researcher	Yes
7	Younger	Female	44	Professional	Accountant	Yes
8	Younger	Female	26	Degree	Engineer	Yes
9	Younger	Male	29	Degree	Access Consultant	Yes
10	Younger	Male	25	Degree	Researcher	Yes
11	Younger	Female	24	Degree	Engineer	Yes
12	Younger	Male	26	Degree	Engineer	Yes
13	Younger	Male	26	Degree	Engineer	Yes
14	Younger	Male	25	Degree	Engineer	Yes
1	Older	Male	68	GSCE	Retired	Yes
2	Older	Female	66	Degree	Physics Teacher	Yes
3	Older	Female	74	GSCE	Motor Insurance Supervisor	Yes
4	Older	Male	75	Degree	Teacher/Engineer	Yes
5	Older	Male	74	GSCE	Retired Engineer	Yes
6	Older	Female	72	A-Level	Retired	Yes
7	Older	Female	65	GSCE	Retired	Yes
8	Older	Male	66	Professional	Retired Firefighter	Yes
9	Older	Female	62	Degree	Retired Office Manager	Yes
10	Older	Male	74	GSCE	Instrument Maker	Yes

Prior Experience and Technology Use

Do you have a digital programmable thermostat in your home?	Do you programme it or does someone else?	If someone else please state who	If you, how many times have you programmed the thermostat in the past year?	Do you use a computer?	How long have you used a computer?	How frequently do you use one?	Do you have a mobile phone?	Do you use it to text and make phone calls regularly?	How frequently do you use it?
No				Yes	12	Daily	Yes	Both	Daily
No				Yes	27	Daily	Yes	Both	Daily
No				Yes	15	Daily	Yes	Both	Daily
No				Yes	10	Daily	Yes	Both	Daily
Yes	Myself		Never	Yes	15	Daily	Yes	Both	Daily
Yes	Myself		Never	Yes	15	Daily	Yes	Both	Daily
No				Yes	20	Daily	Yes	Both	Daily
Yes	Someone Else	Landlord (live in-his house)		Yes	13	Daily	Yes	Both	Daily
Yes	Someone Else	Girlfriend	Quarterly	Yes	15	Daily	Yes	Both	Daily
No				Yes	15	Daily	Yes	Both	Daily
No				Yes	17	Daily	Yes	Both	Daily
Yes	Someone Else	Father (his hous	Never	Yes	17	Daily	Yes	Both	Daily
No				Yes	20	Daily	Yes	Both	Daily
No				Yes	15	Daily	Yes	Both	Daily
No				Yes	16	Daily	Yes	Phone Calls	Once a month
No				Yes	20	Daily	Yes	Both	Less frequently
Yes	Myself		Monthly	No	-		Yes	Text Message	2-3 times a week
Yes	Myself		Never	Yes	40	Daily	Yes	Phone Calls	2-3 times a week
Yes	Both	Wife	Once or Twice a Ye	Yes	25	Daily	Yes	Phone Calls	2-3 times a week
No				No			No		
Yes	Someone Else	Gas Engineer	Once or Twice a Ye	Yes	30	Daily	No		
Yes	Myself		Once or Twice a Ye	Yes	8	Daily	Yes	Both	2-3 times a week
Yes	Both	Son/Son-in-Law	Quarterly	Yes	20	Daily	Yes	Both	Daily
No				Yes	7	Once a week	Yes	Both	Once a month

Honeywell CMT927 **Mental Work Load** **Mental Model**

Participant	Mental Demand	Physical demand	Temporal demand	Performance	Effort	Frustration Level	Total	as a %age	Type of Model
BH - 1	7.5	11.7	4.9	4.7	5	10.6	44.4	53.6%	Network
BH - 2	8.3	4.1	4.1	1.4	9.1	8.3	35.3	42.6%	Chain
BH - 3	9.1	6.3	6.3	2.6	8.9	8.9	42.1	50.8%	Onion
BH - 4	9.1	7.6	7.5	4.9	7.6	7.6	44.3	53.5%	Hierarchy
BH - 5	10.3	7.6	7.6	2	10.2	8.9	46.6	56.3%	Chain
BH - 6	7.5	4.9	6.3	4.8	9	3.5	36	43.5%	Chain
BH - 7	9.1	7.6	10.3	6.1	10.4	13.2	56.7	68.5%	Hierarchy
BH - 8	3.2	10.2	1.8	2.4	4.7	4.7	27	32.6%	Chain
BH - 9	8.3	8.3	9.1	1.4	8.3	1.4	36.8	44.4%	Hierarchy
BH - 10	10.3	7.7	9	2.7	7.6	5.9	43.2	52.2%	Hierarchy
BH - 11	7.5	3.5	2.1	0.8	7.4	2.1	23.4	28.3%	Chain
BH - 12	6	6.2	13.1	6.3	4.7	13.1	49.4	59.7%	Chain
BH - 13	6.2	2	2.2	0.7	2.1	0.6	13.8	16.7%	Hierarchy
BH - 14	8.7	3.2	5.7	6.6	5.8	3.4	33.4	40.3%	Hierarchy
	7.9	6.5	6.4	3.4	7.2	6.6		45.9%	
	61.6%	50.4%	49.9%	26.3%	55.9%	51.1%			
Brunel - 1	7.1	9	13	7.5	10.3	7.5	54.4	65.7%	Hierarchy
Brunel - 2	6.1	0.8	2.2	6.1	4.8	2	22	26.6%	Chain
Brunel - 3	10.3	11.7	7.5	7.9	11.7	7.7	56.8	68.6%	Hierarchy
Brunel - 4	7.5	4.9	4.8	13.2	10.3	13	53.7	64.9%	Network
Brunel - 5	7.2	7.2	7.4	13.3	10.4	7.5	53	64.0%	Chain
Brunel - 6	6.9	0.5	13.1	13.3	0.5	0.5	34.8	42.0%	I don't know
Brunel - 7	7.6	13.1	4.8	2.1	9	4.4	41	49.5%	Network
Brunel - 8	6.4	1.9	7.4	11.8	2.2	2.1	22	38.4%	Chain
Brunel - 9	9	1.9	4.7	4.8	8.8	11.5	40.7	49.2%	Chain
Brunel - 10	13.1	1.9	10.2	13.1	8.9	7.5	54.7	66.1%	Hierarchy
	8.1	5.3	7.5	9.3	7.7	6.4		53.5%	
	58.8%	38.3%	54.4%	67.5%	55.7%	46.2%			

Younger Users	61.6%	50.4%	49.9%	26.3%	55.9%	51.1%
Older Users	58.8%	38.3%	54.4%	67.5%	55.7%	46.2%
Honeywell average	60.2%	44.4%	52.2%	46.9%	55.8%	48.6%

Siemens REV24-RF **Mental Work Load** **Mental Model**

Participant	Mental Demand	Physical demand	Temporal demand	Performance	Effort	Frustration Level	Total	as a %age	Type of Model
BH - 1	10.3	13	4.9	2.1	9	10.2	49.5	59.8%	Chain
BH - 2	8.3	4.1	6.9	0.1	6.9	1.4	27.7	33.5%	Chain
BH - 3	11.7	9	8.8	9	10.3	11.7	60.5	73.1%	Hierarchy
BH - 4	13.1	13.1	7.5	3.6	10.3	11.7	59.3	71.6%	Hierarchy
BH - 5	5.9	5	5.1	2	6.3	5.2	29.5	35.6%	Hierarchy
BH - 6	11.7	13.1	11.9	6.2	11.8	13.2	67.9	82.0%	Chain
BH - 7	9	3.5	10.4	2.1	9	10.3	44.3	53.5%	Chain
BH - 8	8.9	4.8	4.8	7.6	3.6	8.9	38.6	46.6%	Hierarchy
BH - 9	8.3	12.4	11	1.4	12.4	11	56.5	68.2%	Chain
BH - 10	11.5	8.7	8.8	2.2	10.3	7.5	49	59.2%	Network
BH - 11	10.5	10.2	3.3	4.9	9.1	6.2	44.2	53.4%	Chain
BH - 12	4.9	13.1	13.1	4.9	9	4.8	49.8	60.1%	Chain
BH - 13	8.9	10.2	2	3.5	7.4	2.1	34.1	41.2%	Chain
BH - 14	7.2	8.6	7.4	5.2	4.1	3.1	35.6	43.0%	Chain
	9.3	9.2	7.6	3.9	8.5	7.7		55.8%	
	72.2%	71.4%	58.7%	30.4%	66.3%	59.5%			
Brunel - 1	13.2	13.3	13.2	12.9	13.2	13	78.8	95.2%	I don't know
Brunel - 2	7.6	0.7	9.1	13.2	6.1	11.8	48.5	58.6%	Hierarchy
Brunel - 3	13.1	2	7.7	13.1	13.3	9	58.2	70.3%	Network
Brunel - 4	11.8	6.3	8.9	11.6	7.6	13.2	59.4	71.7%	I don't know
Brunel - 5	13.1	10	13.1	13.4	13	13.2	75.8	91.5%	Hierarchy
Brunel - 6	4	2.6	3.1	0	13.8	13.8	37.3	45.0%	Pyramid
Brunel - 7	13	0.6	0.6	13.2	7.6	13	48	58.0%	Pyramid
Brunel - 8	11.7	11.7	11.7	13.4	11.7	10.4	70.6	85.3%	Network
Brunel - 9	13.2	8.8	13	13.2	8.8	12.8	69.8	84.3%	Network
Brunel - 10	11.1	3.3	3.3	11.8	9	10.4	48.9	59.1%	Chain
	11.2	5.9	8.4	11.6	10.4	12.1		71.9%	
	81.0%	43.0%	60.7%	83.9%	75.4%	87.4%			

Younger Users	72.2%	71.4%	58.7%	30.4%	66.3%	59.5%
Older Users	81.0%	43.0%	60.7%	83.9%	75.4%	87.4%
Siemens average	76.6%	57.2%	59.7%	57.1%	70.9%	73.4%

Drayton Digistat+ 3RF **Mental Work Load** **Mental Model**

Participant	Mental Demand	Physical demand	Temporal demand	Performance	Effort	Frustration Level	Total	as a %age	Type of Model
BH - 1	7.5	11.6	3.4	3.4	10.4	2	38.3	46.3%	Hierarchy
BH - 2	13.1	2.2	6.9	9.7	11	13.8	56.7	68.5%	Network
BH - 3	11.8	7.5	6.2	3.4	10.6	11.7	51.2	61.8%	Hierarchy
BH - 4	4.8	4.7	5.9	3.6	6.4	7.5	32.9	39.7%	Hierarchy
BH - 5	8.9	4.8	6.2	6.1	6.4	7.7	40.1	48.4%	Hierarchy
BH - 6	11.7	10.4	10.5	9	11.8	13.2	66.6	80.4%	Hierarchy
BH - 7	8.9	7.6	10.3	7.6	10.4	13.2	58	70.0%	Chain
BH - 8	7.6	7.4	4.7	3.6	3.2	6.2	32.7	39.5%	Chain
BH - 9	13.8	8.3	9.2	1.4	11	13.8	57.5	69.4%	Onion
BH - 10	10.2	8.8	11.7	2.2	6	7.4	46.3	55.9%	Chain
BH - 11	11.7	6.1	1.8	10.4	6.2	8.8	45	54.3%	Chain
BH - 12	10.5	7.6	11.8	10.3	7.5	13.2	60.9	73.6%	Chain
BH - 13	10.3	11.7	2	13.3	9.1	10.3	56.7	68.5%	Chain
BH - 14	8.5	2	5.9	5.1	7.4	8.8	37.7	45.5%	Chain
	10.0	7.2	6.9	6.4	8.4	9.8		58.7%	
	77.3%	55.8%	53.5%	49.4%	65.1%	76.3%			
Brunel - 1	13.1	13.2	0.7	13.1	13.2	13.1	66.4	80.2%	I don't know
Brunel - 2	8.6	0.7	4.2	13.2	3.6	4.2	34.5	41.7%	Hierarchy
Brunel - 3	8.9	6.1	8.9	11.8	10.3	10.2	56.2	67.9%	Pyramid
Brunel - 4	11.8	6.3	9	10.4	9.1	10.3	56.9	68.7%	Hierarchy
Brunel - 5	13	7.5	13.1	13.3	13.1	13.1	73.1	88.3%	Chain
Brunel - 6	6.9	0.4	3.4	0.8	0.5	13.2	25.2	30.4%	I don't know
Brunel - 7	9.1	13	6.3	13.2	7.3	10.5	59.4	71.7%	Network
Brunel - 8	7.6	7.6	7.6	6.2	7.6	7.6	44.2	53.4%	Chain
Brunel - 9	13.1	0.6	2.1	0.9	10.2	13.1	40	48.3%	Hierarchy
Brunel - 10	13.1	10.3	6.2	11.7	11.8	9.1	62.2	75.1%	Network
	10.5	6.6	6.2	9.5	8.7	10.4		62.6%	
	76.2%	47.6%	44.6%	68.6%	62.8%	75.7%			

Younger Users	77.3%	55.8%	53.5%	49.4%	65.1%	76.3%
Older Users	76.2%	47.6%	44.6%	68.6%	62.8%	75.7%
Drayton average	76.7%	51.7%	49.0%	59.0%	64.0%	76.0%

Honeywell Performance Data

Participant	Time (no instructions)	Successful	Instructions Required	Time (with instructions)	Successful	Notes
BH - 1	00:11:12	No	No	-		Participant thought he ha
BH - 2	00:05:35	Yes	No	-		
BH - 3	00:10:16	Yes	No	-		
BH - 4	00:01:11	No	Yes	00:03:48	No	
BH - 5	00:03:53	No	Yes	00:09:59	Yes	
BH - 6	00:08:08	No	No	-		Participant thought she ha
BH - 7	00:08:17	Yes	No	-		
BH - 8	00:04:04	Yes	No	-		
BH - 9	00:04:50	Yes	No	-		
BH - 10	00:03:33	Yes	No	-		
BH - 11	00:05:15	Yes	No	-		
BH - 12	00:04:37	No	No	-		
BH - 13	00:04:07	Yes	No	-		
BH - 14	00:05:11	Yes	No	-		

Brunel - 1	00:15:04	No	No	-		
Brunel - 2	00:08:22	No	No	-		
Brunel - 3	00:22:23	No	No	-		
Brunel - 4	00:01:45	No	Yes	00:02:17	No	
Brunel - 5	00:01:12	No	Yes	00:07:01	No	could do it but would take
Brunel - 6	00:01:01	No	No	-		Thought task was achieve
Brunel - 7	00:12:40	No	No	-		
Brunel - 8	00:05:26	No	No	-		Did not know how to char
Brunel - 9	00:10:12	No	No	-		performed well, didn't se
Brunel - 10	00:12:02	No	No	-		performed well, didn't se

Siemens Performance Data

Participant	Time (no instructions)	Successful	Instructions Required	Time (with instructions)	Successful	Notes
BH - 1	00:07:09	No	Yes	00:02:52	Yes	
BH - 2	00:03:36	Yes	No	-		
BH - 3	00:01:10	No	Yes	00:12:25	Yes	
BH - 4	00:00:59	No	Yes	00:07:55	No	Once PASS is displayed on i
BH - 5	00:06:53	Yes	No	-		
BH - 6	00:01:09	No	Yes	00:10:39	Yes	
BH - 7	00:03:35	No	Yes	00:07:40	No	
BH - 8	00:06:41	Yes	No	-		
BH - 9	00:04:11	Yes	No	-		
BH - 10	00:04:15	Yes	No	-		
BH - 11	00:05:27	No	Yes	00:06:55	Yes	Got extremely stuck with tl
BH - 12	00:03:17	Yes	No	-		
BH - 13	00:06:21	Yes	No	-		
BH - 14	00:05:36	Yes	No	-		

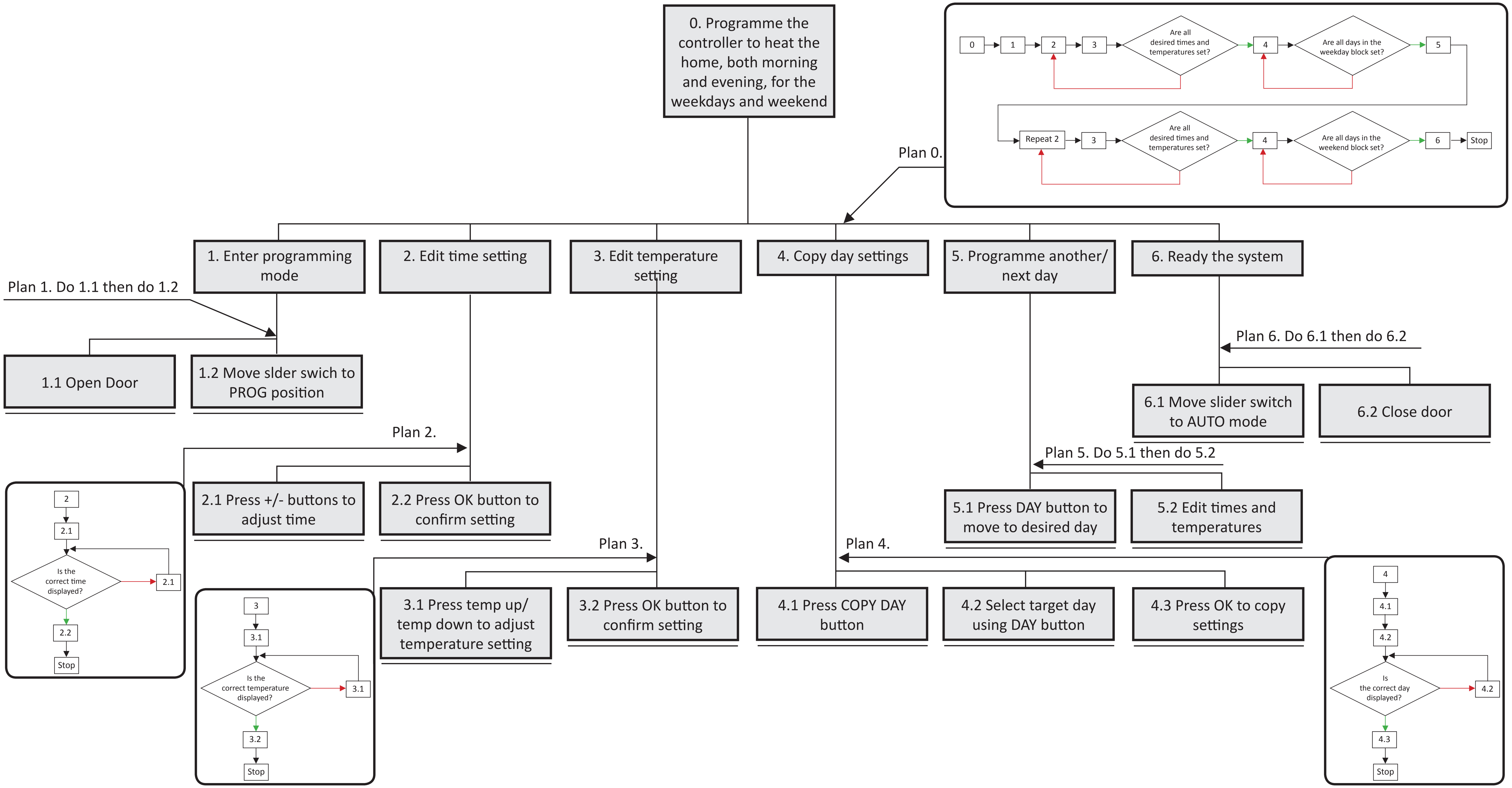
Brunel - 1	00:02:02	No	Yes	00:06:01	No	
Brunel - 2	00:01:59	No	Yes	00:09:33	No	
Brunel - 3	00:09:52	No	Yes	00:14:01	No	
Brunel - 4	00:00:35	No	Yes	00:00:22	No	Was too intimidated by the
Brunel - 5	00:00:52	No	Yes	00:03:10	No	
Brunel - 6	00:01:35	No	Yes	00:05:19	No	Thought task was achieved
Brunel - 7	00:05:54	No	Yes	00:00:21	No	Was too intimidated by the
Brunel - 8	00:01:56	No	Yes	00:03:52	No	Was too intimidated by the
Brunel - 9	00:01:15	No	Yes	00:00:18	No	Was too intimidated by the
Brunel - 10	00:12:49	No	No	-		Set three out of four settin

Drayton Performance Data

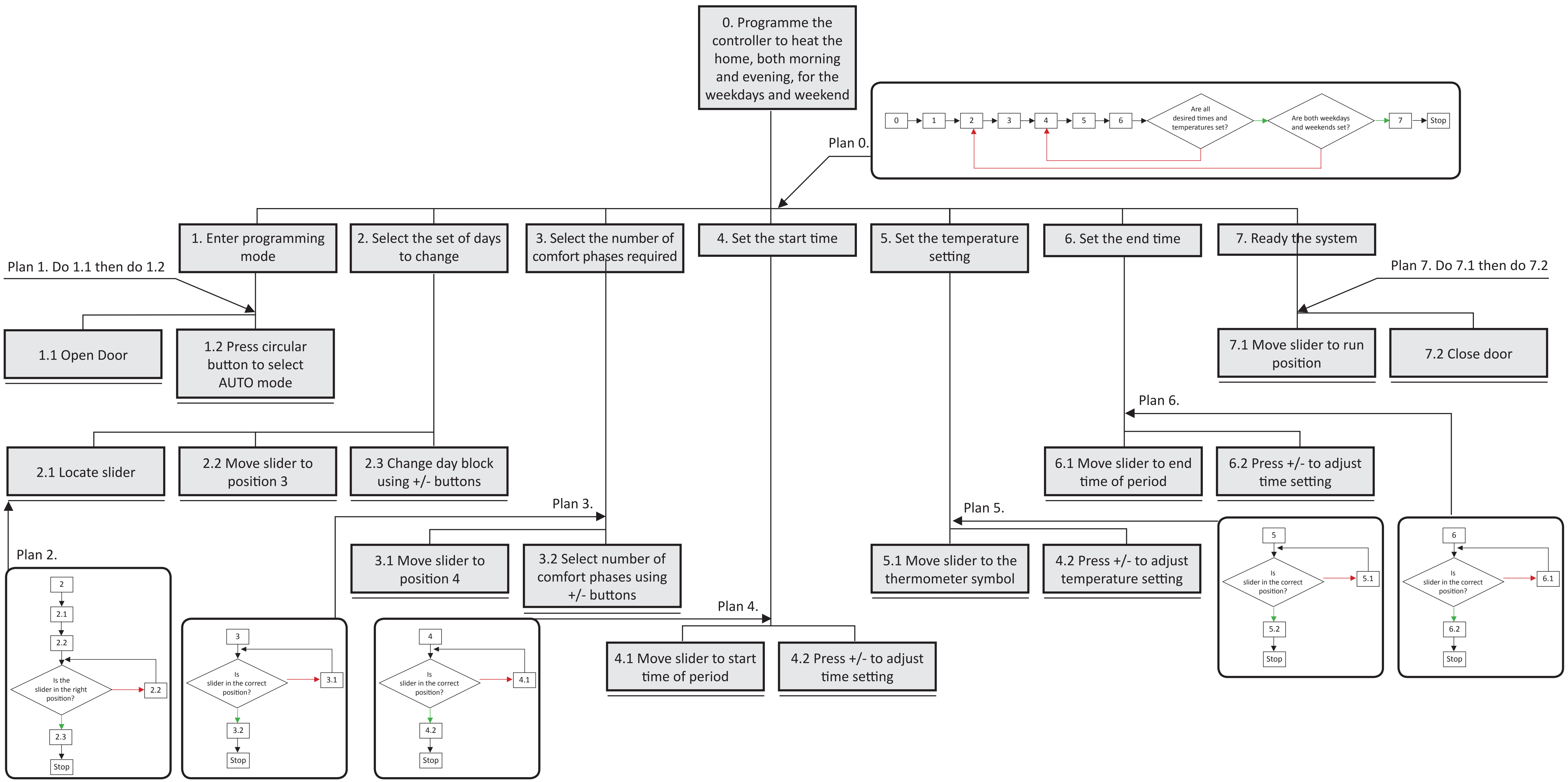
Participant	Time (no instructions)	Successful	Instructions Required	Time (with instructions)	Successful	Notes
BH - 1	00:07:55	No	No	-		Participant thought he had
BH - 2	00:01:31	No	Yes	00:09:21	No	User knew what he wanted
BH - 3	00:05:08	No	Yes	00:13:07	Yes	
BH - 4	00:01:08	No	Yes	00:04:15	Yes	
BH - 5	00:02:22	No	Yes	00:05:48	Yes	
BH - 6	00:02:04	No	Yes	00:08:49	Yes	User made a mistake at tim
BH - 7	00:09:11	Yes	No	-		
BH - 8	00:02:49	Yes	No	-		
BH - 9	00:04:38	Yes	No	-		
BH - 10	00:05:22	Yes	No	-		
BH - 11	00:03:03	No	Yes	00:07:19	No	Participant gave up due to
BH - 12	00:04:45	No	No	-		
BH - 13	00:04:29	No	Yes	00:06:32	Yes	
BH - 14	00:05:35	No	No	-		

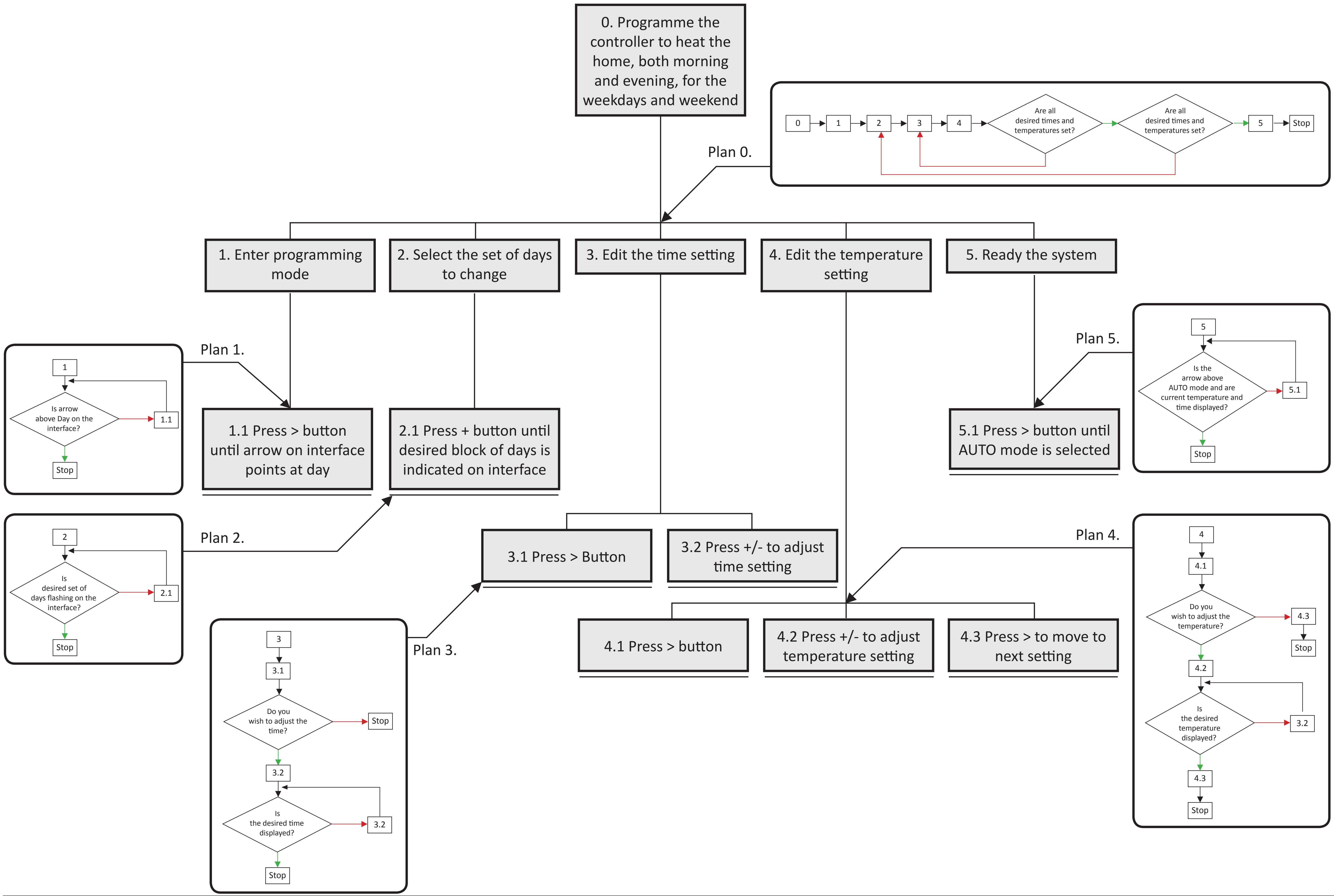
Brunel - 1	00:00:57	No	Yes	00:06:49	No	
Brunel - 2	00:01:48	No	Yes	00:14:41	No	Felt she could do it but it w
Brunel - 3	00:07:54	No	Yes	00:03:44	No	
Brunel - 4	00:02:08	No	Yes	00:02:42	No	
Brunel - 5	00:02:05	No	Yes	00:04:07	No	
Brunel - 6	00:00:46	No	No	-		
Brunel - 7	00:03:42	No	Yes	00:07:49	No	
Brunel - 8	00:03:56	No	Yes	00:13:15	No	Thought task was achieved
Brunel - 9	00:01:47	No	Yes	00:05:55	No	
Brunel - 10	00:04:39	No	No	-		

Appendix 5 - Hierarchical Task Analysis for Existing Heating Controls (Chapter 5)



0. Programme the controller to heat the home, both morning and evening, for the weekdays and weekend
Plan 0.
0
1
2
3
Are all desired times and temperatures set?
4
Are all days in the weekday block set?
5
Repeat 2
3
Are all desired times and temperatures set?
4
Are all days in the weekend block set?
6
Stop
1. Enter programming mode
2. Edit time setting
3. Edit temperature setting
4. Copy day settings
5. Programme another/ next day
6. Ready the system
Plan 1. Do 1.1 then do 1.2
1.1 Open Door
1.2 Move slder swich to PROG position
Plan 2.
2.1 Press +/- buttons to adjust time
2.2 Press OK button to confirm setting
2
2.1
Is the correct time displayed?
2.1
2.2
Stop
Plan 3.
3.1 Press temp up/ temp down to adjust temperature setting
3.2 Press OK button to confirm setting
3
3.1
Is the correct temperature displayed?
3.1
3.2
Stop
Plan 4.
4.1 Press COPY DAY button
4.2 Select target day using DAY button
4.3 Press OK to copy settings
4
4.1
4.2
Is the correct day displayed?
4.2
4.3
Stop
Plan 5. Do 5.1 then do 5.2
5.1 Press DAY button to move to desired day
5.2 Edit times and temperatures
Plan 6. Do 6.1 then do 6.2
6.1 Move slider switch to AUTO mode
6.2 Close door


0. Programme the controller to heat the home, both morning and evening, for the weekdays and weekend
Plan 0.
Are all desired times and temperatures set?
Are both weekdays and weekends set?
Stop
1. Enter programming mode
2. Select the set of days to change
3. Select the number of comfort phases required
4. Set the start time
5. Set the temperature setting
6. Set the end time
7. Ready the system
Plan 1. Do 1.1 then do 1.2
Plan 7. Do 7.1 then do 7.2
1.1 Open Door
1.2 Press circular button to select AUTO mode
7.1 Move slider to run position
7.2 Close door
Plan 6.
2.1 Locate slider
2.2 Move slider to position 3
2.3 Change day block using +/- buttons
6.1 Move slider to end time of period
6.2 Press +/- to adjust time setting
Plan 3.
Plan 5.
Plan 2.
3.1 Move slider to position 4
3.2 Select number of comfort phases using +/- buttons
5.1 Move slider to the thermometer symbol
4.2 Press +/- to adjust temperature setting
Plan 4.
4.1 Move slider to start time of period
4.2 Press +/- to adjust time setting
Is the slider in the right position?
Is slider in the correct position?


0. Programme the controller to heat the home, both morning and evening, for the weekdays and weekend
Plan 0.
0
1
2
3
4
Are all desired times and temperatures set?
Are all desired times and temperatures set?
5
Stop
1. Enter programming mode
2. Select the set of days to change
3. Edit the time setting
4. Edit the temperature setting
5. Ready the system
Plan 1.
1
Is arrow above Day on the interface?
1.1
Stop
1.1 Press > button until arrow on interface points at day
2.1 Press + button until desired block of days is indicated on interface
Plan 2.
2
Is desired set of days flashing on the interface?
2.1
Stop
Plan 5.
5
Is the arrow above AUTO mode and are current temperature and time displayed?
5.1
Stop
5.1 Press > button until AUTO mode is selected
3.1 Press > Button
3.2 Press +/- to adjust time setting
Plan 3.
3
3.1
Do you wish to adjust the time?
Stop
3.2
Is the desired time displayed?
3.2
Stop
4.1 Press > button
4.2 Press +/- to adjust temperature setting
4.3 Press > to move to next setting
Plan 4.
4
4.1
Do you wish to adjust the temperature?
4.3
Stop
4.2
Is the desired temperature displayed?
3.2
4.3
Stop

Appendix 6 - Product Design Specification Developed for Prescriptive Study

Product Design Specification – User Centred Heating Controls

Element of Specification	Sub-Element	Requirement of new system
FUNCTION	Ability	The product is required to control the supply of heat the home. This will require control over both temperature and duration of heating.
	Utilisation	It is envisioned that full programming would be done quarterly with adjustments made to override/boost system sporadically (depending on the weather).
	Size and Shape	The size and shape should be appropriate for the majority of users to operate using one hand only.
	Lifespan	The lifespan of the product should be 7-10 years as frequency, this would be linked to the installation of boilers and full heating systems
	Scope	The control will only control the heating system. It will not control electrical appliances or hot water. Ideally it will have the potential to monitor the heating consumption and feedback usage to the user.
MATERIAL	Strength	The materials should be strong enough to withstand the stress of the user interaction, installation and minor abuse such as being dropped.
	Texture	Providing contrasting textures (or materials) may help some users identify where buttons are and to differentiate between functions.
	Colour	Traditionally products of this type are white. However this provides little contrast with neutrally coloured walls. Levels of contrast should be sufficient to see the product again a white wall.
	Conductivity	The material selection should not conduct heat or electricity readily. The system should be double insulated if necessary.

	Appearance	The materials should be of appearance that is appropriate for the cost of the product. The aesthetics should entice and engage users, not deter them from using the product.
DEPENDABILITY	Reliability	The system should be reliable and transparent to the user. Warnings should be given when the batteries require replacement (in the form of text not symbols).
	Durability	The product will have to withstand operating force of the user, the installation process and general use and abuse.
	Maintainability	The only maintenance required should be replacing the batteries if a separate box mounted on the wall. Other maintenance could be part of routine maintenance or servicing of the boiler.
	Disposal	The physical version of the product should be designed for disassembly and separation of materials at the end of life. It will be subject to the WEEE directive covering disposal of electronic products. An online or application version would avoid this completely.
ENVIRONMENT	Location	The product is designed for indoor use. A physical version would be situated with at least 300mm from the corner of a room and between 900-1100mm from the finished floor level, in accordance with BS8300:2009. An application or online version would be available on a laptop/desktop/tablet computer.
	Temperature	CIBSE Guide A recommends living accommodation should be between 17-24oC, however indoor temperatures in the UK will likely range between 10-30oC
ERGONOMICS & AESTHETICS	Size and Shape	The physical version of the product should be of an appropriate size and shape for a user in the 95th %ile to interact with the buttons and controls with ease. Miniaturisation of controls can cause difficultly for older users in particular.
	Colour	Contrast and colour can be used to great effect to help users with a visual impairment. Common colour

		associations such as green being positive and red being negative should be capitalised upon.
	Illumination	Any screen should be back lit to aid the user seeing the screen in low light levels. Illumination can also provide feedback to indicate a button press has been successful.
	Culture	The research the proposal is based on is based in a UK context therefore the product will be primarily based in a Western culture. This is a culture where a large proportion of energy is used to maintain indoor temperatures and expected levels of comfort are high.
	Accessibility	Accessibility of the product will be a key concern. Every effort should be made to ensure the product is usable for the widest possible range of users. Guidelines for implementing an inclusive design process can be found in BS7000-6 and useful data and guidance in BS8300:2009.
	Operating Force	Operating force will be kept to a minimum to ensure users with arthritis are not excluded. This force should be less than 50N.
	Visual Impact	The physical product should have enough visual impact to differentiate itself from its surroundings. This visual impact should be positive as should the experience of using the product.
	Noise	Audio feedback should be an option to help users however this could become an annoyance and should be able to be turned off / removed if it is a separate module.
INTERFACE	Visibility	Visibility of the interface is important and should be carefully considered in the development of concepts. The size and selection of fonts must be carefully considered as should the contrast of the interface. Visibility is also affected by the lighting and an optional back light could be a helpful function.
	Compatibility	The product must be compatible with a standard gas central heating system and energy efficiently boiler

		systems as well as renewable heat sources.
	Security	It may be linked to a smart meter in the future however the user should be made explicitly aware what data is being transferred and where it will be stored. Furthermore access to the data collected should be accessible free of charge to the user. Personal details should not be transmitted to third parties.
	Feedback	The interface should provide feedback on the settings programmed, energy consumed and cost of energy (if available). Feedback must be meaningful to the user and not add confusion. Ideally units would be in £ and pence not kWh or CO2.
COST & TIMING	Unit Cost	Top of the range heating controls retail around £80-£125 currently (2012). The unit cost should be under £100.
	Life Cycle Costs	A streamline LCA of the final concepts can be conducted however the selection of default settings will have the biggest impact over the product lifecycle. This should be done with care to ensure there is a balance between human comfort and
	Installation & Commissioning	A qualified heating engineer or plumber should do installation and commissioning.
	Documentation	Documentation should include Instructions, Guarantee documentation and Energy Saving Advice.
TRAINING	Language	The default language will be English (British). Other language products may be added at a later date.
	Numeric Units	Temperature should be in degrees Celsius ^{o}C. Time should be in twenty-four hour clock as default. The number of units on the display should be limited to three types to avoid confusion of users.
	Safety	The product should not harm the user in any way. It should be rated in accordance with the relevant IP rating (assume IP 66).

Appendix 7 - User Testing Evaluation Forms from Descriptive Study II (Chapter 6)

Informed Consent Letter

This study is about the interface of a new heating control system intended to be more simple and easier to use. The goal is to understand your preferences and thoughts about using such a system and your participation will really help accomplish this.

During the session you will be asked to attempt a typical task to programme the controls. This will typically involve setting an on and off time and a temperature for the weekdays or weekend. A facilitator who will provide you with instructions will observe this and you can ask them for clarification if you get stuck.

All information collected during the study in the session will be stored anonymously by the researcher and may be published as part of the overall research study. With your permission any comments you make will be audio recorded for reference purposes only. You will never be referred to directly by name or any other means. All information will collected will be kept confidential and anonymous.

To the best of our knowledge there are no physical or psychological risks associated with participating in the study. You can take breaks if needed and you may ask for the session to be stopped at any time. You can also withdraw from the study at any point.

Statement of informed consent

I have read the description of the study and my rights as a participant. I voluntarily agree to participate in the study.

Print Name: ______________________________

Signature: ______________________________

Date: ______________________________

Nicola Combe – Telephone 07841195854 – Email Nicola.Combe@BuroHappold.com

Approved by the Research Ethics Committee of the School of Engineering and Design, Brunel University

Information Sheet About You And Your Heating Use

Background Questions

Name (please print) ______________________________

Age ______________________________

Sex Female/Male

Level of education GCSE equivalent/A-Level equivalent/Degree/Professional Qualifications

Profession ______________________________

Would you like to be informed of the study results? Yes/No

Your Heating Use

Do you have a digital programmable thermostat in your home? Yes/No

Can you control both the temperature and duration of your heating? Yes/No

If yes, have you used these controls within the last 12 month? Yes/No

Do you pay towards the cost of your heating? Yes/No

Please rate the following statements about your heating use:	Strongly Disagree		Neutral		Strongly Agree
1. I know how to change the thermostat settings in the house	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
2. I know how to change the radiator valve settings throughout the house	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
3. Reducing my heating from its current usage will reduce my comfort ...	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
4. I believe it is difficult to use my heating controls	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
5. When the house is unoccupied I try to ensure the heating is switched off	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
6. Saving money on my heating bills is important to me...............	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
7. Saving energy is important to me...............	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

Your Technology Use

Do you use a computer? Yes/No

If yes, how frequently do you use it?

Daily/2-3 times a week/Once a week/Once a month/Less frequently

Do you use a mobile phone?

No/Yes - To make phone calls/Yes - To send text messages/Yes-Both

How frequently do you use it?

Daily/2-3 times a week/Once a week/Once a month/Less frequently

Nicola Combe – Telephone 07841195854 – Email Nicola.Combe@BuroHappold.com

Approved by the Research Ethics Committee of the School of Engineering and Design, Brunel University

Technical Confidence

Please rate the following statements about your technology use:

	Strongly Disagree		Neutral		Strongly Agree
1. Technology has always fascinated me	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
2. I really like to try out new gadgets	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
3. I successfully cope with technical problems	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
4. Even if problems occur, I continue working on technical problems	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
5. I really enjoy solving technical problems	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
6. Up to now I managed to solve most of the technical problems, and I am not afraid of technical problems in future	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
7. I feel uncomfortable and helpless about using technical devices	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
8. Technical devices are often not transparent and difficult to handle	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
9. When I solve a technical problem successfully, it mostly happens by chance	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
10. Most technical problems are too complicated for me to deal with	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

Workload Assessment

Please put an X on each scale where you feel it is appropriate:

Mental Demand
How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Low **High**

Physical Demand
How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low **High**

Temporal Demand
How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely, or rapid and frantic?

Low **High**

Performance
How successful do you think you were in accomplishing the goals of the task set by the researcher? How satisfied were you with your performance in accomplishing these goals?

High **Low**

Effort
How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low **High**

Frustration Level
How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Low **High**

Nicola Combe – Telephone 07841195854 – Email Nicola.Combe@BuroHappold.com
Approved by the Research Ethics Committee of the School of Engineering and Design, Brunel University

Appendix 8 - User Testing Data from Descriptive Study II (Chapter 6)

Variable Name	Type	Width	Decimals	Label	Value	Missing	Columns	Align	Measure	Role
UserGroup	Numeric	8	0	User Group	1 Older Users, 2 Younger Users	None	8	Right	Nominal	Input
Age	Numeric	11	0	Age	None	None	11	Right	Scale	Input
Sex	Numeric	8	0	Gender	1 Male, 2 Female	None	11	Right	Nominal	Input
TaskSuccess	Numeric	11	0	Task Success	0 Unsuccessful, 1 Successful	None	11	Right	Nominal	Input
SuccessfulTime	Numeric	11	1	Successful Time	None	None	11	Right	Scale	Input
UnsuccessfulTime	Numeric	11	1	Unsuccessful Time	None	None	11	Right	Scale	Input
TSC	Numeric	11	0	Technical Self Confidence	None	None	11	Right	Scale	Input
TLXMental	Numeric	8	1	TLX Mental Demand	None	None	8	Right	Scale	Input
TLXFrustration	Numeric	8	1	TLX Frustration Level	None	None	10	Right	Scale	Input
TLXEffort	Numeric	8	1	TLX Effort Level	None	None	8	Right	Scale	Input

UserGroup	Age	Sex	TaskSuccess	SuccessfulTime	UnsuccessfuTime	Technical Self Confidence	TLX Mental Demand	TLX Frustration Level	TLX Effort Level
Older Users	64	Male	Successful	591	#NULL!	29	64.6	65.6	63.5
Older Users	68	Male	Unsuccessful	#NULL!	218.8	37	34.4	43.8	25
Older Users	65	Female	Successful	138.7	#NULL!	41	13.5	13.5	14.6
Older Users	75	Male	Unsuccessful	#NULL!	316.3	36	46.9	25	34.4
Older Users	52	Female	Successful	157.4	#NULL!	22	24	4.2	14.6
Older Users	64	Male	Successful	253.4	#NULL!	40	43.8	15.6	25
Older Users	64	Female	Successful	243.6	#NULL!	24	54.2	16.7	25
Older Users	78	Male	Unsuccessful	#NULL!	831.2	45	54.2	64.6	55.2
Older Users	75	Female	Unsuccessful	#NULL!	381.1	30	44.8	34.4	45.8
Older Users	66	Female	Unsuccessful	#NULL!	522.7	11	72.9	93.8	74
Older Users	76	Female	Successful	349.2	#NULL!	27	25	5.2	34.4
Older Users	61	Female	Successful	426.4	#NULL!	30	63.5	34.4	34.4
Older Users	77	Male	Unsuccessful	#NULL!	873.3	48	54.2	84.4	62.5
Older Users	70	Male	Successful	567.6	#NULL!	38	53.1	75	76
Older Users	65	Female	Successful	259.5	#NULL!	19	26	6.3	16.7
Older Users	77	Female	Unsuccessful	#NULL!	350.2	38	84.4	83.3	63.5
Younger Users	31	Male	Successful	188	#NULL!	44	60.4	38.5	15.6
Younger Users	26	Female	Successful	87.9	#NULL!	41	64.6	34.4	44.8
Younger Users	29	Female	Successful	135.3	#NULL!	33	19.8	0	10.4
Younger Users	35	Female	Successful	111.2	#NULL!	47	4.2	4.2	6.3
Younger Users	33	Female	Successful	195.4	#NULL!	38	25	5.2	15.6
Younger Users	26	Female	Successful	139.3	#NULL!	31	15.6	6.3	14.6
Younger Users	28	Female	Successful	209.9	#NULL!	38	64.6	54.2	74
Younger Users	28	Male	Successful	107.2	#NULL!	39	26	5.2	26
Younger Users	24	Male	Successful	244.1	#NULL!	46	55.2	55.2	55.2
Younger Users	24	Male	Unsuccessful	#NULL!	155.1	40	35.4	24	65.6
Younger Users	23	Male	Successful	114.6	#NULL!	21	30.2	0	9.4
Younger Users	29	Male	Successful	127.2	#NULL!	39	13.5	13.5	14.6
Younger Users	23	Male	Successful	141.8	#NULL!	45	14.6	0	0
Younger Users	30	Male	Successful	125.8	#NULL!	42	25	25	25
Younger Users	30	Female	Successful	165.9	#NULL!	33	55.2	43.8	25

UserGroup	Age	Sex	TaskSuccess	SuccessfulTime	UnsuccessfuTime	TSC	TLXMental	TLXFrustration	TLXEffort
1	64	1	1	591	#NULL!	29	64.6	65.6	63.5
1	68	1	0	#NULL!	218.8	37	34.4	43.8	25
1	65	2	1	138.7	#NULL!	41	13.5	13.5	14.6
1	75	1	0	#NULL!	316.3	36	46.9	25	34.4
1	52	2	1	157.4	#NULL!	22	24	4.2	14.6
1	64	1	1	253.4	#NULL!	40	43.8	15.6	25
1	64	2	1	243.6	#NULL!	24	54.2	16.7	25
1	78	1	0	#NULL!	831.2	45	54.2	64.6	55.2
1	75	2	0	#NULL!	381.1	30	44.8	34.4	45.8
1	66	2	0	#NULL!	522.7	11	72.9	93.8	74
1	76	2	1	349.2	#NULL!	27	25	5.2	34.4
1	61	2	1	426.4	#NULL!	30	63.5	34.4	34.4
1	77	1	0	#NULL!	873.3	48	54.2	84.4	62.5
1	70	1	1	567.6	#NULL!	38	53.1	75	76
1	65	2	1	259.5	#NULL!	19	26	6.3	16.7
1	77	2	0	#NULL!	350.2	38	84.4	83.3	63.5
2	31	1	1	188	#NULL!	44	60.4	38.5	15.6
2	26	2	1	87.9	#NULL!	41	64.6	34.4	44.8
2	29	2	1	135.3	#NULL!	33	19.8	0	10.4
2	35	2	1	111.2	#NULL!	47	4.2	4.2	6.3
2	33	2	1	195.4	#NULL!	38	25	5.2	15.6
2	26	2	1	139.3	#NULL!	31	15.6	6.3	14.6
2	28	2	1	209.9	#NULL!	38	64.6	54.2	74
2	28	1	1	107.2	#NULL!	39	26	5.2	26
2	24	1	1	244.1	#NULL!	46	55.2	55.2	55.2
2	24	1	0	#NULL!	155.1	40	35.4	24	65.6
2	23	1	1	114.6	#NULL!	21	30.2	0	9.4
2	29	1	1	127.2	#NULL!	39	13.5	13.5	14.6
2	23	1	1	141.8	#NULL!	45	14.6	0	0
2	30	1	1	125.8	#NULL!	42	25	25	25
2	30	2	1	165.9	#NULL!	33	55.2	43.8	25

Appendix 9 - Heating Profiles Developed for Energy Modelling (Chapter 7)

Heating Profiles Weekdays

all values in oC

Time	Default of Honeywell	Default of Siemens	Default of Drayton	Default of Salus	Task Settings	Misuse Scenario
00:00:00	16	8	7	17	5	21
00:30:00	16	8	7	17	5	21
01:00:00	16	8	7	17	5	21
01:30:00	16	8	7	17	5	21
02:00:00	16	8	7	17	5	21
02:30:00	16	8	7	17	5	21
03:00:00	16	8	7	17	5	21
03:30:00	16	8	7	17	5	21
04:00:00	16	8	7	17	5	21
04:30:00	16	8	7	17	5	21
05:00:00	16	8	7	17	5	21
05:30:00	16	8	7	17	5	21
06:00:00	16	20	7	21	5	21
06:30:00	21	20	20	21	5	21
07:00:00	21	20	20	21	19	21
07:30:00	21	20	20	21	19	19
08:00:00	21	20	20	21	19	19
08:30:00	18	8	20	17	19	19
09:00:00	18	8	16	17	19	19
09:30:00	18	8	16	17	5	19
10:00:00	18	8	16	17	5	19
10:30:00	18	8	16	17	5	19
11:00:00	18	20	16	17	5	19
11:30:00	18	20	16	17	5	19
12:00:00	21	20	16	17	5	19
12:30:00	21	20	16	17	5	19
13:00:00	21	20	16	17	5	19
13:30:00	21	8	16	17	5	19
14:00:00	21	8	16	17	5	19
14:30:00	18	8	16	17	5	19
15:00:00	18	8	16	17	5	19
15:30:00	18	8	16	17	5	19
16:00:00	18	8	16	21	21	21
16:30:00	18	8	21	21	21	21
17:00:00	18	8	21	21	21	21
17:30:00	18	8	21	21	21	21
18:00:00	21	8	21	21	21	21
18:30:00	21	8	21	21	21	21
19:00:00	21	20	21	21	21	21
19:30:00	21	20	21	21	21	21
20:00:00	21	20	21	21	21	21
20:30:00	21	20	21	21	21	21
21:00:00	21	20	21	21	21	21
21:30:00	21	20	21	21	21	21
22:00:00	21	20	21	21	21	21
22:30:00	16	8	21	17	21	21
23:00:00	16	8	7	17	21	21
23:30:00	16	8	7	17	5	21
00:00:00	16	8	7	17	5	21

Heating Profiles Weekends

all values in oC

Time	Default of Honeywell	Default of Siemens	Default of Drayton	Default of Salus	Task Settings	Misuse Scenario
00:00:00	16	8	7	17	5	21
00:30:00	16	8	7	17	5	21
01:00:00	16	8	7	17	5	21
01:30:00	16	8	7	17	5	21
02:00:00	16	8	7	17	5	21
02:30:00	16	8	7	17	5	21
03:00:00	16	8	7	17	5	21
03:30:00	16	8	7	17	5	21
04:00:00	16	8	7	17	5	21
04:30:00	16	8	7	17	5	21
05:00:00	16	8	7	17	5	21
05:30:00	16	8	7	21	5	21
06:00:00	16	20	7	21	5	21
06:30:00	16	20	7	21	5	21
07:00:00	16	20	20	21	19	19
07:30:00	16	20	20	21	19	19
08:00:00	21	20	20	21	19	19
08:30:00	21	8	20	21	19	19
09:00:00	21	8	18	21	5	19
09:30:00	21	8	18	21	5	19
10:00:00	21	8	18	21	5	19
10:30:00	21	8	18	21	5	19
11:00:00	21	20	18	21	5	19
11:30:00	21	20	18	21	5	19
12:00:00	21	20	21	21	5	19
12:30:00	21	20	21	21	5	19
13:00:00	21	20	21	21	5	19
13:30:00	21	8	21	21	5	19
14:00:00	21	8	18	21	5	19
14:30:00	21	8	18	21	5	19
15:00:00	21	8	18	21	5	19
15:30:00	21	8	18	21	5	19
16:00:00	21	8	21	21	5	19
16:30:00	21	8	21	21	5	19
17:00:00	21	8	21	21	5	19
17:30:00	21	8	21	21	5	19
18:00:00	21	8	21	21	21	21
18:30:00	21	8	21	21	21	21
19:00:00	21	20	21	21	21	21
19:30:00	21	20	21	21	21	21
20:00:00	21	20	21	21	21	21
20:30:00	21	20	21	21	21	21
21:00:00	21	20	21	21	21	21
21:30:00	21	20	21	21	21	21
22:00:00	21	20	21	17	21	21
22:30:00	21	8	21	17	21	21
23:00:00	16	8	7	17	5	21
23:30:00	16	8	7	17	5	21
00:00:00	16	8	7	17	5	21