THE ADOPTION PROCESS OF LOW-CARBON HOME RETROFIT AMONG UK HOMEOWNERS

A socio-technical perspective and system dynamics model

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Declaration

I, Yekatherina Bobrova confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

The promotion of low-carbon home retrofit among UK homeowners is widely recognised as an important strategy to reduce energy consumption and mitigate climate change. The current literature points to a lack of understanding of the combined links between retrofit motivation, decision processes, physical characteristics of low-carbon retrofits and post-retrofit energy use. To address this issue, the thesis conceptualises low-carbon retrofit as an innovation process situated in the context of meanings people attach to their homes.

The research uses a multiple-case study design approach in an empirical analysis of eight home retrofit case studies of homeowners, who achieved more than 60% carbon emission reductions as a result of retrofit activities. The theoretical framework for the thesis uses the notion of *affordance* to develop a framework of home-meanings, and combines it with Rogers' *innovation diffusion theory* to conceptualise retrofit as a process, situated and shaped by the conditions of everyday life. Hockey's *motivation control theory of fatigue* is used to develop a system dynamics simulation model and develop insights into the implementation difficulties during low-carbon retrofit process.

The main insights of the thesis are: (i) low-carbon homes are associated with enhanced feelings of comfort, safety, security and control, as well as an identity of a broader social responsibility; (ii) low-carbon home retrofit as an innovation encompasses three aspects: a product, a design option and a socio-technical system; (iii) homeowners collect information through different communication channels, which are non-substitutable by one another; (iv) a positive retrofit experience for homeowners is necessary for low post-retrofit energy use, as well as to persuade others to retrofit their homes. A feeling of control over the retrofit experience, which can be achieved through a step-by-step retrofit approach, might ease the implementation burden for homeowners. Future research is necessary to investigate how such feeling is established during retrofit.

Impact statement

This thesis advances the understanding of homeowner retrofit-decision processes and its implications on the overall transition to a low-carbon housing stock. The key research contributions in the area of policy extension are:

(i) The thesis suggests the use of visual images of everyday activities, coupled with textual messages, to explain how low-carbon dwellings provide more comfort, safety, security and control for everyday activities, compared to a non-low-carbon one. It is also suggested to support the development of homeowner identity of a broader social responsibility that is recognised by others, for instance, on a communal level through peer-to-peer trading system.

(ii) The thesis provides evidence that homeowners collect information about different products, design options and low-carbon home systems at different decision stages through different communication channels, which are non-substitutable by one another. The thesis suggests to support information provision at all decision stages for all aspects of low-carbon home innovation.

(iii) The thesis suggests that a policy focus on the establishment of a feeling of homeowner control over the retrofit experience can help to: (a) achieve a sustained reduction in post-retrofit energy use; (b) create a positive word of mouth regarding low-carbon retrofit, which can persuade others to retrofit their homes. One way to establish the feeling of control for homeowners is a step-by-step approach to retrofit.

The research contributions of the thesis in the areas of theory development and research methods are:

(i) The thesis develops a conceptual framework of home-meanings, which represents a rich synthesis of current empirical and theoretical literature. Future research can start with the framework to develop a theory to explain how the home comes to have meaning for an individual.

(ii) The thesis raises the following points, which might have broader applicability within innovation diffusion discourse: (a) disaggregation on a unit of analysis into three levels: a particular product, a design option and a socio-technical system; (b) the importance of a good implementation experience for the actors for the successful adoption and use of an innovation; (c) the differences between a one-step vs step-by-step adoption of technologies, and the associated impact on the overall innovation diffusion in the population.

(iii) Hockey's motivation control theory of fatigue is formalised into a simulation model. The simulation results reveal two additional behavioural patterns for work management, not previously conceptualised by Hockey: (a) sustained proactive coping; and (b) oscillations between proactive to reactive coping. Simulation development suggests future research to further clarify the construct of *Perceived Control*.

(iv) The thesis illustrates a three-step approach to develop a generic, theory-based simulation model that can be applied to specific cases: (a) the application of a process research design to multiple-case studies to reveal a behavioural pattern of interest, specific to the cases; (b) the application of a generic theory, which is formalised in a simulation model, to bring further insights into the dynamics of the behavioural patterns identified in the cases; (c) further exploratory data collection to parametrise the model to the cases observed, explore model behavior and derive policy implications.

Dedication

This work is dedicated to my dear mum — Galina Bobrova — the best mum ever!

Мамочка,

я тебя очень люблю!

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Work dissemination

Thesis findings have been presented to the government:

Bobrova, Y. (2019) 'The adoption process of low-carbon home retrofit among UK homeowners: A socio-technical perspective and system dynamics model'. [Presentation]. Presented at: PhD seminar series at the Department for Business, Energy and Industrial Strategy. 25 September. London, UK.

Part of the thesis findings have been previously published in the following journal:

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Preliminary findings have been presented at the following national and international conferences:

Bobrova, Y. and Papachristos, G. (2019) 'Work management under stress: A dynamic exploration of a motivation control theory of fatigue'. **Student Prize Award for the best student paper of the year**. In: *UK Chapter of the System Dynamics Society. Annual Conference 2019*. 4–5 April. London, UK. Available at: http://systemdynamics.org.uk/wp-content/uploads/2019AC-Day2-Bobrova-Rep.pdf

Bobrova, Y. and Tikhomirova, S. (2018) 'Psychological home-meanings as a factor in low-carbon retrofit behaviour' [Presentation]. Presented at: *The all-Russian anniversary conference «Problems of social and economic psychology: Results and future research»*. 7 December. Moscow, Russia: Institute of Psychology of Russian Academy of Sciences. Conference programme available at: http://www.ipras.ru/engine/documents/document13354.pdf (in Russian).

Bobrova, Y., Chiu, L.F. and Papachristos, G. (2018) ‘Understanding homeowners’ renovation decisions resulting in low-carbon retrofit’. In: *BEHAVE 2018. 5th European Conference on Behaviour and Energy Efficiency*. 6–7 September. Zurich, Switzerland: Zurich University of Applied Sciences. Available at: https://portal.research.lu.se/portal/files/51725611/behave_2018_proceedings.pdf

Bobrova, Y., Papachristos, G. and Zimmermann, N. (2018) ‘A dynamic model of psychological fatigue in the process of low-carbon home retrofit’. In: *36th International Conference of the System Dynamics Society*. 6–10 August 2018. Reykjavík, Iceland: System Dynamics Society. Available at: http://proceedings.systemdynamics.org/2018/proceed/papers/P2148.pdf

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Abbreviations

°C	Degree Celsius
2,4-D	2,4-Dichlorophenoxyacetic acid
A levels	
AIDS	Acquired Immunodeficiency Syndrome
BEIS	Department for Business, Energy & Industrial Strategy
CAT	Centre for Alternative Technology
CAQDAS	Computer-Assisted Qualitative Data Analysis Software
CCC	Committee on Climate Change
CFL	Compact Fluorescent Lamp
CLD	Causal Loop Diagram
CO_2	Carbon Dioxide
DCLG	Department for Communities and Local Government
DECC	Department for Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DTI	Department of Trade and Industry
DIY	Do It Yourself
ECEEE	European Council for an Energy Efficient Economy
ECO	Energy Company Obligation
e.g.	exempli gratia (means "for example")
EnerPHit	Passivhaus refurbishment standard
EPC	Energy Performance Certificate
ESCO	Energy Service Company
EST	Energy Saving Trust

et al.	Et aliī (means “and others”)
FIT	Feed-in Tariff
GB	Great Britain
H.M. Treasury	Her Majesty’s Treasury
i.e.	id est (means “in other words”)
ibid.	ibīdem (means “in the same place”)
IBSS	International Bibliography of the Social Sciences
IEDE	Institute for Environmental Design and Engineering
IMechE	Institution of Mechanical Engineers
IPCC	International Panel on Climate Change
JDM	Judgement and Decision Making
kg	kilogram
kWh	Kilowatt-hour
LED	Light-Emitting Diode
m^2	Square metre
MHCLG	Ministry of Housing, Communities & Local Government
MVHR	Mechanical Ventilation with Heat Recovery
NA	Negative Affect
NHER	National Home Energy Rating
NHS	National Health Service
PA	Positive Affect
PhD	Doctor of Philosophy
PHPP	Passive House Planning Package
PV	Photovoltaic Panel
PVHR	Passive Ventilation Heat Recovery
RfF	Retrofit for the Future Project

RHI	Renewable Heat Incentive
SAP	Standard Assessment Procedure
SD	System Dynamics
SFD	Stock and Flow Diagram
TIPI	Ten-Item Personality Inventory
UCL	University College London
UK	United Kingdom
UN	United Nations
VERD	Value Propositions for Energy Efficient Renovation project
W/m^2K	Watts per metre square Kelvin

Chapter 1

Introduction

The introduction chapter presents the contextual information against which this study positions itself in section 1.1, and outlines the motivation of the study in section 1.2. The main research aim and objectives are outlined in section 1.3. This section also outlines the scope of the thesis and the research methods used to address the objectives of the study. The main areas of the thesis contribution to the field are discussed in section 1.4. Finally, the outline of the structure of the thesis is laid out in section 1.5.

CHAPTER CONTENTS

1.1. CONTEXT: THE NEED TO ENCOURAGE LOW-CARBON HOME RETROFIT AMONG UK HOMEOWNERS

Scientific evidence shows that a change in climate patterns has been taking place since the industrial revolution driven by increased CO_2 emissions (IPCC, 2018; 2014). The degree of this change is partially attributed to natural environmental variations, but can only be fully explained together with anthropogenic influences (IPCC, 2014). On 27th June 2019 the UK government formalised the target for net-zero greenhouse gas emission by 2050 into law (Climate Change Act 2008 (2050 Target Amendment) Order 2019), in order to stabilise the concentration of carbon in the atmosphere at its current levels and avoid potentially disastrous consequences (CCC, 2019).

Energy use in homes accounts for just under a third of total energy use in the UK, up from a quarter in 1970 (Palmer and Cooper, 2013). Overall, there has been a broad downward trend in CO_2 emissions from housing, but a reduction of only about 5% against a 1990 baseline was achieved by 2010, which is attributed primarily to the increased number of dwellings (ibid.). Greenhouse gas emissions from natural gas combustion for heating and cooking in the residential sector reduced only by 16% between 1990 and 2017 (GB. BEIS, 2019). Thus, an additional reduction in operational energy use in dwellings is required to meet the UK 2050 targets.

Operational energy use in dwellings is associated with the energy-efficiency of building components as well as variations in the energy-related behavioural patterns of occupants. The promotion of low-carbon home retrofit among UK homeowners, who represent 70% of the UK housing stock (GB. MHCLG, 2019a; Palmer and Cooper, 2013), is widely recognised as an important strategy to achieve further reductions in operational energy use in dwellings and mitigate climate change (GB. BEIS, 2017; GB. DTI, 2007). A range of policies has been implemented in the UK in an attempt to reduce operational energy use in owner-occupied dwellings and associated carbon emissions (Dowson et al., 2012; Abu-Bakar et al., 2013). Despite that, the rate of sustainability-related retrofit remains persistently low (Egger, 2015; Fawcett, 2014; Fawcett and Killip, 2014; Jenkins et al. 2019). The most recent governmental scheme, Green Deal, was launched in January 2013 (GB. DECC, 2013), and scrapped in 2015 as unsuccessful (GB. DECC et al., 2015). The UK government has since sought evidence and views on how to encourage homeowners to retrofit their homes to low-carbon standards (CCC, 2017; CCC, 2019; GB. BEIS, 2017).

1.2. MOTIVATION: A LACK OF UNDERSTANDING OF LOW-CARBON RETROFIT-DECISION PROCESSES

The formulation of governmental policies, such as the Green Deal, is primarily focused on the techno-economic aspects of achieving energy savings (Vlasova and Gram-Hanssen, 2014). The implication is that policy aims to identify *cost-efficient* options to reduce energy use in dwellings and provide *information* about such options to homeowners (Wilson et al., 2015). This techno-economic focus has been repeatedly criticised for being too narrow, and, thus, limiting view on retrofit decisions. The literature suggests that low-carbon retrofit is not just a technical problem that can be solved through information provision, but should be understood as a socio-technical problem with social, economic, and sustainability dimensions (Chiu et al., 2014; Gram-Hanssen, 2014b; Karvonen, 2013; Lutzenhiser, 2014; Munro and Leather, 2000; Rosenow and Eyre, 2016; Tweed, 2013; Wilson et al., 2015).

Building research and policy has traditionally focused on the decisions that homeowners make with regard to low-carbon retrofit as isolated events (Wilson et al., 2015). The logic is that when homeowners weigh the benefits and costs of particular options, information provision and various incentives may influence their decisions in favour of more sustainable solutions. Thus, research and policy has a narrow focus on the identification of drivers and barriers of various options, in order to make the desired options seem more beneficial than alternatives and bring about a desired outcome (Fyhn and Baron, 2017; Wilson et al., 2015). Recent research argues that there is a need to look beyond the scope of the isolated moment, when a certain retrofit decision is made, and focus on the whole process that can lead to, or away from, this isolated moment of decision-making (Fyhn and Baron, 2017). Recent process-driven research on domestic retrofit suggests that retrofit decisions should be conceptualised as processes comprised of a series of stages (Fawcett, 2014; Gram-Hanssen, 2014a; Wilson et al., 2015). The differentiation between retrofit stages makes it possible to distinguish different levels of influences that vary in their nature, intensity, and timing, which can potentially provide a platform for policy formulation that is specific to different levels of influences. For instance, Wilson et al. (2015) differentiate between immediate, proximate and ultimate influences, e.g. the costs of a specific insulation, the trust in builders to deliver good quality work, and the meanings people attach to their homes respectfully.

A suitable approach to study decision-making process must take into account "the complex relations of the individual in context" (McFall, 2015: p. 56). Several calls have been made to understand retrofit decision-making process as situated within the specific context that homeowners face (Bartiaux et al., 2014; Kastner and Stern, 2015; Wilson et al., 2015). Wilson et al. (2015) argue that retrofit decisions should be understood in the context of meanings people attach to their homes to understand their motivations. However, to date, home-meanings have not been used to bring insights into contextual heterogeneity of low-carbon home retrofit.

Previous research has looked separately on energy retrofit motivations and decision processes. However, to date, the combined links between these components have not been directly studied. There is little understanding in the current literature of what are the feedbacks between different stages of individual retrofit-decision processes, how such feedbacks affect the overall transition to a low-carbon housing stock, and how such understanding could be used to facilitate the uptake of low-carbon measures and technologies among UK homeowners.

1.3. RESEARCH AIM, OBJECTIVES AND METHODS

Motivated by the outlined gap in knowledge, the thesis aims to improve the understanding of individual low-carbon retrofit-decision processes and explore the implications on the uptake of low-carbon measures and technologies on a population level. The thesis does so by addressing the following general research question:

How can the individual retrofit decisions of UK homeowners be influenced to accelerate the rate of low-carbon retrofit in the population?

The following research objectives outline the scope of the thesis:

- Objective 1. Understand how home-meanings can be used to promote low-carbon home retrofit.
- Objective 2. Capture the dynamics of individual retrofit-decision processes that result in low-carbon operational energy use, and explore the implications for the transition to a low-carbon housing stock.
- Objective 3. Identify patterns and regularities in retrofit implementation difficulties, captured when addressing objective 2. Develop a simulation model based on these and explore ways to minimise them via different simulation scenarios. Consider the implications for the transition to a low-carbon housing stock.

The research uses a multiple-case study design with a qualitative and a quantitative approach for data collection and analysis. Eight home retrofit cases are selected with a convenience purposeful sampling strategy. The sample of dwellings is selected from the SuperHomes network (National Energy Foundation, 2015; SuperHomes, 2011). It is a UK-based voluntary network of homeowners that achieved more than 60% carbon reductions as a result of retrofit activities.

The objectives of the thesis are addressed in the following way. First, the framework of home-meanings is developed to bring insights into contextual heterogeneity of low-carbon home retrofit.

Second, retrofit decisions are conceptualised as an innovation-decision process in line with Rogers' innovation diffusion theory (Rogers, 2003). A combined framework of home-meanings and retrofit stages is used to gain insights into retrofit goals, retrofit-decision processes and living experiences of the homeowners in the study sample. The case study data for the contextualised retrofit-decision processes are collected via in-depth interviews with homeowners and associative experiments. Homeowner retrofit experiences are documented via visual process mapping. Detailed reports of individual cases are written to gain familiarity with the cases. Cross-case analysis compares and contrasts the variables of interest across the cases, while keeping in mind particularities and context of individual cases. Matrices, process and causal diagrams are used for analytic display. A second set of interviews is carried out to confirm the preliminary results. The process of case-by-case and cross-case analysis is repeated. The analysis demonstrates the existence of stages in a contextually-rich retrofit decisions, and suggests how governmental policies can diversify their efforts, targeting households at different stages of the process. Retrofit-associated psychological fatigue is identified is one of the implementation barriers to low-carbon retrofit.

Third, a system dynamics simulation model is developed to represent the causal relations of retrofit-related psychological fatigue. Hockey's motivation control theory of fatigue is suggested as a theoretical framework for further analysis. The original theory description is analysed via thematic coding and formalised into a simulation model. The model is validated in several ways, including a review with Hockey himself, tested and parameterised to the case studies in the sample. To do this, further empirical data is collected via in-depth interviews, questionnaires and associative experiments. Computer simulation is used to explore various retrofit scenarios and possible policy implications. These methodological steps are summarised in the Box 1.1.

Box 1.1. Research objectives and methods used

Objective 1. Understand how home-meanings can be used to promote low-carbon home retrofit.

Objective 2. Capture the dynamics of individual retrofit-decision processes that result in low-carbon operational energy use, and explore the implications for the transition to a low-carbon housing stock.

a. Collect empirical data via in-depth interviews, conduct associative experiments and visual process mapping of the homeowner retrofit experiences.
b. Conduct case-by-case and cross-case analysis to develop insights into retrofit goals, retrofit-decision processes, living experiences and associations of the homeowners in the sample.
c. Conduct a second set of interviews to confirm preliminary findings.
d. Repeat the process of case-by-case and cross-case analysis. Reveal relations between the retrofit context and different retrofit stages, specific to individual retrofit-decision processes. Explore the implications for the transition to a low-carbon housing stock.
e. Demonstrate the existence of stages in contextually-rich retrofit decisions. Suggest how governmental policies can diversify their efforts, targeting households at different stages of the process.

Objective 3. Develop a generic simulation model of retrofit-associated fatigue. Explore via the simulation model how the development of fatigue can be neutralised to ensure an overall positive experience of low-carbon retrofit by the homeowners.

f. Justify the use of Hockey's motivation control theory of fatigue as a suitable theoretical lens to bring insight into the development of retrofit-associated fatigue, and develop the theory into an endogenous, dynamic causal hypothesis.
g. Formalise the theory into a simulation model.
h. Test and validate the model.
i. Collect additional empirical data via in-depth interviews, questionnaires and associative experiments. Parameterise the model to the case studies in the sample and explore the behaviour of interest.
j. Explore the theoretical and case-based based simulation results in terms of policy implications for low-carbon retrofits.

1.4. RESULTS AND CONTRIBUTION

This thesis intends to make contribution to the areas of theory development, innovative methods and policy implications for low-carbon home retrofit.

The intended contributions to the area of **theory development** are:

(i) The thesis is aimed to document a range of successful cases of low-carbon home retrofit. The qualitative analysis of the cases intends to develop insights into the implications of individual retrofit journeys on the overall transition to a low-carbon housing stock.

(ii) The thesis is aimed to build a conceptual framework to understand the meanings people attach to their homes.

(iii) The thesis is aimed to tailor Rogers' innovation diffusion theory to study low-carbon home retrofit decisions. The thesis also intends to explore the retrofit process from the novel perspective of psychological fatigue.

(iv) The thesis is aimed to build a formal model of motivation control theory of fatigue, which tests the internal validity of the theory. The thesis intends to explore the dynamic implication from the theory and point to areas that need further research.

The intended contributions to the area of **innovative methods** are:

(v) The thesis is aimed to develop and apply a sequential multi-method approach to the study of home retrofits that bridges empirical qualitative data, interviews and a formal simulation model of fatigue development in home retrofits.

(vi) The thesis is aimed to develop a theory-based generic simulation model, the formulation of which is triggered by specific cases and that can be applied to these cases.

The intended contributions to the area of **policy extension** are:

(vii) This thesis is aimed to propose new ways, different from mainstream policy, to encourage UK homeowners to retrofit their homes to low-carbon standards. New insights and suggestions will become possible as a result of understanding retrofit decisions as processes, shaped in the context of meanings people attach to their homes.

1.5. STRUCTURE OF THE THESIS

The rest of the thesis consists of seven chapters.

Chapter 2. *Research context* provides an overview of the relevant literature and situates the current study in it. The chapter highlights the importance of the UK owner-occupied residential sector in the broader context of climate change mitigation. A case is made for a socio-technical approach to understand homeowner decisions as processes, embedded in the context of meanings people attach to their homes. The chapter provides a qualitative meta-synthesis of current empirical studies that capture stages of low-carbon retrofit-decision processes, as well as drivers and barriers specific to these stages. This synthesis is used to outline the gap in current knowledge, which concludes the *Research context* chapter.

Chapter 3. *Research methodology* formulates the research aim and identifies specific research objectives. It outlines the epistemological and paradigmatic positioning of the thesis. The chapter presents a rationale for a combination of multiple case study design with simulation modelling to address the research objectives. Following that, it describes the methods chosen and justifies the way they are integrated in the research process followed in the thesis. The chapter concludes with a discussion of credibility strategies employed in the thesis.

Chapters 4. *Analysis context* provides a rich description of individual cases, used in the thesis, necessary to familiarise the reader with them. The chapter also summarises descriptions across all the cases.

Chapters 5 and 6 present the *Results* of the data analysis. The research findings involve two main elements: (i) *Chapter 5* presents the qualitative analysis of retrofit-decision processes, understood in the context of meanings people attach to their homes. The chapter suggests how the stages of the processes can be influenced, and the implications they can have on the overall transition to a low-carbon housing stock. Retrofit-associate psychological fatigue is suggested as one of the implementation barriers. (ii) *Chapter 6* develops a generic system dynamics model of motivation control theory of psychological fatigue. The model is used to explore the theory, and is parameterised to explore empirical cases.

Chapter 7. *Discussion* brings together the findings from chapters 5 and 6, and jointly discusses their implications for research and for practice in relation to current literature that is outlined in the *Research context* chapter. The chapter also reviews how the research objectives have been addressed, and discusses the research limitations and ideas for future research.

Chapter 8. *Conclusions* summarises the key findings in relation to initial research aim, outlines the contributions of the thesis, the implications for policy guidance and provides recommendations for future research.

Chapter 2

Research context: Comprehension of low-carbon home retrofit decisions

This chapter sets the necessary background for the subject matter that is the focus of this thesis and the methods used in its study. Low-carbon retrofit of existing domestic stock is important in light of the need to mitigate climate change-related emissions. Dwelling retrofit process involves not only technical aspects, but also a range of social dimensions that are pertinent to the process. It is these dimensions that this chapter elucidates. Section 2.1 defines the phrase 'low-carbon retrofit' as used in this thesis. It subsequently outlines the role of low-carbon retrofit in climate change mitigation and provides evidence of a low rate of sustainability-related retrofit in the owner-occupied sector. Section 2.2 evaluates the variance perspective on retrofit decisions, which is widespread in both policy and research. Subsequently, the section questions the appropriateness of this perspective to understand homeowner retrofit decisions. Section 2.3 reviews the evidence from the process research perspective and synthesises current qualitative research on the topic. Section 2.4 discusses low-carbon retrofit decisions as processes embedded in a socio-technical context. First, the section argues that it is important to understand home-meanings as a context for low-carbon retrofit decisions. Second, the section develops an argumentation for the conceptualisation of retrofit decisions as innovation-decision processes in line with Rogers' innovation diffusion theory. The section then discusses implementation difficulties in the process of innovation diffusion. Section 2.5 develops a conceptual framework of home-meanings around the notion of affordance. Section 2.6 outlines a gap in knowledge in understanding low-carbon retrofit decisions among UK homeowners this thesis aims to fill. The chapter concludes with a summary in section 2.7.

CHAPTER CONTENTS

2.1. LOW-CARBON RETROFIT IN THE UK AND ITS ROLE IN CLIMATE CHANGE MITIGATION

2.1a. In search of a definition of low-carbon retrofit

There is no agreed definition of what constitutes low-carbon home retrofit, in terms of targets to be reached, the measures that need to be installed or the behaviour changes necessary to reach these targets (Fawcett, 2014). Fawcett (2014) points out to the multitude of the terminology, as the term 'retrofit' is used interchangeably with the terms 'refurbishment' and 'renovation', and the term 'low-carbon' is used interchangeably with such terms as 'green', 'energy-efficient', 'deep' or 'thermal'. This diversity of terms reflects the early stages of the development of low-carbon retrofit activity, which has yet a long way to go to become an established practice (Bartiaux et al. 2014).

There are several programmes and projects established or represented in the UK, which developed specific definitions of low-carbon retrofit, albeit using different names to describe the concept. The Passivhaus refurbishment standard (EnerPHit) specifies a particular heating demand of 25 kWh/m^2/year (Passivhaus Institut, 2012). The Retrofit for the Future (RfF) programme aimed to achieve 80% carbon reductions in each dwelling compared with 1990 average levels (Technology Strategy Board, 2013). The SuperHomes network gives a SuperHome label to a dwelling, if carbon emissions have been reduced by at least 60% as a result of retrofit activities (SuperHomes, 2011). The Open Eco Homes network is more flexible and assesses each home individually, based on whether a property can demonstrate many ways to reduce energy use and carbon emissions (Open Eco Homes, 2016). The programmes and projects are presented in alphabetical order in Table 2.1. This list is not intended to be exhaustive, but rather aims to illustrate the diversity of opinions in both industry and academia on what constitutes 'low-carbon retrofit'.

Table 2.1. A selection of low-carbon retrofit definitions

Programme/ project title	Definition of low-carbon retrofit
Open Eco Homes (Open Eco Homes, 2016)	This network does not have specific criteria to define an Eco Home. Instead, Eco Homes are defined as the ones that demonstrate many ways to reduce energy use and carbon emissions, whilst making homes more comfortable.
Passivhaus refurbishment standard (EnerPHit) (Passivhaus Institut, 2012)	This international building standard requires a heating demand below 25 kWh/m^2/year, which is calculated by the specialised Passive House Planning Package (PHPP) tool.
Retrofit for the Future (RfF) (Technology Strategy Board, 2013)	The programme aimed to achieve 80% reduction in the in-use emissions of each property compared with 1990 average performance levels for a three-bedroom semi-detached property, a proxy for which was calculated by Energy Saving Trust. The figure was then normalised by the average gross internal floor area. This translated into a primary energy target of 115 kWh/m^2/year and an emissions target of 17 kgCO_2/m^2/year.
SuperHomes (SuperHomes, 2011)	This network consists of dwellings that have reduced their carbon emissions by at least 60% as a result of retrofit activities. Pre-retrofit emissions are on a modelled basis, post-retrofit emissions are either on a modelled or measured basis.

Despite their differences, all these definitions of low-carbon retrofit are determined in terms of post-retrofit operational use only. There are two interesting points to note in light of this observation. First, retrofit activity is associated with embodied carbon, to which a significant portion comes from the extraction of raw materials, transportation and manufacturing of goods (Pomponi et al., 2018). Second, these definitions exclude implicitly the role of occupant's energy practices of final energy use, even though research has shown that such practices might be at least as important to reduction in energy use as the physical properties of products and technologies (Gram-Hanssen, 2013).

This thesis draws upon the biggest source of data on low-carbon home retrofit in the owner-occupied sector, the SuperHomes database (SuperHomes, 2011). For this reason, the phrase 'low-carbon retrofit' is used to describe retrofit activities that resulted in at least 60% carbon reductions compared with pre-retrofit emissions in line with the definition developed by the network. Pre-retrofit emissions are estimated on a modelled basis, and, thus, are not representative of the households' specific energy behaviour and practices, as models tend to have standard assumptions about behaviour. Post-retrofit carbon savings might be calculated based on a modelled or a measured basis. For the former, specific patterns of households' energy behaviour and practices are not accounted for. However, for the latter, they are. Thus, the phrase 'low-carbon retrofit' is used in this thesis to describe savings delivered via energy efficiency of building envelope and building components (including lights and appliances), the use of renewable energy technologies, as well as a change in energy-related behaviour and practices.

2.1b. The role of low-carbon retrofit in owner-occupied sector in climate change mitigation

Energy use in homes accounts for just under a third of total energy use in the UK, up from a quarter in 1970 (Palmer and Cooper, 2013). Operational energy use in dwellings is associated with the energy efficiency of building components as well as variations in the energy-related behavioural patterns of occupants. The theoretical understanding and the technology needed to reduce heat loss in buildings have been available for over 40 years (Lowe and Oreszczyn, 2008).

The UK government views housing as the most cost-effective and technologically ready sectors to reduce carbon emissions (GB. DECC, 2012). Similar views are expressed in academia. For instance, Tuominen et al. (2012) estimate potential energy savings for the UK by 2030 to be around 20% of 2012 heating energy consumption. There is ambiguity among the research community about the number of cost-effective energy efficiency measures that are yet to be implemented throughout the UK housing stock. Some researchers claim that there is still great potential for further energy efficiency improvements (Roberts, 2008), and that the installation of some energy-efficient building elements can even come at negative net costs (Uihlein and Eder, 2010). Other researchers argue that a large proportion of the most cost-effective measures have already been implemented (Lowe and Oreszczyn, 2008).

In England, where 84% of the UK population lives (Office for National Statistics, 2018), 64% of households are owner-occupiers and 92% of homes in owner-occupation are single-family homes (GB. MHCLG, 2019a). Given the predominance of owner-occupied single-family homes in the UK housing stock, the promotion of low-carbon home retrofit in this sector is widely recognised as an important strategy to achieve further reductions in operational energy use in dwellings and mitigate climate change (GB. BEIS, 2017; GB. DTI, 2007).

2.2c. Evidence of a low rate of sustainability-related retrofit among homeowners

There is a considerable concern with the amount of low-carbon retrofit that needs to be undertaken in the owner-occupied domestic sector in the UK. The most widely cited number is 600,000 dwelling per year reported by Energy Saving Trust (EST, 2010a). The number in the repost is obtained by including an estimation of all dwellings that will exist in 2050 after subtraction of the number of dwellings that were not in SAP band A or B in 2010. An overview of Standard Assessment Procedure (SAP) is given in Box 2.1.

Box 2.1. An overview of Standard Assessment Procedure (SAP) (based on Palmer and Cooper, 2013)

The Standard Assessment Procedure (SAP) represents the government's official method of rating the energy efficiency of the houses, which has been used since 2003. The rating is using a non-linear scale from 1 to 100 with higher rates indicating lower annual energy costs and, thus, better energy efficiency. EPC band A equates to 92–100 SAP points, and EPC band B equates to 81–91 SAP points. The average SAP rating of the UK housing stock has steadily increased from below 20 in 1970 to about 55 in 2010, an improvement largely attributed to improved energy efficiency of existing housing stock.

SAP does not measure the level of fabric energy efficiency itself (using U-values for instance). Instead, the ratings are based on annual energy costs, which include space heating, water heating, lighting and ventilation loads. In that sense, the rating serves rather as an indicator of a change in the energy efficiency of the housing stock.

Energy Saving Trust published its report in February 2010, thus, in this thesis it is assumed that 2009 statistics have been used. There were estimated to be 27.3 million dwellings in England, Scotland, Wales and Northern Ireland in 2009 (GB. MHCLG, 2018b; Northern Ireland. Department for Communities, 2018; Scottish Government, 2018; Welsh Government, 2018). The report considers dwellings with SAP band of A and B as the ones with acceptable CO_2 emissions (EST, 2010a). Around half a million SAP certificates in bands A and B have been lodged from 2008 to 2010 in England in Wales (GB. MHCLG, 2019b). The number is not expected to be significantly different, if the certificates in Scotland and Northern Ireland are also taken into account. In summary, the number 600,000 per year is obtained as following: from the total number of dwellings (27.3 million) half a million is subtracted as these dwellings are already in SAP band A and B. Another million is added to account for dwellings built between 2010 and 2016 (estimation in EST, 2010a: p. 5). It was expected that building regulations would enforce 'zero carbon' standards for new built dwellings in 2016, but the Government announced that it would not proceed with such plans in July 2015 (GB. H.M. Treasury, 2015). From the remaining number of dwellings another three million are subtracted as they are expected to be demolished before 2050 (estimation in EST, 2010a: p. 5). The remaining 24 million dwellings are divided by 40 years (time between the date of the report, 2010, and 2050), which gives a number of 600,000 dwellings per year. It should be noted that this number includes all dwellings that were not in SAP band A or B in 2010. This means, that for some of these dwellings a lot of work needs to be done to retrofit to low-carbon standards, while other dwellings might already be near the standard.

Renovation and refurbishment rates are estimated to be between 2.9% and 5% of existing stock for domestic buildings (Stafford et al., 2011), which is between about 790,000 and 1,365,000 dwellings per year. However, most of these renovations are amenity renovations, and homeowners often do not use amenity and maintenance retrofit as an opportunity to carry out energy efficiency works (Stieß and Dunkelberg, 2012). There are no centralised records of how many sustainability-related renovations projects are carried out, but there is consensus among both practitioners and academics that the rate of such renovations is stubbornly low (Egger, 2015; Fawcett, 2014; Fawcett and Killip, 2014; Jenkins et al. 2019). For instance, Fawcett (2014: p. 487) argues that the actual low-carbon home retrofit activity is "in the order of hundreds" annually.

Policy documents that consider the technological and economic feasibility of sustainability-related retrofit conclude routinely that the relevant technology is available for different applications, and in most cases its adoption is cost-effective (Levine et al., 2007; UNEP, 2009). Nevertheless, the majority of homeowners do not carry out sustainability-related retrofit (Crosbie and Baker, 2010). This is a well-known long-standing problem (Gillingham and Palmer, 2014), and a wealth of policies, regulations and incentives have been introduced over the years to encourage such retrofit.

This section introduced the working definition of low-carbon retrofit used in this thesis, highlighted the importance of low-carbon retrofit in the domestic sector in climate change mitigation and highlighted the evidence for low incidence of such retrofit in the private housing market. The next section outlines the predominant perspective to explain the situation.

2.2. VARIANCE PERSPECTIVE ON RETROFIT DECISIONS: A PREDOMINANT FRAMEWORK TO UNDERSTAND THE SITUATION

2.2a. Policy views on homeowner retrofit decisions

UK governmental policy initiatives and legislation on decarbonisation of the built environment range from broad overarching legislative requirements outlined in *Climate Change Act 2008* to specific requirements for energy performance of buildings set in building regulations, which cover new construction as well as retrofit (GB. MHCLG, 2018a). There is no UK policy that supports specifically owner-occupiers to reduce carbon emissions by at least 60% as a result of retrofit activities. Government incentive schemes represent a key driver to deliver necessary reductions in energy consumption and carbon emissions of the existing housing stock. Most governmental policies are designed to support households in the social housing sector rather than owner-occupiers (Dowson et al., 2012). Nevertheless, a range of policies has been implemented in the UK, with varying levels of success, in an attempt to reduce operational energy use in owner-occupied dwellings and associated carbon emissions (Dowson et al., 2012; Abu-Bakar et al., 2013).

Throughout the time, many consecutive governmental schemes took the form of legal obligations for energy supplier to reduce carbon emissions of dwellings through various energy efficiency measures. The Affordable Warmth Obligation, a revised version of Energy Company Obligation (ECO) schemes remains today (GB. BEIS, 2018). The scheme is primarily targeted at deprived and vulnerable households. There are also schemes that encourage homeowners to install renewables at their properties. Those currently available are the Feed-in Tariff (FiT) and the Domestic Renewable Heat Incentive (RHI) (The Feed-in Tariffs (Closure, etc.) Order 2018; The Renewable Heat Incentive Scheme Regulations 2018). The Green Deal scheme, a form of a loan available to private households towards energy efficiency retrofit measures, was launched in January 2013 (GB. DECC, 2013) and was meant to revolutionise the housing stock. Instead, it resulted in a "collapse of the domestic energy efficiency market" (Rosenow and Eyre, 2016: p. 144), and was scrapped in 2015 as unsuccessful (GB. DECC et al., 2015). The Green Deal scheme remains the only widely launched governmental scheme, intended to support the installation of energy efficiency measures, that targeted the homeowners themselves.

There is consensus among practitioners and academics alike that current European policies in general, and UK policies in particular are not enough to achieve a significant increase in renovation rates (ECEEE, 2011; Egger, 2015). An understanding of homeowner decisions that result in low-carbon retrofit is an important step to build successful policies to encourage such retrofit. Overall, building policy has traditionally maintained a technical-economic focus on operational energy use reduction in dwellings, which asserts that economically viable technical improvements of building envelope and building components are a means to achieve the desired energy and carbon emissions reductions (Vlasova and Gram-Hanssen, 2014). The implication is that policy aims to identify *cost-efficient* options to reduce energy use in dwellings and provide *information* about such options to homeowners (Wilson et al., 2015). The policy has traditionally been engaged in both. For instance, Energy Saving Trust has estimated the costs of low-carbon retrofit at the level of individual buildings or dwelling types (EST, 2010b).

One of the most important legal documents designed as a tool to provide information and increase awareness about carbon emissions from dwellings is Energy Performance Certificates (EPCs) on buildings, which was introduced in Europe through the Energy Performance of Buildings Directive (Directive 2010/31/EU). The policy makes it obligatory to provide an EPC whenever the dwelling is built, sold or rented (GB. DCLG, 2017). The EPC contains information about a property's energy use, as well as recommendations how to reduce energy and save money. However, the effectiveness of EPCs as such a tool has been questioned, as research has shown that EPCs have little impact of homeowners' retrofit decisions (Bartiaux et al., 2014). A 2011 UK survey of 2,049 adults concluded that though almost most homeowners with EPC found the rating and recommendation simple to understand, only a minority (17%) acted on recommendations (Lainé, 2011). Research has long concluded that information provision and voluntary standards are insufficient to encourage homeowners to retrofit to low-carbon standards (Sustainable Development Commission, 2006). With this understanding in mind, there is growing concern about "where demand for energy efficiency measures will come from" (Consumer Focus, 2012: p. 4).

The technical-economic focus on operational energy use reduction in dwellings has been repeatedly criticised for a too narrow, and, thus, limiting view on retrofit decisions. The literature suggests that low-carbon retrofit is not just a technical problem that can be solved through information provision, but should be understood as a socio-technical problem with social, economic, and sustainability dimensions (Chiu et al., 2014; Karvonen, 2013; Lutzenhiser, 2014; Munro and Leather, 2000; Rosenow and Eyre, 2016; Tweed, 2013; Wilson et al., 2015).

2.2b. Empirical evidence on drivers and barriers to low-carbon retrofit decisions

Empirical research identifies various influences on low-carbon retrofit decisions, often in a form of drivers and barriers. Lists of such influences can be found in Martiskainen and Kivimaa (2019), Kaveh et al. (2018), Organ et al. (2013), Peng (2013) and Christie et al. (2011) to name a few. Stieß and Dunkelberg (2013) put such list in a form of a visual framework. Wilson et al. (2015: p. 14) carried out an extensive search to identify "the full scope of renovation decision influences". The identified influences include: (i) contextual influences, such as demographics and property characteristics; (ii) personal influences, such as attitudes and previous experience of low-carbon retrofit; and (iii) benefits and drawbacks associated with both the products and the process of low-carbon retrofit. It is not suggested here that categorisation proposed by Wilson et al. (2015) is the only possible one. For instance, Kastner and Stern (2015) grouped such influences in the following six categories: (i) demographic/ housing characteristics/location of residence; (ii) decision-maker dispositions; (iii) beliefs about consequences for the household; (iv) beliefs about consequences beyond the household; (v) social influences and (vi) policy measures. The categorisation proposed by Wilson et. al (2015) is used here for illustration purposes (Table 2.2).

Table 2.2. Drivers, barriers and other influences to homeowner low-carbon retrofit decision (adapted from Wilson et al., 2015: p. 15)

Structure	Commonly identified	Occasionally identified
Drivers (also: motivations)		
	Cost savings Thermal comfort Environmental benefits	Draughts, condensation, air quality, health Property value Aesthetics, appearance
Barriers (also: constraints)		
Finances	Capital availability, interest rates	Irreversibility
	Delayed gains	
Information	Uncertain cost savings Contractor reliability & quality	Uncertain comfort or health outcomes Low salience of energy, misperceptions of energy use
Decision making	Disruption, hassle	Cognitive burden, transaction costs, information search costs
Attributes of efficiency renovations		
Technical	Energy savings	Complexity
Financial	Capital cost, cost savings, payback period Relative advantage	Financing mechanisms
Other	Comfort	

(continued)

Table 2.2. Drivers, barriers and other influences to homeowner low-carbon retrofit decision (adapted from Wilson et al., 2015: p. 15) *(continued)*

Structure	Commonly identified	Occasionally identified
Personal influences		
Information & awareness	Expert advice or recommendations, energy audits or assessments Expected cost savings	Availability and credibility of information sources Peer (interpersonal) advice, communication Behaviour, social learning
Attitudes & beliefs	Beliefs and understanding of energy-environment issues Attitudes towards specific energy-environment issues	Attitudes towards renovating and homes Implicit rates of time preference Future energy prices
Experience, skills		DIY, technical skills, know-how Past experience with renovating or efficiency measures
Contextual influences		
Household characteristics	Size, composition, lifecycle (e.g., number of children)	Gender, decision making roles Routines, habits Room occupancy profiles
Socio-demographics	Age, education, income, employment	Location (e.g., urban–rural)
Home tenure	Status (own, mortgage)	Duration (current, expected)
Property characteristics	Size, age heating system, insulation	Number of different types of room Infrastructure availability (e.g., gas network)
Salient events	Moving home	Triggers or disruptions to routine (e.g., boiler breaking down, tenants moving in or out)
Policy incentives	Amount	Ease of access, timing, salience

This section makes no attempt to create a better or a more comprehensive summary. Instead, an attempt is made to highlight some ambiguity associated with the practical use of such lists. Research often aims to identify drivers and barriers to sustainability-related retrofit, in an attempt to suggest strategies to strengthen drivers and lower barriers (Yeatts et al., 2017). However, as a summary presented by Wilson et al. (2015) rightfully suggest, the characterisation of such influences as either drivers or barriers is not straightforward.

For instance, financial considerations are often used to explain retrofit investment behaviour. However, such considerations can be used to explain both, drivers and barriers to retrofit. Financial concerns associated with low-carbon retrofit, such as capital costs as well as associated energy savings as a result of such retrofit, have been traditionally used to explain homeowner retrofit decisions (Tovar, 2012). However, it has been shown that the notion of payback periods is not the key to investments decisions (Gram-Hanssen, 2014a; Fawcett and Killip, 2014). Rather, the homeowners are likely to talk about retrofit affordability. Fawcett and Killip (2014: p. 442) observed that the owners showed “creativity and opportunism” in assembling the necessary retrofit budgets, and the people on lower incomes have found ways to make such retrofit affordable, whether by doing work DIY or spreading the costs over time.

Retrofits of middle-class homeowners are characterised by “comfort, conspicuous consumption” and are part of “their self-expression of taste and class” (Sunikka-Blank et al., 2018: p. 124). Aspirational retrofit, such as refitting a kitchen or a bathroom is often prioritised above energy conservation retrofit (Gram-Hanssen, 2014a). The understanding of middle-class homeowners’ retrofit intentions as lifestyle-driven enjoys universal consensus among researchers and practitioners alike, and is often used to explain underinvestment in sustainability-related investment. However, lifestyle driven goals and aspirations do not necessarily cancel the opportunity to realise low-carbon solutions. For instance, Passivhaus standard is identified as a “designer label” and a matter of prestige among higher income groups in the UK (Sunikka-Blank et al., 2018).

Recent socio-technical research in the built environment shifts the perspective of the notion of comfort from primarily physiological matter to a broader notion that takes into account various dynamic social psychological, behavioural and other aspects (Cole et al., 2008; Shove et al., 2008). In particular, social practice theorists understand comfort as something that can be achieved through performance of various household practices that often require energy (Chiu et al., 2014; Gram-Hanssen, 2010a). If comfort is achieved through everyday practices, comfort-driven aspirational retrofit should aim to accommodate such practices. Indeed, Judson and Maller (2014: p. 510) conclude that renovation intentions are determined by “everyday practices, both those currently performed and anticipated in the future”. The changing nature of such practices is related to the stage of household lifecycle, as practices can be expected to differ between a young family household with children and a pensioner empty-nester household. The accommodation of such changes involves often a re-arrangement of internal spaces and their functions.

The accommodation of changing household practices does not mean that low-carbon retrofit options cannot be realised. On the contrary, it is exactly the promise of increased comfort, associated with low-carbon dwellings, that can lead to investment in energy-saving technologies (Mlecnik, 2010; 2013). Owners are more easily convinced to carry out energy-related improvements, such as insulation or ducting for mechanical ventilation, if they plan substantial internal layout changes, needed to accommodate changing everyday practices (Mlecnik, 2010). Research carried out by Energy Saving Trust (EST, 2011) in the UK suggests that up to 85% of homeowners are willing to stretch their retrofit budgets to include energy efficiency works.

A change in everyday practices is not the only underlying process that can trigger owners to carry out retrofit works. Another commonly identified process is the physical deterioration of the house structure. Different building components have different lifetimes that range from 15 years for a gas boiler to 40 years for cavity or loft insulation (Fawcett, 2014). Most homeowners are not aware of the precise conditions of the components of their houses, how far are these components in their lifespan and when they need to be replaced. Homeowners often realise the need for structural and utility works only after a breakdown (Buser and Carlsson, 2017). A breakdown or a need to replace building components is also often seen as an opportunity to replace these components with more energy-efficient options. Figure 2.1 captures both processes: a change in household lifecycle stages and a deterioration of the structure of the house.

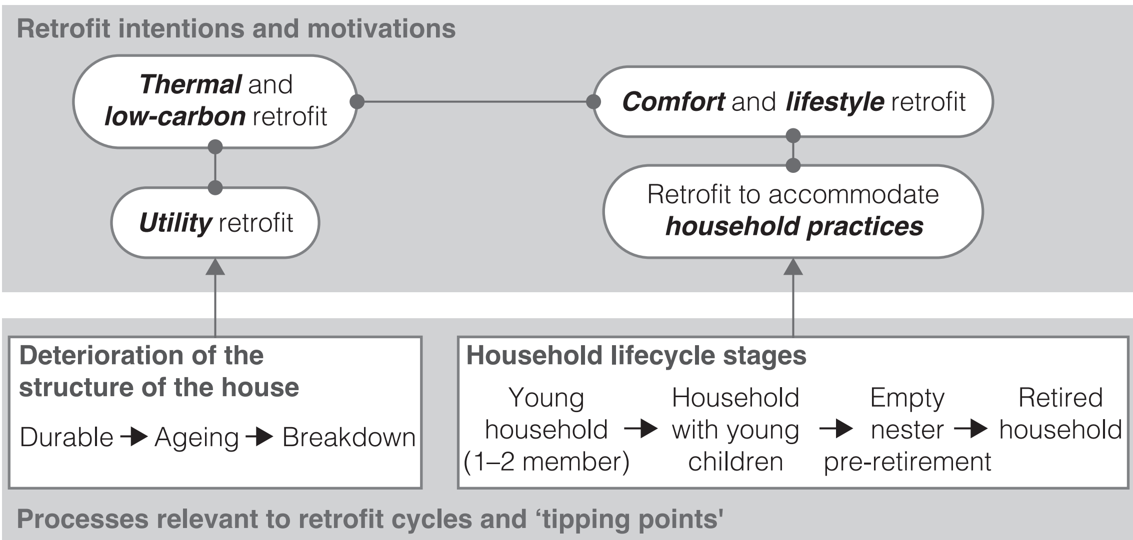

Figure 2.1. Understanding connections between utility, comfort and energy-related retrofit

People are often reluctant to compromise aesthetically pleasing features for the sake of energy efficiency (Sunikka-Blank and Galvin, 2016). Indeed, a building's values and properties, such as aesthetical values and historical significance, are taken into account when retrofit decisions are made (Sunikka-Blank and Galvin, 2016; Vlasova and Gram-Hanssen, 2014; Yarrow, 2016). However, the relationship between aesthetic and sustainability-related considerations is not straightforward. For instance, photovoltaic panels (PVs) can be seen as intruding to the character of a building in one setting, while in another setting they can be seen as improving the appearance of a building (Yarrow, 2016). Homeowners, in general, tend to see retrofit as an opportunity to enhance aesthetical qualities of a building, whether through the preservation of particular features or the introduction of aesthetic value through retrofit (Sunikka-Blank and Galvin, 2016; Yarrow, 2016). Moreover, a heightened "understanding of what may be lost" (Yarrow, 2016: p. 348), if insufficient actions are taken to mitigate climate change, might actually help to promote sustainability-related retrofit in the heritage sector.

Such arguments illustrate that the same influences might support or prevent low-carbon retrofit from happening. The lists of influences, such as the one offered by Wilson et al. (2015), allow an appreciation of the complexity of the problem and a diversity of potential stimuli. However, as Martiskainen and Kivimaa (2019: p. 1408) noted the "right mixture" of various influences is required to transform UK housing stock to low-carbon standards. The lists of various influences, however, do not allow an understanding of how such a mixture can be created.

2.2c. Variance vs process perspective to understand retrofit decisions: An appraisal of the predominant approach

Building research and policy has traditionally focused on the decisions that homeowners make with regard to low-carbon retrofit as isolated events (Wilson et al., 2015). The logic is that when homeowners weight the benefits and costs of particular options, information provision and various incentives may influence their decisions in favour of more sustainable solutions. Thus, the focus of research and policy has narrowed to the identification of drivers and barriers of various options, in order to make desired options seem more beneficial than alternatives and bring about a desired outcome (Fyhn and Baron, 2017; Wilson et al., 2015). The described assumptions are representative of a *variance* type of research.

The terms *variance* and *process* theory have been coined by Mohr (Mohr, 1982, as cited in Van de Ven, 1992; Langley, 1999). *Variance* type of research focuses on discussing observed inputs (independent variables) and outcomes (dependent variables), and involves data collection and processing aimed to determine the correlations between sets of variables (Van de Ven, 1992). This research strategy is well-equipped to answer questions 'how often', and 'how many', and questions about relative empirical importance of constructs. While acknowledging that this approach can give fruitful insights into some decisions, the appropriateness of variance type of research to describe energy-related behavior has faced growing criticism (Shove, 2003).

Even though each of the independent variables might play a role in individual's decision-making process, a list of such variables does not enable an understanding of the temporal sequence of events: what are the influences that play a role first, next, and so on, and how each influence in a stage affects the next stage of the decision process. Understanding the temporal sequence of events requires a different perspective. *Process* type of research focuses on how processes emerge, develop, transform and terminate over time (Langley, 1999; Langley et al., 2013). The difference between variance and process research is visualised in Figure 2.2.

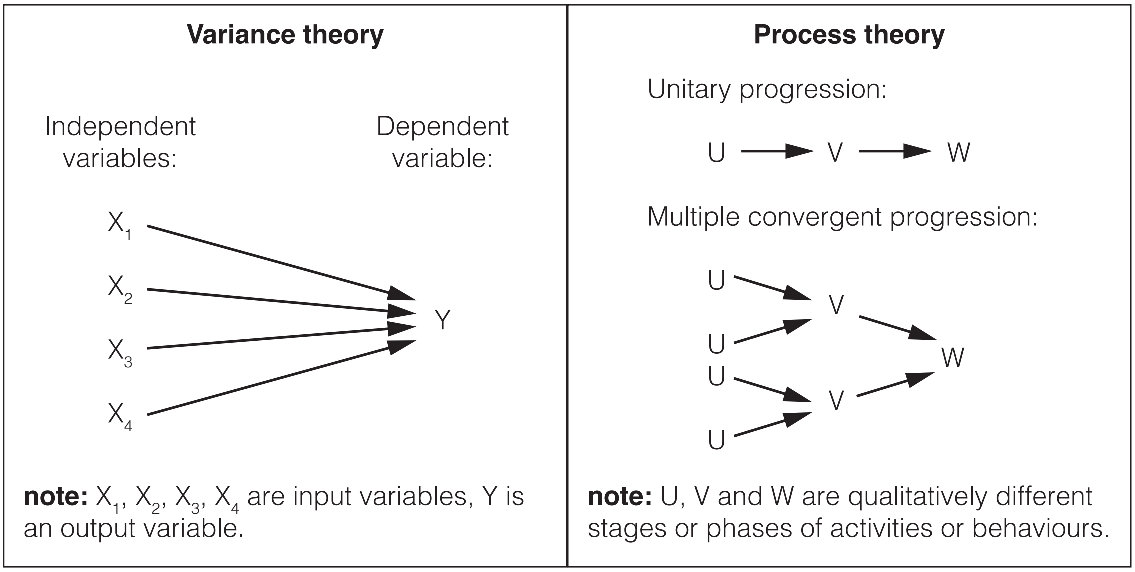

Figure 2.2. Variance vs process research. Two examples of process progression shown: unitary and multiple convergent ones (Van de Ven, 1992: p. 172–173; and Langley, 1999: p. 693)

Research on domestic retrofit suggests that retrofit decisions are often associated with a lengthy time period, over which renovation decisions unfold and strengthen (Fawcett, 2014). Recent process-driven research on domestic retrofit suggests that retrofit decisions should be conceptualised as processes comprised of a series of stages (Fawcett, 2014; Gram-Hanssen, 2014a; Pettifor et al., 2015; Wilson et al., 2018; Wilson et al., 2015; Wilson et al., 2014; Wilson et al., 2013a; Wilson et al., 2013b). Evidence of the existence of stages in renovation decisions is provided by Wilson et al. (2013b), who carried out a nationally representative online survey of UK homeowners in September 2012. The respondents confirmed the differentiation between the stages. They identified the stage they are at with a multiple-choice survey as "not currently thinking about renovations as a possibility"; "currently thinking about renovations as a possibility"; "currently planning renovations to be done at some point in the near future"; "currently finalising plans for renovating or in the middle of renovating" (Wilson et al., 2013b: p. 2). Some research suggests that an even broader approach should be taken and retrofit decisions should be understood as an ongoing process of making a house habitable (Fyhn and Baron, 2017).

A process perspective can facilitate the identification of decision stages and the links among contributing mechanisms to decision outcomes, and, thus, lead to an understanding of how to facilitate the shift through the decision process stages. Driven by this evidence of a temporal dimension of retrofit decisions, this thesis adopts a process research strategy to investigate homeowner retrofit decisions.

This section identified variance type of research as the predominant view to understand homeowner retrofit decisions both in policy and academia. The review of the relevant literature suggests that process type of research is a more suitable approach to research homeowner retrofit decisions, and, thus, it is adopted in this thesis. The next section looks at the process view on homeowner retrofit decisions, available in current literature.

2.3. PROCESS PERSPECTIVE ON RETROFIT DECISIONS: METASYNTHESIS OF CURRENT QUALITATIVE RESEARCH

A *qualitative metasynthesis* approach has been used to assemble a process view on retrofit decisions. Qualitative metasynthesis originates in Noblit and Hare's (1988) method of meta-ethnographic synthesis. Very few formal guidelines exist on carrying out qualitative metasynthesis. Notable examples include already mentioned Noblit and Hare's (1988), Sandelowski and Barroso (2007) and Major and Savin-Baden (2012). This thesis follows the methodological steps outlined by Sandelowski and Barroso (2007, 2003a, 2003b).

Qualitative metasynthesis is a systematic approach to the collection and analysis of qualitative studies with the focus on synthesising the findings from these studies with the use of qualitative methods (Sandelowski and Barroso, 2003b). The method of qualitative metasynthesis makes an emphasis on maintaining the richness and essence of the original studies while creating an integrated whole. Metasynthesis is more than a summary of findings, instead, it offers novel interpretations of findings and a possibility to construct larger narratives than in any individual report (Sandelowski and Barroso, 2007). A qualitative metasynthesis of findings is an act of re-representing representations. It constitutes an interpretation at least three times removed from participants' lives, thus, it is crucial to clarify analytical strategies used to create such synthesis (Sandelowski and Barroso, 2003b). A detailed description of the sampling strategy and procedure to data analysis are presented next.

2.3a. Sample strategy and configuration: Focus on case-studies

Potentially relevant articles with no timespan restrictions were identified by search in *Web of Science*, *Scopus* and *International Bibliography of the Social Sciences (IBSS)* databases. Key search terms included *low-carbon*, *home*, *retrofit*, *homeowner* and *qualitative research*. Several search strategies were used to identify relevant search concepts, including footnote chasing, citation search, journal manual search and author search (Sandelowski and Barroso, 2007). A list of all the 62 search concepts eventually used is presented in *Appendix AA. Search concepts used in the metasynthesis*. The UCL subject librarian for the built environment was consulted for the choice of electronic databases, as well as for the choice of the search terms.

This synthesis was directed at capturing qualitative studies that represent a process view on retrofit decision-making. Thus, the sampling strategy focused on case study research, as case study reports often include in-depth descriptions of decision-processes of interest (Yin, 2018). All qualitative studies, which depicted rich description of retrofit processes that resulted in improved energy efficiency in owner-occupied dwellings, were eligible for inclusion. Some reports used case study approach for data collection and analysis, however, the findings were presented in a variable-oriented, rather than case-oriented manner, probably due to the page limit imposed by academic journals. As it was not possible to see the cases in these reports, such reports were excluded. Case-study research on retrofitting existing dwellings is scarce (Kivimaa and Martiskainen, 2018). To compensate for that, no geographical constraints were imposed. 'Qualitative research' was liberally defined as empirical research with human participants that used, what are commonly viewed, as qualitative techniques for sampling, data collection, data analysis and interpretation. Research conducted in any paradigm and guided by any theoretical framework was eligible for inclusion. Studies had to be written in English, and only peer-reviewed original journal articles were included.

The search recall was 445 items, the titles were scanned and relevant abstracts checked. Some studies were excluded after a familiarisation with the full text of the report. Only ten articles were eligible for inclusion, which reflects the scarcity of the case study research on dwelling retrofit (Kivimaa and Martiskainen, 2018). A qualitative metasynthesis does not usually attempt to synthesise all studies in a given topic (Sandelowski and Barroso, 2007). However, due to a very small number of articles eligible for inclusion, all ten articles were used in the synthesis.

The first article was published in 2010. Four articles were from Scandinavian countries, one from Australia and five from the UK. Three out of these five British articles were based on the same sample. The primary author's disciplinary affiliations in the seven out of ten articles was in the field of built environment, ranging from architecture to engineering, management and planning. In the other three articles the primary author's disciplinary affiliations were in energy, social science and social anthropology. Sample size ranged from one to 20. The sampling strategy was of convenience in most cases. A maximum variation sampling strategy was used only in two studies. All the studies used pre-existing theoretical frameworks to guide the inquiry, and some of them used more than one framework. Three reports referred to social practice theory. Other theoretical frameworks were only used once and included one-stop-shop framework, the notion of socio-materiality, generic project development stages, socio-technical systems theory, human centred research approach and ethnographic research. A typology of qualitative findings was used to emphasise the differences in the kind of findings (Sandelowski and Barroso, 2007). In seven out of ten articles the findings were presented in a form of thematic or conceptual description, in two reports — in a form of interpretative explanation, and in one report — in a form of thematic survey. Profile characteristics of the qualitative studies used in the synthesis can be found in Table 2.3.

Table 2.3. Profile characteristics of qualitative studies in the metasynthesis

Study	Affiliation	Country	Theory	Method	Type of findings	Sampling plan	Relevant sample*	Data collection strategy, timing and period
Bjørneboe et al., 2017	Built environment: Civil engineering	Denmark	One-stop-shop framework and Vanhoutteghem's stages of renovation process	Case study	Thematic description	Volunteer	1 case of energy home retrofit using one-stop-shop approach	Longitudinal study of retrofit project from the beginning to completion. Retrofit carried out in summer 2013.
Buser & Carlsson, 2017	Built environment: Architecture and civil engineering, construction management	Sweden	Socio-materiality	Qualitative, part of a broader action research study	Conceptual description	A subsample from larger qualitative study	1 case of home retrofit with initial intentions for energy efficiency (from 8 sampled)	1-year observations of retrofit practices and interviews.
Judson & Maller, 2014	Built environment: Urban planning	Australia	Social practice theory	Qualitative, no method citations	Interpretive explanation	Convenience	2 cases of self-identified 'green-renovators' (from 16 sampled); 1 case of a heritage home retrofit (from 20 sampled)	Hindsight interviews and walk-through tours. 1st interview set — from April 2008 to March 2009; 2nd interview set — from February to May 2011.
Martiskainen & Kivimaa, 2009	Social science	UK	Non-specified, uses project development phases	Case study	Thematic description	Convenience	2 cases of low-energy domestic retrofit (from 6 sampled)	Hindsight interviews and other relevant documents.
Mlecnik, 2010	Built environment: Housing management	Belgium	Rogers' innovation diffusion	Case study stated, survey for data collection	Thematic survey	Maximum variation	1 case study of domestic retrofit to Passivhaus standard (from 15 sampled)	Questionnaires with open ended questions.

(continued)

Table 2.3. Profile characteristics of qualitative studies in the metasynthesis *(continued)*

Study	Affiliation	Country	Theory	Method	Type of findings	Sampling plan	Relevant sample*	Data collection strategy, timing and period
Galvin & Sunikka-Blank, 2014	Energy: environmental science	UK	Socio-technical systems theory	Qualitative, case study and grounded theory references	Thematic description	Convenience	7 cases of thermal home retrofit (from 9 sampled)	Hindsight interviews and walk-through tours, carried out in February – May 2014.
Sunikka-Blank & Galvin, 2016	Built environment: Sustainable architecture	UK	Human centred research approach	Qualitative, case study reference	Thematic description	Convenience	7 cases of thermal home retrofit (from 9 sampled)	Hindsight interviews and walk-through tours, carried out in February – May 2014.
Sunikka-Blank et al., 2018	Built environment: Sustainable architecture	UK	Bourdieu's habitus and Schatzki's social practice theory	Qualitative, no method citations	Thematic description	Convenience	7 cases of thermal home retrofit (from 9 sampled)	Hindsight interviews and walk-through tours, carried out in February – May 2014.
Vlasova & Gram-Hanssen, 2014	Built environment: Socio-technical research	Denmark	Social practice theory and Moore & Karvonen's types of sustainable architecture production	Case study	Interpretive explanation	Maximum variation	2 cases of energy-focused home retrofit; 1 case of energy related retrofit activities in a village in Denmark	Observations, interviews and other documents. Longitudinal study of retrofit projects from the beginning to completion.
Yarrow, 2016	Social anthropology	UK	Ethnographic study	Ethnographic study	Thematic description	Not stated	1 case of energy-related retrofit activities in Cotsworld area	4 months observations of retrofit practices and semi-structured interviews.

Note: Shading is to show related samples. *Indicates number of cases from a particular report that are used in the metasynthesis.

These articles were retrieved between 13th March and 31st May 2019. The entire content of every article was analysed using a reading guide, adapted from the original appraisal guide developed by Sandelowski and Barroso (2007). The reading guide used for this synthesis can be found in *Appendix AB. Reading guide for the appraisal of individual reports*.

Overall, the ten reports used in the synthesis constitute a combined sample of 79 cases. However, not all of these cases were visible in the reports. In several instances, the authors chose to present only a few cases in detail due to the page limit of journal papers. The synthesis was only able to explicitly draw upon the cases that were visible in the reports. The sample size of visible cases was 19 and their profile characteristics can be found in Table 2.4. All households comprised of at least two members. The dwellings were of varied construction type with the age range from 19th century to mid-1960s. Sustainability-related retrofit activities ranged from fabric insulation only to in-depth retrofit to Passivhaus standard. In 17 cases the unit of analysis was the household and their experience. In two cases the unit of analysis was a specific area rather than a household: (i) Cotswolds area in England, characterised by a vernacular tradition of building that is widely celebrated as a symbol of regional and national identity; and (ii) a village in Denmark, which was a subject of a municipality-led project, targeting energy retrofit in private houses.

Table 2.4. Profile of relevant samples represented in reports

Case & Country	Household(s) characteristics	Property/ area characteristics	Retrofit characteristics
BSH*-A Denmark	A couple, who are willing to spend enough for an extensive renovation.	1965; typical construction (single-family, one floor, no basement, 160 m^2); in a need of renovation; energy consumption 205 kWh/m^2 a year.	Retrofit carried out in summer 2013 and included new roof, windows and doors; cavity insulation and MVHR. Computer simulation showed reduction in energy consumption by 42.3%.
BC*-B Sweden	More than one household member (referred to as 'owners').	1956; detached wooden-framed house built for workers; 3-storey (6 rooms) with a concrete cellar; district heating; in a need of renovation; energy consumption — grade D.	A year later, no sustainability-related improvements have been made. The owners bought a hybrid gas car to express their environmental concerns.
JM*-C Australia	A married couple (number of children unknown). Husband is a technical engineer.	Early 19th century; single-family, three-bed, weatherboard cottage.	Internal layout adjustment; two-storey extension, adding two common areas and en-suite bedroom; extension designed to passive solar principles (insulation, double-glazing, a solar hot water system, PV panels and hydronic heating); evaporative air-conditioning.

(continued)

Table 2.4. Profile of relevant samples represented in reports *(continued)*

Case & Country	Household(s) characteristics	Property/ area characteristics	Retrofit characteristics
JM*-D Australia	A family of four (two young children). Husband has background in environmental economics.	Edwardian, two-bed brick terraced cottage.	Two-storey extension, adding a common area, two bedrooms and two bathrooms; extension designed to passive solar principles (underfloor heating, ceiling fans and natural ventilation, high-performance insulation, triple-glazing of all but one window, solar hot water and PV panels); limited evidence that household energy consumption had reduced due to the extensive expansion of the interior space.
JM*-E Australia	A mature couple, both work from home.	Late 19th century; 4-bed detached villa of heritage value with four bathrooms and a separate guest annex; constructed of weatherboard and stone; a primary source of heating — electricity; wood heater is used in winter, and liquefied petroleum gas for cooking.	Five-year retrofit, which included wall, ceiling and floor insulation; draught sealing of doors, windows and chimneys; secondary glazing to selected windows; and heavy curtains; electric wall-mounted convection heaters to individual rooms, and a split system unit for heating/cooling in the kitchen; an electric-boosted solar hot water system. Analysis of the electricity bills showed reduction in electricity consumption by 13%.
MK*-F UK	More than one household member (referred to as 'owners').	1860, 3-bed terraced house with solid walls, 126 m^2.	Retrofit during 2013, which included external wall insulation, loft insulation, double glazing, condensing boiler, low-energy lighting and appliances. £10,000 covered by a governmental grant. The owners reported 13% reduction in gas consumption.
MK*-G UK	More than one household member (referred to as 'owners'). One of the owners has an engineering background and undertook environmental masters' courses at the Centre for Alternative Technology (CAT).	1867, 4-bed terraced house, 125 m^2.	Retrofit during 2008–2009, which included external and internal insulation, loft insulation, double glazing, solar thermal, wood burning stove, low-energy lighting and appliances, natural paints and materials throughout; loft conversion. £35,000 covered by private finance and local authority grant; 65% reduction in carbon emissions compared to an average UK home (estimated based on measured annual energy use).

(continued)

Table 2.4. Profile of relevant samples represented in reports *(continued)*

Case & Country	Household(s) characteristics	Property/ area characteristics	Retrofit characteristics
M*-H Belgium	At least two household members: an owner-architect and an asthmatic child.	150-year old 'modest' workman's terraced house: two-floor, simple construction.	Retrofit to Passivhaus standard, which included internal insulation, airtightness, triple glazing, mechanical ventilation with air-to-air heat recovery including a ground-to-air heat exchanger, and the use of a pellet heater and external sun protection using solar collectors. Re-arrangement of internal layout, demolition of an old and re-construction of a new wooden-framed annex, new roof. Calculated space heating demand post-retrofit 10 kWh/m^2 a year.
GS*-I UK	Middle-aged couple, professional, no children.	Victorian, 3-storey semi-detached brick house of considerable heritage value (judged by the researchers). Located by a busy thoroughfare road, in a need of renovation. Existing heat recovery ventilation system.	Internal wall insulation to preserve period details, new roof, double glazed windows, contemporary bay window; combined space-heating and mains-pressure water heating system that integrated solar thermal panels, a highly efficient gas boiler and an outdoor temperature sensor. Garden side extension, replacement of an old part of the facade, which had originally been a shop.
GS*-J UK	At least two members in the household (referred to as 'homeowner' and a 'partner'). The owner is a middle-aged male, professional.	1930s, semi-detached brick house. Heritage values somewhere between minimal and considerable (judged by the researchers). Cold and draughty prior to retrofit.	External wall insulation, floor and loft insulation, new windows and doors.
GS*-K UK	Middle-aged couple, professional, one child with special needs.	1930s, 2-storey semi-detached house, brick facades, located in a uniform residential street with similar houses. Was judged by the researchers to be of a minimum heritage value prior to retrofit.	Loft and cavity insulation (entitled to a subsidy), internal insulation in the main bedroom; garden side extension, suitable for the child's needs.
GS*-L UK	Middle-aged couple, professional. Female lives in the house during weekends only.	1930s, 2-storey semi-detached brick house, located in a residential street with similar properties. Heritage values somewhere between minimal and considerable (judged by the researchers).	Internal wall insulation for the front facade with bay, external wall insulation to the rest of the house, floor insulation, double glazing, solar panels.

(continued)

Table 2.4. Profile of relevant samples represented in reports *(continued)*

Case & Country	Household(s) characteristics	Property/ area characteristics	Retrofit characteristics
GS*-M UK	Middle-aged couple, one retired, one self-employed, no children.	1960s, 3-story end-of-terrace house, located in a residential street with a variety of building types. Was judged by the researchers to be of a minimum heritage value prior to retrofit.	Externally insulated facades (with the exception of brick pillars), double glazing.
GS*-N UK	Middle-aged couple, professional, with children.	1930s, semi-detached brick house of considerable heritage value (judged by the researchers), located in a busy residential street with similar properties. The house was cold prior to retrofit.	Internal wall insulation, bay window restoration and double glazing, heavy curtains; garden side extension and a side extension that acts as a thermal buffer.
GS*-O UK	Middle-aged couple, professional, no children. Male is an academic physicist.	Two 1930s 2-storey semi-detached houses joined together, located in a quiet residential street with similar properties. Cambridge white brick facades, old slate roof. Heritage values somewhere between minimal and considerable (judged by the researchers).	Internal wall insulation in the kitchen, installed in 1979. A zonal heating system introduced after the houses were joined together. Reconfiguration of the condensing boiler for optimal efficiency.
VG*-P Denmark	A couple in their mid-30s and their two small children. Husband works as an energy consultant.	19^{th} century; poorly insulated smallholding. In a need of a deep retrofit.	Open-ended time-frame of the project (10 years would not have been considered a problem). Insulation of the building envelope, new roof, new floor, new windows; floor heating, stone oven and heat pump; solar thermal and PV panels; reorganisation of the floor space and room distribution, and conversion of the attic into a habitable second floor of the house, doubling the living space of the house.

(continued)

Table 2.4. Profile of relevant samples represented in reports *(continued)*

Case & Country	Household(s) characteristics	Property/ area characteristics	Retrofit characteristics
VG*-Q Denmark	A middle-aged couple with one teenage child.	1970s, detached single family house, which needed extensive energy-focused retrofit.	Initiated in 2010 by a contracting company. The timeframe of the project was initially 6 months, but eventually took one year. The whole building envelope insulation, vapour-resistant membrane throughout, mechanical ventilation, heat pump, floor heating, windows replaced; solar thermal and PV panels. Retrofit upgraded the dwelling to a Class 1 low-energy house.
VG*-R Denmark	Municipality-led ESCO** project, targeting energy retrofit in private housing. Participation in the project was voluntary.	Village of Føns, Denmark. The project evolved into the idea of making the whole of Føns a sustainable village.	The energy report was produced for each house. The actual changes made to the houses ranged from deep retrofit involving insulation of the facade, replacement of the roof, changing the heating system, installing solar thermal, PV panels and heat pumps, to minimal changes such as changing light bulbs in the house and replacing an oil boiler.
Y*-S UK	Most of the home-owners interviewed self-identified as middle-class.	Cotswolds area, England, characterised by a vernacular tradition of building that is widely celebrated as a symbol of regional and national identity. Many buildings are of considerable heritage value.	Uptake of energy-efficient technologies is significantly determined by assessments of 'appropriateness' that involve various intersecting considerations about the significance of a building's past.

Note: * **BSH** – Bjørneboe et al., 2017; **BC** – Buser & Carlsson, 2017; **JM** – Judson & Maller, 2014; **MK** – Martiskainen & Kivimaa, 2009; **M** – Mlecnik, 2010; **GS** – Galvin & Sunikka-Blank, 2014 and Sunikka-Blank & Galvin, 2016 and Sunikka-Blank et al., 2018; **VG** – Vlasova & Gram-Hanssen, 2014; **Y** – Yarrow, 2016.

** ESCO – Energy Service Company

2.3b. Analytical strategies used to synthesise findings

The report findings were transformed into a conceptual form in several steps. First, the 19 cases, visible in the reports, were coded to see the evolution of homeowner retrofit decision-making journeys over time. Three generic themes were used in coding to capture the wide timespan relevant to the process: (i) homeowner goals, motivations, influences and considerations before the retrofit; (ii) the retrofit process itself; (iii) post retrofit living experience. The themes were chosen deductively beforehand. Within the themes the codes were inductively developed from the case findings and then refined by moving back and forth between the findings and the coding tree. The purpose was not to determine the prevalence or quantitative strength of each finding, but to identify the underlying concepts implied, but not necessarily expressed explicitly in the findings. The coding tree shows the conceptual range of findings and provides a foundation for the development of an overarching conceptual description. Cross-tabulation was used at this stage to support constant systematic comparison (Miles et al., 2014).

Two additional metasynthesis techniques used was used to transform the findings into a conceptual form: the use of *in vivo* concepts, and the use of *imported* concepts (Sandelowski and Barroso, 2007). The use of *in vivo* concepts involves the identification of interpretative concepts, developed by the researchers themselves in different reports, to determine whether they can be translated into each other or combined to produce a metasynthesis of findings across all studies in a domain. The use of *imported* concepts involves the identification of pre-existing concepts used by the researchers in different reports to interpret their data and, the subsequent use of imported concepts to produce a metasynthesis of findings across all reports. The analysis process included the documentation of all procedures, changes in procedures or results. These notes were regularly revisited to keep track of the evolving nature of the synthesis.

2.3c. Results of the review and implications for research

Low-carbon solutions as part of overall retrofit intentions

Homeowner retrofit activity (or an absence of it) is often used as an indicator of homeowner retrofit goals and motivations (or a lack of them). However, attributing retrofit outcomes to homeowner intentions only is a simplification of reality. Homeowner retrofit decisions and solutions are narrated by the materiality of a given dwelling and are shaped by various actors, such as contractors, advisors, planners and conservation officers (Buser and Carlsson, 2017; Yarrow, 2016). These actors often have different "understandings, motivations and expectations of the renovation process" (ibid.: p. 283), which makes it difficult to align them in a successful retrofit implementation. The physical arrangements of the house and each of the actors involved can push the retrofit decision closer to or further from a low-carbon solution. Figure 2.3 captures schematically the overlap between different actor motivations and expectations of the retrofit on one hand and implementation of low-carbon solutions on the other.

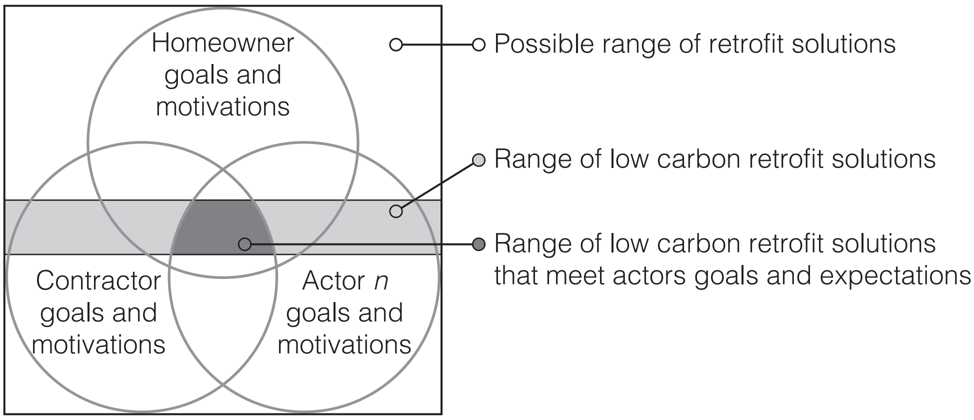

Figure 2.3. The overlap between retrofit motivations and intensions of different actors and an opportunity to realise low-carbon potential within a range of possible retrofit solutions

In most cases, the owners were the ones who insisted on sustainability-related solutions and had to do extensive research to make sure such solutions are realised (cases JM-D; MK-G; M-H; GS-I). In several cases, building professionals were given credit for encouraging owners towards a retrofit solution that was more energy conscious than they initially envisioned (cases BSH-A, VG-Q, VG-R). In other cases, on the contrary, the building professionals discouraged the owners to install some sustainability-related measures as not viable (case BC-B). Owen and Mitchell (2015) report that building professionals believe that energy bills reduction is a primary concern of homeowners, and thus, would only offer solutions that can guarantee such reductions. The diversity of intensions behind homeowner low-carbon retrofit decisions is often misinterpreted by other actors involved, which might mean that the full potential for carbon emission reductions through retrofit may not be realised.

One of the goals of a building professional is to finish the job as soon as possible not to waste money and resources. To achieve this goal, they might take shortcuts at an expense of quality (cases GS-I, GS-K). In case GS-I, the owners were able to persuade the building professionals to carry out the job properly. In case GS-K, the loft and cavity wall insulation were subsidised jobs, the headworkers were on strict time budget and were only willing to do jobs in standardised ways. Sometimes, the building professionals were fixated on the theoretical thermal potential of a building and were not flexible to discuss how to incorporate owners' wishes, for instance to preserve the brick façade in case GS-J. In other cases, such as GS-M and GS-N, the owners praised their builders for listening to their concerns and working on finding creative retrofit solutions to accommodate several objectives.

Despite the possible diversity of different actor goals and motivations in the retrofit, homeowners remain the crucial actors in the process. This thesis focuses on homeowner goals and motivations, and how these can push the retrofit decisions towards or away from low-carbon solutions. In particular, this thesis is interested in middle-class homeowners, who potentially can invest in low-carbon retrofit.

An overarching vision and quality of retrofit: Who should be in charge?

Low-carbon retrofit projects require typically the installation of a collection of energy-saving measures and appliances, and often the installation of energy-generation technologies such as photovoltaics. These technologies have a great potential to improve building performance and reduce carbon emissions. Nevertheless, the adoption of energy-efficient measures and building services, as well as energy-generation technologies, is difficult and inherently uncertain as to its outcomes. Reductions in energy use and associated carbon emissions are often not guaranteed, and it is not clear how many technologies and measures need to be installed to achieve the desired outcome. The uncertainty is associated also with the trade-off between achieving the sustainability and non-sustainability related retrofit goals, and minimising the risk of unintended consequences associated with low-carbon retrofit (Shrubsole et al., 2014; 2019). For instance, high levels of insulation and airtightness not only reduce heat loss through fabric, but also reduce air penetration in the building. Therefore, an appropriate ventilation strategy should be considered to compensate for an increased airtightness and ensure good air quality. Special consideration should also be given to the control of moisture and dew points to avoid condensation and mould.

The problem of poor installation quality in sustainability-related retrofit market has been previously highlighted (Bonfield, 2016). However, even a properly installed measure can lead to a "domino effect" of the changes in the material structure of the house and result in unintended consequences (Buser and Carlsson, 2017: p. 283). Thus, it is beneficial to have a person on a project team, who can propose an overarching vision of what needs to be done during the retrofit as a whole, and ensure the overall quality of construction.

The review showed that the homeowners had difficulties in finding an architect willing "to think in an integrated approach" about the needs of a property (Mlecnik, 2010: p. 44). Building professionals and tradespeople "tend to keep to their own roles", so a person who makes a house airtight might not be aware if there is any appropriate ventilation strategy in place and, vice versa, a person who installs mechanical ventilation might not be aware if the building is appropriately airtight (Sunikka-Blank and Galvin, 2016: p. 105). Bjørneboe et al. (2017) explore the benefits and a viability of a one-stop-shop approach to low-carbon retrofit, in which homeowners have only one point of contact, who also serves as an expert to ensure the realisation of low-carbon potential of a dwelling and the quality of construction. Even though the approach brought the expected benefits, it was time- and resource-consuming, and the authors conclude that it is unlikely to be viable on the market.

Policy in the UK often assumes that homeowners merely apply technologies and solutions offered to them (Galvin and Sunikka-Blank, 2014). Despite that, in many cases, the people with an overarching vision were homeowners themselves. Research shows that the homeowners themselves were “thinking in integrated approaches” (Mlecnik, 2010: p. 43) and showed “willingness and ability to gather information from different sources and put it into practice” (Galvin and Sunikka-Blank, 2014: p. 661). The owners show a tendency to carry out the research themselves, often to verify the solutions proposed by building professionals (Buser and Carlsson, 2017; Judson and Maller, 2014; Mlecnik, 2010; Galvin and Sunikka-Blank, 2014; Vlasova and Gram-Hanssen, 2014). In case GS-I, for instance, it was “the initiative and resourcefulness of the homeowners” that allowed several technologies to be brought together in a successful retrofit solution (Galvin and Sunikka-Blank, 2014: p. 660). In case GS-N, the owners had to talk “persuasively” to their building professionals to convince them to do the extra work required to preserve the features they wanted (Sunikka-Blank and Galvin, 2016: p. 104). The owners often had to check the quality of works as well (Mlecnik, 2010).

The owners in case GS-N were of the opinion that they themselves should be in charge of an overarching vision of the house, as the they know their house, and can indicate specific problems such as thermal bridges or draughts (Sunikka-Blank et al., 2018). However, as noted earlier, such overarching vision requires technical competence. For homeowners with technical background it was more natural to come up with the technical solutions themselves. For instance, it happened in case M-H, where one of the owners is a professional architect, or in case GS-O, where one of the owners is an academic physicist. Some owners approached specialised energy consultants to determine the best set of technologies needed for the house (Mlecnik, 2010). This, however, did not prove to be a universal solution. In case BC-B, for instance, the divergence of opinion between different actors regarding what needs to be done, created “doubt for the owners, complicating their decision-making process” (Buser and Carlsson, 2017: p. 283), which ultimately diverted them from their initial sustainability-related retrofit intentions.

Another way to ensure an overarching vision is through legislation enforcement. For instance, Bjørneboe et al. (2017) suggest that EPCs should be complemented by an initial planning on which works need to be done to make a house energy-efficient, and that such initial planning should be a mandatory part of selling a house. Yarrow (2016: p. 349) cautions against an overly prescriptive regulation as decision-making process in the area of dwelling retrofit is "characterised by complex, context-specific assessments", which cannot be adequately captured in policy of a prescriptive nature.

The knowledge needed for such solutions is always local-specific, so local authorities have an important role in the realisation of successful retrofit solutions on a wide scale (Yarrow, 2016). These insights are reflected in the case VG-R (Vlasova and Gram-Hanssen, 2014). The case describes a municipality-led project that targeted energy retrofit in private housing in a village in Denmark. The municipality attracted potentially interested homeowners through advertisement, contacted energy consultants to produce energy reports for each house that expressed interest, and supported local builders to acquire new skills to perform energy-focused retrofit. The municipality's role was to manage the overall network rather than to participate in individual retrofit decisions. The project resulted in a new level of relationship between the builders and the municipality and the role of energy consultant was found "superfluous" (ibid.: p. 520). These findings, yet again, highlight that homeowner retrofit decisions, or the absence of them, should not be understood in isolation from the action of other relevant actors.

The role of everyday practices and low-carbon retrofit in energy reduction

There are different strategies that can be used to reduce energy use. The Institution of Mechanical Engineers introduced an energy hierarchy, a basic framework to guide energy policy, which lists activities to reduce energy consumption in ascending order of the strength of their potential impact on achieving energy reduction (IMechE, 2009). The five-point hierarchy is as follows:

Priority 1: Energy conservation: Change wasteful behaviour to reduce demand.
Priority 2: Energy efficiency: Use technology to reduce demand and eliminate waste.
Priority 3: Use of renewable, sustainable resources.
Priority 4: Use of non-sustainable resources using low-carbon technologies.
Priority 5: Use of conventional resources as we do now.

It should be noted that changing wasteful behaviour is prioritised above improvements in energy efficiency of technologies and exploitation of renewable resources. The same logic applies to low-carbon retrofit. It should be remembered that energy efficiency retrofit is not an ultimate goal in and of itself, but rather a necessary step to reduce operational energy use (Davoudi et al., 2014). The goal of such retrofit is to reduce energy use, not to support wasteful behaviour through increased efficiency of building components. Energy-efficient dwellings often do not perform to the maximum of their technological potential, as occupants operate the refurbished buildings in unexpected ways (Tweed, 2013), a behaviour described by the *energy-efficiency gap* (Jaffe and Stavins, 1994; Hirst and Brown, 1990).

Research in domestic retrofit, underpinned by social practice theory, highlights repeatedly that pre-retrofit energy-related practices, such as cooling and heating, tend to carry on after low-carbon retrofit, even if they cannot be considered optimal from energy perspective in the new technical configuration of the house (Chiu et al., 2014; Vlasova and Gram-Hanssen, 2014). Moreover, the owners tend to carry retrofit activities to accommodate current, often non-sustainable, everyday practices (Judson and Maller, 2014; Judson et al., 2014; Maller and Horne, 2011; Maller et al., 2012). In case VG-Q the retrofit was initiated by a contracting company, which aimed to deliver a retrofit solution with maximum technical potential at acceptable costs with minimum disturbance to everyday life of the occupiers. Vlasova and Gram-Hanssen (2014) question how viable such intention is. A good low-carbon retrofit should ideally facilitate a transition to more sustainable energy consumption practices. Instead, the owners in case VG-Q did not appreciate the technical complexity of the offered solution and switched off the ventilation systems as they perceived it consumed too much energy.

Psychological and socio-technical research has documented that occupants' intrinsic motivation (van der Linden, 2015) and everyday routines (Gram-Hanssen, 2010b, Hargreaves, 2011) are at least as important to a sustained decrease in operational energy use in buildings as are the technical characteristics of the building structure and components (Gram-Hanssen, 2013; Janda, 2011). Socio-technical studies have shown that everyday practices and technologies co-evolve and shape motivational priorities of individuals. Thus, the buildings and technologies not only influence the final energy consumption through the technical energy efficiency of the building envelope and building components, but they also influence consumption through the way they structure the everyday practices of the inhabitants, which themselves contribute to shaping motivational priorities of retrofit activities. The owners in the review sample showed the ability to change their pre-retrofit practices as they committed to the retrofit options, about which they spent prolonged time making decisions. In cases JM-D and VG-P, which were initiated and planned by the owners, some previous heating practices were substituted by new, more sustainable practices, such as a change in the heating of the house with oil to the use of a stone oven and solar thermal (Judson and Maller, 2014; Vlasova and Gram-Hanssen, 2014). Some cases demonstrated substantive reduction in energy consumption due to behaviour change. In cases JM-E and GS-J the owners were able to achieve lower levels of energy consumption than the ones predicted by computer simulation, primarily due to their extensive familiarity with their buildings (Galvin and Sunikka-Blank, 2014; Judson and Maller, 2014). However, other assumptions regarding sustainability of everyday practices remained unquestioned. Judson and Maller (2014) observed that the narratives of environmental sustainability were associated with products, such as environmentally friendly materials, rather than changes in everyday routines to reduce consumption.

While acknowledging that the “sheer will” of the owners is important to achieve overall good energy performance (Mlecnik, 2010: p. 43), this synthesis highlighted the need to change everyday practices of occupiers to realise such potential and the role of material arrangement of a house in such process. The energy retrofit of buildings should focus not only on the technical characteristics of the structure and components, but also on how the material structure of the buildings can shape more sustainable everyday practices of the inhabitants, and how such practices shape motivational priorities and influence retrofit decisions that result in low-carbon living. It is very likely that policy makers need to address the experiences of occupants post-retrofit, as, even when low-carbon retrofit takes place, it often does not assist new and lower resource consumption (Vlasova and Gram-Hanssen, 2014).

This section looked at the process view on homeowner retrofit decisions, available in current literature, and highlighted the importance of the alignment process of retrofit goals of different actors, the creation of an overarching vision for low-carbon retrofit and a need for a practice change to accommodate lower resource consumption. The next section details the theoretical framework used in the thesis.

2.4. LOW-CARBON RETROFIT DECISIONS AS A PROCESS EMBEDDED IN A SOCIO-TECHNICAL CONTEXT

In order to persuade homeowners to retrofit their homes to low-carbon standards, it is necessary to understand their relation to their homes and their attitudes towards home improvements. This section discusses the theoretical framework used in the rest of the thesis to guide inquiry. First, the section clarifies the difference between the notions of *concept*, *conceptual framework*, *theoretical framework* and *theory*, based on differentiation proposed by Imenda (2014) and visualised in Figure 2.4.

A *concept* is a smallest symbolic representation of an abstract idea. Clear and unambiguous concepts discipline thinking (Forrester, 1994). A *theoretical framework* is understood as an application of a *theory*, where the concepts in the framework are derived from the theory. Thus, the concepts and the relations between them are clearly defined. A *conceptual framework* is understood as a synthesis of "the existing views in the literature concerning a given situation — both theoretical and from empirical findings" (Imenda, 2014: p. 189). Thus, the clarity of the concepts and the relations between them might not be ideal. For this reason, a conceptual framework usually has a limited scope and tends to be applicable to a particular study only. With time, a conceptual framework can give rise to a clearly articulated theory.

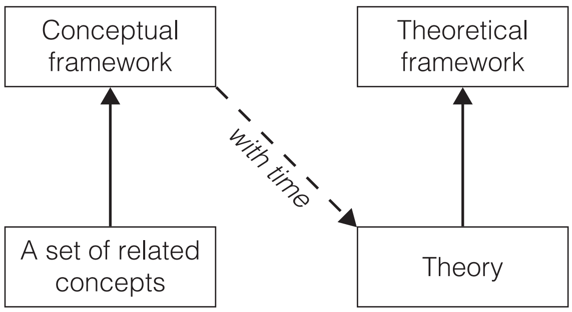

Figure 2.4. Relations between the notions of a concept, conceptual framework, theory and theoretical framework (based on Imenda, 2014: p. 189)

This thesis combines several elements in a single framework to guide inquiry on homeowner home retrofit decisions that result in low-carbon setting. The rest of the section outlines the framework.

2.4a. A contextually embedded socio-technical approach

This thesis argues for a contextually embedded *socio-technical systems* approach to bring insights in homeowner retrofit decisions that result in low-carbon settings. The concept of 'socio-technical systems' within the context of built environment and, in particular, low-carbon retrofit decisions, requires further clarification.

A theoretical understanding of a *system* is drawn upon von Bertalanffy's *general system theory* (Bertalanffy, 1969). In order for a group of elements to constitute a system, they have to interact with each other. However, element interaction is not enough to constitute a system. The idea of a system implies the notion of 'wholeness', where the interaction between elements of the system through feedback mechanisms leads to a change from the initial state of these elements, and, subsequently, a change in the system state. It follows that the system behaviour cannot be understood through an examination of its respective elements in isolation.

A socio-technical systems approach is well established in academic literature. Despite that, "[t]here is no single body of concepts that can claim to be the theory of socio-technical systems" (Emery, 1957: p. 160). Concepts in use vary from highly abstract ones to specific descriptive ones. The socio-technical systems approach asks questions concerning how society and technology develop in relation to each other. The key insight is that the society and technology mutually form each other, as different values specific to a particular societal context shape technological change, while technology constantly influence society (Bijker et al. 2012; Hughes, 1983).

It has been established that the conceptualisation of the technical aspects of the built environment in isolation from its societal aspects is insufficient to understand the occurring patterns of the development of the human-made environment (du Plessis and Cole, 2011; Hassler and Kohler, 2014a; Moffatt and Kohler, 2008). A socio-technical systems approach is widely used in urban architecture, urban economics and environmental architecture (Rhodes, 2012). In recent years, the approach has received recognition in the studies of energy demand in the built environment (Jenkins and Hopkins, 2019).

The question is: which of the many frameworks and its elements present in the literature should be chosen to study, understand and suggest changes in energy use in a socio-technical system of the built environment? There is no simple answer to this question. In discussing the transformation of energy systems in general, which include energy use in the built environment, Jenkins, Sorrell, Hopkins and Roberts state that:

> Achieving this goal will require the rapid and extensive deployment of low-carbon technologies throughout all sectors of the global economy, with far-reaching implications for markets, infrastructures, institutions, social practices and cultural norms. What is more, emission reduction efforts will simultaneously have to address other concerns, including questions of social justice, energy access and energy security. (Jenkins et al., 2019: p. 1)

The level of aggregation and the focus of analysis of a study on energy use in buildings might vary significantly. Many specific theories, theoretical and conceptual frameworks have been developed to bring insights into particular aspects of the problem. Sovacool and Hess (2017) conducted semi-structured interviews with knowledgeable experts in technology and social science theory, who identified 96 theories and conceptual approaches useful to explain socio-technical change. Social practice theory and sociotechnical transitions have been mentioned by more than a third of respondents (see Table 2.5 for 14 most frequently mentioned theoretical approaches).

Table 2.5. Most frequently mentioned theoretical approaches useful to explain socio-technical change. Total number of respondents 35 (adapted from Sovacool and Hess, 2017: p. 709)

	Respondents who mentioned the theory/ framework	
Theory/ framework name	**№**	**%**
Sociotechnical transitions	15	43
Social practice theory	14	40
Discourse theory	10	29
Domestication theory	9	26
Large technical systems	9	26
Social construction of technology	9	26
Sociotechnical imaginaries	7	20
Actor-network theory	7	20
Social justice theory	7	20
Sociology of expectations	6	17
Sustainable development	6	17
Values beliefs norms theory	5	14
Lifestyle theory	4	11
Universal theory of acceptance and use of technology	4	11

Arguably, social practice theory is the most often used theory to investigate low-carbon domestic retrofit decisions. *Social practice theory* is concerned with the duality of agency and structure and explains their interaction through practices, while it emphasises the human aspects of practices (Gram-Hanssen, 2011, Reckwitz, 2002, Schatzki, 2002, Shove et al., 2012; Warde, 2005). The theory has been used to bring insights in homeowner sustainability-related retrofit decisions in Australia (Judson and Maller, 2014; Judson et al. 2014; Maller and Horne, 2011; Maller et al., 2012), Scandinavia (Fyhn and Baron, 2017; Vlasova and Gram-Hanssen, 2014), UK (Sunikka-Blank et al., 2018). Bartiaux et al. (2014) featured a cross-national European study on the topic. This, however, does not mean that it is the only or the 'right' theory to bring insights into the phenomenon.

The current thesis aims to understand how homeowner retrofit decisions are formed by the conditions of everyday life, how they unfold over time, and how social and material structure that constitutes low-carbon retrofit can narrate the formation of collective sustainable retrofit patterns. There is considerable contextual diversity in this, so the framework adopted has to account for it. It is decided not to force the data collection and analysis into a pre-existing theoretical framework with a defined selective focus, such as social practice theory. Instead, a conceptual framework is brought within a broader socio-technical systems approach to navigate the inquiry.

2.4b. Contextual heterogeneity in homeowner low-carbon retrofit

A suitable approach to study decision-making process must take into account "the complex relations of the individual in context" (McFall, 2015: p. 56). Several calls have been made for the need to understand retrofit decision-making process as situated within the specific context homeowners face (Bartiaux et al., 2014; Kastner and Stern, 2015; Wilson et al., 2015). One way to understand and accommodate in the analysis the contextual heterogeneity in low-carbon home retrofit, is to categorise the retrofitting population itself. In research on retrofit decisions there are regular calls to view homeowners not as a homogeneous, but rather a heterogeneous group (Hoicka et al., 2014; Wilson and Dowlatabadi, 2007). Such an approach is similar to market segmentation, which is a well-established strategy in marketing aimed at dividing a broad consumer market into smaller segments, based on some type of shared characteristics. Once the market is segmented, the products or services are positioned in a way that resonates with the targeted segment of the market. Several categorisations of consumers relevant to this thesis can be identified.

The Department for Environment, Food and Rural Affairs (GB. DEFRA, 2008) classified the UK population into seven categories based on the willingness of the consumers to act pro-environmentally: (i) positive greens (18% of the population); (ii) waste watchers (12%); (iii) concerned consumers (14%); (iv) sideline supporters (14%); (v) cautious participants (14%); (vi) stalled starters (10%); (vii) honestly disengaged (18%). The framework is undoubtedly valuable to visualise the existence of multiple ways to promote greener lifestyles. However, as Stern (2000) notes different kinds of environmentally significant behavior have different causes. As the important causal factors may vary greatly across behaviours and individuals, each target behavior should be theorised separately. The framework presented by DEFRA is neither at a household level nor is it focused on home renovation activities, thus, it cannot be directly used to bring insights into a diversity of retrofit motivations that result in low-carbon homes.

Munro and Leather (2000) distinguished six occupancy patterns, related to five household lifecycle stages, that are relevant to domestic renovation behaviour: (i) young household; (ii) household with children without intention to move; (iii) household with children with an intention to move; (iv) empty nester pre-retirement; (v) older household and (vi) household dissolution/death. They described different retrofit-related behaviour specific to different household lifecycle stages, and suggest pressure points specific to each stage. The approach allows the visualisation of the level of household activity and makes assumptions regarding financial abilities of households at different lifecycle stages. However useful this framework is to understand general retrofit patterns, it does not enable the identification of a difference between a household that retrofitted to low-carbon standards and a household that chose not to do so.

Haines and Mitchell (2014) used a persona-based approach to categorise retrofit behaviour. Persona-based approach was first introduced as a tool to support software development (Cooper, 2004). Software developers often had a poor understanding of the end-user of the products they were developing and would make their design decisions based on unfounded assumptions about the end-user preferences. Cooper (2004) suggested to use archetypal users, or personas, to assist the developers to relate to the needs of the final user. Haines and Mitchell (2014) developed the following seven personas of home improvement behaviour: (i) the idealist restorer: the property is a project; (ii) the affluent service seeker: the property is a pleasure; (iii) the property ladder climber: the property is a step up; (iv) the functional pragmatist: the property is a place to live; (v) the aesthetic pragmatist: the property is a home; (vi) the stalled due to the lack of finance: the property is a shelter; (vii) the stalled due to pressures of life: the property is a necessity. The authors proposed these personas to aid the development of policies regarding energy efficiency interventions. However, the sampling strategy for the interviews, which were used to develop the personas, targeted homeowners who live in solid wall dwellings. It is not clear whether interviewees did any sustainability-related retrofit work or any retrofit work in general. Thus, the owners might not have a narrative capability to tell a story of low-carbon retrofit behavior.

Kerr, Gouldson and Barrett (2018) used Q-methodology to disaggregate homeowner population in the UK and create narratives of retrofit experiences. *Q-methodology* is a method to study people viewpoints, by having participants rank and sort a series of statements, and using factor analysis to develop a set of shared viewpoints (ibid.). Four narratives have been created: (i) organised and seeking greater comfort; (ii) settled and performing a functional upgrade, (iii) growing and needing a family home; and (iv) a household that has a lot to do and feels that there is no time like the present. The results offer insights into a diversity of retrofit experiences and the authors claim that such results help to "develop more appropriate interventions to promote retrofit" (ibid.: p. 90). However, it is not self-evident how such narratives can actually be used to design targeted policy, and the authors provide no illustration.

Another way to understand the contextual heterogeneity specific to low-carbon retrofit is to categorise homeowner retrofit needs and motivations. The review of the literature showed a great variety and an enormous diversity of retrofit goals and motivations, a categorisation of which can be a fruitful way towards targeted policy instruments. Gram-Hanssen (2014a) proposes a two-by-two matrix to categorise homeowner retrofit decisions. The 'process vs. project' axis distinguishes the view of a renovation as something that is interesting in and of itself because of the process, and the view that the primary interest of a renovation is its result. The 'lifestyle vs. wear and tear' axis distinguishes between the renovations that are made for primarily aesthetical reasons, and the renovations that are done as part of the maintenance and repair. While offering fruitful insights, such a categorisation misses out the huge diversity of different goals and aspiration, specific to home improvements, and, thus, cannot be claimed to be comprehensive.

The built environment should be understood as a "depository" of personal, social and cultural values people attach to the physical structure of the buildings (Hassler and Kohler, 2014b). Wilson et al. (2015) argue that ultimate influences behind retrofit decisions should be understood through the meanings people attach to their homes. However, no attempt to categorise retrofit motivations based on home-meanings is known. This thesis intends to use a framework of home-meanings as a tool to bring insights in homeowner retrofit decisions in general, and decisions that result in low-carbon home retrofit, in particular. In the absence of a suitable pre-existing framework this thesis develops a conceptual framework of home-meanings specifically for the needs of current research. The framework and the development process are described in detail in section 2.5. This section 2.4 now describes the overall theoretical framework used for data collection and analysis in the thesis.

2.4c. Home retrofit decisions as an innovation-decision process

Research on judgement and decision making (JDM) has a long tradition that stretches back several centuries at least. A historical overview of the last several decades of JDM research can be found in Goldstein and Hogarth (1997) and Doherty (2003). It is widely accepted that to understand decisions, it is important to understand decision processes, not just the overt choice (Goldstein and Hogarth, 1997). It is fair to say that process-tracing methods "now enjoy wide, if not universal acceptance" (ibid.: p. 19). During the 1940s and 1950s two foci of JDM research, *choice* and *judgement*, were established and continue to dominate the research tradition (ibid.). One group of psychologists focused on the questions of how people *choose* what to do next, how rational are their choices, and by what psychological processes people make their decisions. Another group of psychologists, motivated by the analogy with perception, focused on the questions how people integrate multiple, potentially conflicting cues to arrive to a *judgement* of a situation.

It follows that theories of preferential choice can serve as an appropriate theoretical lens to bring insights into retrofit-decision processes. One of the objectives of this thesis is to explore the individual retrofit-decision processes and the implications of their dynamics for the overall transition to a low-carbon housing stock. Theories of preferential choice would not allow such an exploration, and for this reason they are not used in this thesis.

Instead, retrofit decisions are conceptualised as an innovation-decision process, in line with innovation diffusion theory (Rogers, 2003), which is rooted in communication theory. This choice can be justified as previous research has shown that a degree of information is acquired by potential retrofitters through direct communication, whether it is with neighbours, friends, acquaintances, people from the local community or through 'open home' events (Berry et al., 2014; Gupta et al., 2014; McMichael and Shipworth, 2013).

Stages of home retrofit-decision process

The theory of *innovation diffusion* explains how abstract ideas and concepts, technical information or actual practices spread over time through communication channels in a particular social system (Rogers, 2003). The study of innovations began with Tarde's 1903 book on *The Laws of Imitation*, but the diffusion of innovations paradigm began only forty years later when Ryan and Gross (1943) published their results of their hybrid corn study (Valente and Rogers, 1995; Wejnert, 2002). Since then, over 5000 studies were conducted on the innovation diffusion in a variety of disciplines (Rogers, 2004: p. 13). The generalisability of the diffusion model resulted in its application to a variety of real-world problem, such as STOP AIDS program in San Francisco in the 1980s (Singhal and Rogers, 2003).

Innovation diffusion theory provides a framework to understand retrofit decisions as temporal processes. The most widely known stages of innovation-decision processes are described by Rogers (2003). The theory asserts that individual agents attempt to reduce the inherent uncertainty associated with a new idea during the decision-making process related to its adoption. This process has five stages (Figure 2.5), during which an agent: (i) acquires *knowledge* and becomes aware of a particular innovation, (ii) forms a positive or negative attitude towards this innovation via *persuasion* process, (iii) takes a *decision* to adopt or reject the innovation, (iv) follows through with its *implementation*, and (v) seeks reinforcement or *confirmation* of the decision already made.

The innovation-decision framework adds the important temporal dimension to understand how decisions unfold over time. The decision to adopt an innovation or an idea is conceptualised as a sequential, cumulative process through which a new idea or technology becomes more salient until it is eventually adopted. Different influences play a role at different stages of the decision process. This suggests that different communication channels are likely to be used at different decision stages. For instance, mass-media channels are more effective in sharing knowledge about new ideas, whereas interpersonal communication is more effective in forming attitudes towards these ideas (ibid.).

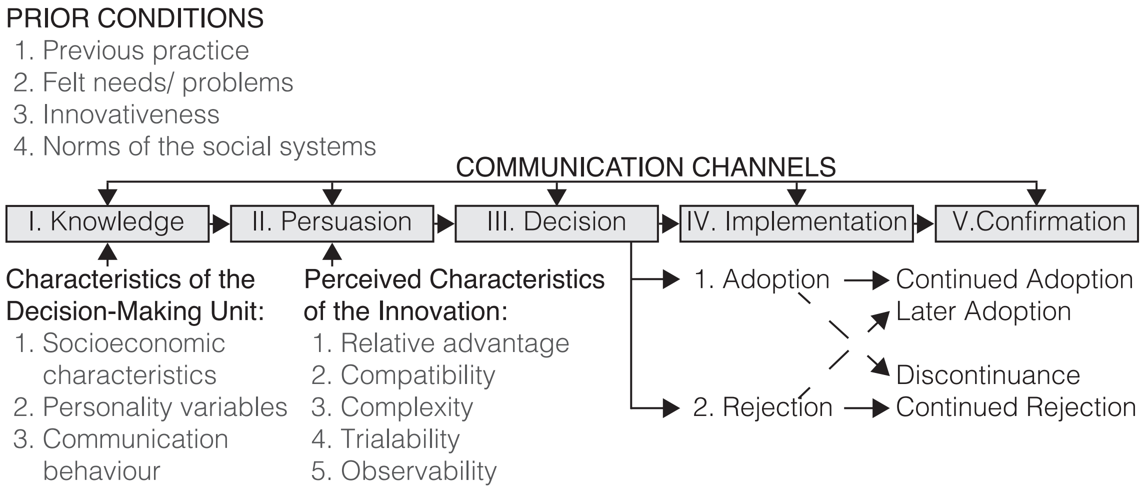

Figure 2.5. A model of five stages in the innovation-decision process (adapted from Rogers, 2003: p. 170)

Rogers was not the first to conceptualise stages of the individual innovation-decision process. The idea of stages was first introduced by Beal and Bohlen (1955) in the report by the North Central Subcommittee *How Farm People Accept New Ideas*. Five stages in the innovation-decision process were postulated: (i) *awareness*, at which stage an individual learns about existence of the idea; (ii) *interest*, at which stage the individual develops interest in the idea; (iii) *evaluation*, at which stage an individual weights the merits of the idea; (iv) *trial*, at which stage the individual applies the idea to practice on a small scale; (v) *adoption*, at which stage the individual accepts the idea. This five-stage model is theoretically appealing, but practically it is difficult to differentiate between interest and evaluation stages in retrofit decisions. Moreover, it is not possible to try low-carbon retrofit on a small scale, such as 10% of the house, before deciding to retrofit the whole house to low-carbon standards. For these reasons, the stages outlined by Beal and Bohlen were not used in this thesis.

The innovation-decision stages presented by Rogers are generic, and Rogers himself highlights that conceptualisation of decision stages specific to a particular process might be fruitful (Rogers, 2003). UK homeowners' retrofit decisions have been previously conceptualised as innovation-decision process. For instance, Nair et al. (2010) used a simplified three-stage model, based on the diffusion theory. The stages are assembled based on the previous literature, rather than empirical evidence, and for this reason are not used in this research.

The authors of the Value Propositions for Energy Efficient Renovation (VERD) project proposed five stages specific to retrofit-decision process, including stage 0: not thinking about renovations; stage 1: thinking about renovations; stage 2: planning renovations; stage 3: finalising renovations; stage 4: experiencing renovations (Pettifor et al. 2015; Tyndall Centre for Climate Change Research, 2013). The stages are not based on empirical evidence, but rather suggested by the researchers based on their expert understanding of the situation. The authors claim that "[e]ach stage in this model is distinctive because it requires varying levels of information and action by homeowners" (Pettifor et al. 2015: p. 163). The authors did not elaborate any further and did not give any example of these differences. It is not clear what the authors mean by levels of information, and what is the difference in action required from homeowners between the thinking and planning stages. For these reasons, the stages outlined by the VERD project are not used in this thesis.

Owen and Mitchell (2015) report interesting insights into the evidence on retrofit stages in retrofit decisions, based on empirical evidence. The authors originally interviewed 54 individuals, including householders, managers of low-carbon energy technology schemes and installers from five areas in England. The data was gathered for a study on household adoption of low-carbon energy technologies (Owen et al., 2014). In 22 of these interviews, the role and importance of intermediaries was mentioned explicitly. Owen and Mitchell (2015) identified five stages, at which intermediaries have a potential to influence a household's retrofit decisions: (i) *option identification*, at which stage the household becomes familiar with various options, including low-carbon retrofit solutions, available to meet their goals and aspirations; (ii) *option formalisation*, at which stage the household acquires specifications and quotes for particular options, gets planning permission and ensures compliance with regulations; (iii) *installation*, at which stage the new technology is installed; (iv) *commissioning*, at which stage the new technologies are switched on and tested to ensure they function as expected; (v) *post-commissioning*, at which stage the installers revisit the site to ensure that the occupiers use the technologies correctly to ensure optimal performance.

The stages, outlined by Owen and Mitchell (2015) correspond with the generic ones theorised by Rogers (2003) (see Figure 2.6). Innovation diffusion literature focuses predominantly on diffusion of a particular innovation. A notable difference with the retrofit process is that an idea of low-carbon retrofit does not imply a particular technology or a set of technologies. Instead, there are many options that can be explored. Thus, the first stage described by Owen and Mitchell show the process of an *identification* and selection of particular technological *options.* This first stage roughly corresponds with the *knowledge* and *persuasion* stages identified by

Rogers. Owen and Mitchell distinguish between *option formalisation, installation and commissioning*, which roughly correspond to an *implementation* stage by Rogers. The *option formalisation* stage also corresponds to the *decision* stage by Rogers. The *post-commissioning* stage by Owen and Mitchell corresponds to a *confirmation* stage by Rogers.

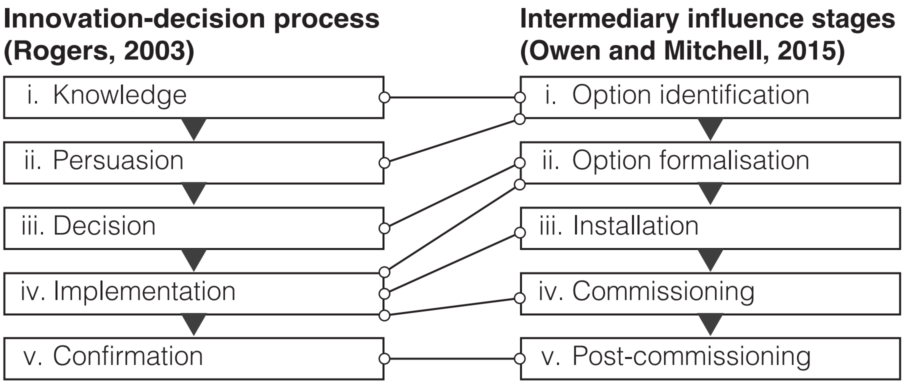

Figure 2.6. Correspondence between innovation-decision stages (Rogers, 2003) and stages of influence by intermediaries on retrofit decisions (Owen and Mitchell, 2015)

The stages identified by Owen and Mitchell (2015) are clearly distinguishable, empirically grounded and are specific to retrofit decisions. However, they are specific to the stages at which intermediaries tend to play an influential role and, thus, might not be the only stages in the process. With this in mind, this thesis will use both set of stages, the generic ones outlined by Rogers and specific ones outlined by Owen and Mitchell, to guide the inquiry. The definitive set of stages will be shaped through the empirical data collection for the thesis.

The rate of adoption

The conceptualisation of the retrofit decisions as an innovation-decision process highlights its temporal dimension. During the process homeowners become aware of a particular low-carbon measure or technology, form a positive or negative attitude towards this technology, decide to adopt or reject it, do the retrofit and assess whether their prior expectations about the retrofit are met during the time they live in the house post-retrofit while they experience the changes.

A significant time period can pass between becoming aware of an innovation and adopting it. For instance, in the famous Ryan and Gross (1943) study Iowa farmers averaged five years between the date they became aware of the hybrid seed corn until the date they tried it. The rate of awareness was also faster than the rate of adoption, as the modal time at which 257 Iowa farmers reached awareness was seven years after hybrid corn was first introduced, whereas the modal time for the beginning of adoption, i.e. trial period, was ten years after hybrid corn was introduced (Figure 2.7). This highlights the importance of shortening the *persuasion* period as a means of shortening the overall innovation-decision process for an individual actor.

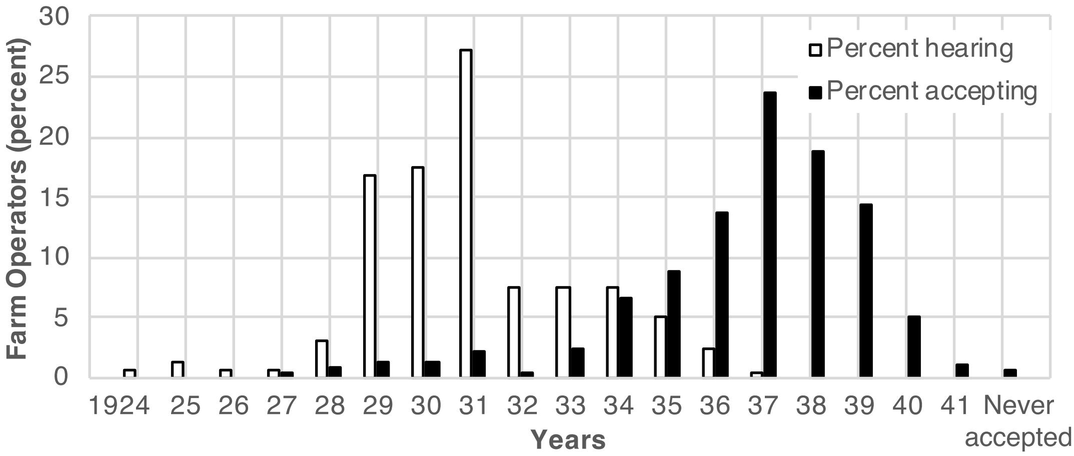

Figure 2.7. Percentage of farm operators first hearing of hybrid seed corn and percentages first accepting it, by years (adapted from Ryan and Gross, 1943: p. 17)

The rate of adoption of an innovation is understood as the relative speed with which it is adopted by members of the social system (Rogers, 2003). One of the main methods to increase the innovation adoption rate in the system is to shorten the decision-making process of individual agents (ibid.: p. 213). These two statements are illustrated in Figure 2.8 with an example from a mini-case study of a new weed spray diffusion in an Iowa farm neighbourhood, carried out by Rogers (Rogers, 2003: p. 292–293). It took nine years for all fourteen farmers in the neighbourhood to adopt the new weed spray, which makes the rate of adoption 1,55 farmers per year. The fourteen Iowa farmers were asked by Rogers: "Where or from whom did you obtain information that convinced you to adopt 2,4-D weed spray?" Their answers are depicted by arrows in the Figure 2.8. The second farmer is clearly an opinion leader in the neighbourhood, as eight of the other 13 farmers adopted the new weed spray based on his recommendation. Thus, the rate of adoption in this small system depends a lot on how quickly the second farmer shifts from first hearing about the new weed spray to adopting it.

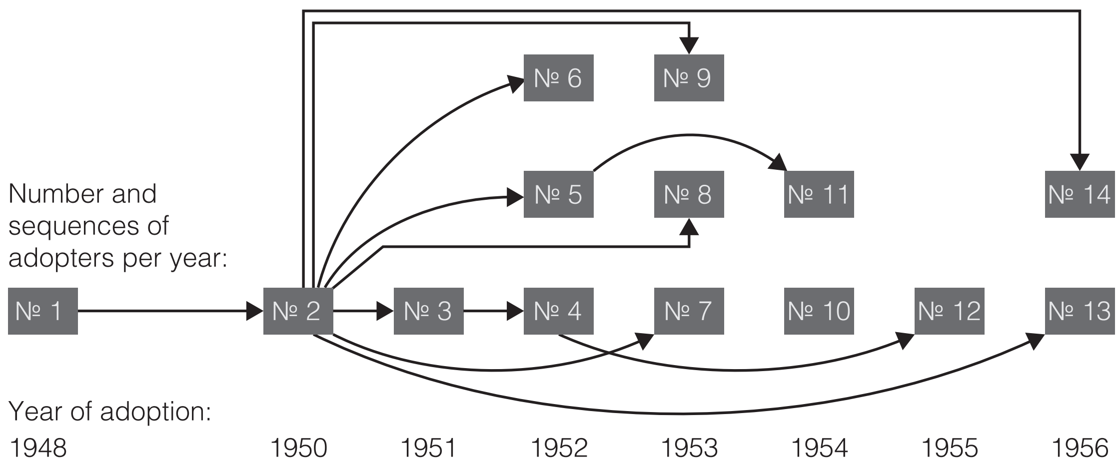

Figure 2.8. The diffusion of a new weed spray in an Iowa farm neighbourhood (based on Rogers, 2003: p. 293)

This thesis assumes that a similar logic applies to bigger systems, such as the transformation of a housing stock to low-carbon standards. The sooner individual agents refurbish their homes to low-carbon standards, the sooner they will form a critical mass of people to spread information about such retrofit to others, and the sooner the rest of the population will follow suit. This subsection introduced the theory of innovation diffusion to conceptualise stages in retrofit decisions. The next subsection introduces the notion of implementation barriers.

2.4d. Implementation barriers to low-carbon retrofit decisions

This review highlighted a persistent low rate of low-carbon retrofit among UK homeowners, despite the technical feasibility and economic viability of many options. This problem can be seen as a problem of implementation. *Implementation science* is commonly defined as the study of methods and strategies to promote uptake of interventions that were proven to be effective (Nilsen, 2015). Implementation science originated in the health care sector and spread with time to other areas of professional practice (ibid.). Nilsen proposes a taxonomy that distinguishes between different categories of theories, models and frameworks in implementation science. The use of these theories, models and frameworks serves different aims. The aim that is most closely linked to the aim of the thesis is to understand and/ or explain what influences implementation outcomes. Theories that originate from the psychology and sociology fields have been widely used to develop such an understanding. Rogers theory of innovation diffusion has been widely used in the implementation science (ibid.) and is considered the single most influential theory in the field of knowledge utilisation, of which implementation science is a part (Estabrooks et al., 2008).

A single theory cannot be used to develop a comprehensive story, as a single theory inevitably focuses on some aspects of implementation at the expense of other aspects (Nilsen, 2015). Multiple theoretical perspectives can offer a more complete understanding and insights. It has been decided to use a sequential approach for the identification of the relevant theoretical lenses. First, the data is analysed with the framework derived from Rogers (2003) innovation diffusion theory, as described in the *Chapter 3*. The insights from this analysis will serve as a platform to identify another theoretical lens to bring further insights into the problem of implementation difficulties associated with low-carbon retrofit.

This section provided the background and rationale to the approach taken in this thesis. A conceptual framework of home-meanings is suggested to bring insights in the context of retrofit decisions. Rogers innovation diffusion theory is used to develop insights into different stages of the decision process and the role of communication channels in such process. The notion of implementation barriers concludes the proposed theoretical framework used in the thesis. The next section develops in detail a conceptual framework of home-meanings to understand retrofit decision context.

2.5. MEANINGS OF HOME AS A CONTEXT FOR LOW-CARBON RETROFIT DECISIONS

2.5a. A need to develop a conceptual framework of home-meanings

It is important to provide some conceptual clarity for a notion of 'home' from an analytical point of view. A definition of a construct can provide such clarity. Home is a place of great significance and meaning for individuals, and thus, it is not a surprise that theoretical and practical research on the topic has a long tradition (Benjamin et al., 1995; Blunt, 2005; Blunt and Dowling, 2006; Blunt and Varley, 2004; Coolen and Meesters, 2012; Després, 1991; Easthope, 2004; Fox, 2002; Heidegger, 1959; Mallett, 2004; Manzo, 2003; Molony, 2010; Moore, 2000; Saunders and Williams, 1988; Somerville, 1997). All of these authors agree that *home* is a complex, multi-layered, multi-faceted and multi-dimensional construct, despite the differences in approach and focus. The existence of different, sometimes opposing, dimensions as well as the complex relations between these dimensions, makes a clear definition of home a difficult task. One of the most comprehensive definitions of home has been put forward by Benjamin:

> The home is that spatially localised, temporally defined, significant and autonomous physical frame and conceptual system for the ordering, transformation and interpretation of the physical and abstract aspects of domestic daily life at several simultaneous spatio-temporal scales, normally activated by the connection to a person or community such as a nuclear family. It is thus the autonomous interpretation of domestic life, and that which is interpreted. (Benjamin, 1995: p. 299)

Benjamin acknowledges that his definition is not inclusive of all dimensions discussed in the literature on home-meanings. For instance, he points out that he chose to regard the home-as-state-of-mind as a metaphor, rather than a part of the definition (Benjamin, 1995). Some authors even argue that a complete definition of home is not only difficult, but is also undesirable (Easthope, 2004). These authors point out that home as a notion is imbued with personal meanings, and, therefore, is likely to mean different things to different people at different times and in different contexts. Thus, a definition of home suited for one individual might not be suited for another. For the same reason, a comprehensive and exhaustive list of all possible meanings that people might attach to their homes, is futile. Such a list of meanings is inevitably just a snapshot, specific to particular people, time and context.

Another way to provide clarity to the concept of home is via a *theoretical* or *conceptual framework* of home-meanings. Several theoretical models arose from different disciplines to describe the forces that shape home-meanings, these models include: (i) geographical, (ii) psychological, (iii) social-psychological, (iv) phenomenological, and (v) sociological ones (Somerville, 1997; Després, 1991). More details on these theoretical models are found in Box 2.2.

Box 2.2. Theoretical models of home-meanings
(based on Blunt and Dowling, 2006; Després, 1991; Porteous, 1976; and Somerville, 1997)

Territorial/ geographical. This approach gives priority to the spatial boundaries associated with home. It emphasises the existence of different physical scales of home boundaries, and the idea that home places are simultaneously shaped in real and imaginative worlds. Home is described as a spatial imaginary. The emphasis in this approach is on the social and psychological attributes that places offer to individuals, primarily feelings of security, control, identity and stimulation.

Psychological. This approach traces the meaning of home in deeply rooted psychological needs. For instance, home can be defined as a powerful extension of psyche and a symbol of one self. Alternatively, home can be understood as a mean to fulfil the hierarchy of human needs, such as a need for privacy, security and control.

Social-psychological. This approach focuses on explaining how home plays a role in people's definition of their self-identity, as well as being an important symbol of individual social identity.

Phenomenological and developmental. These approaches focus on the temporal dimension of home. Home is understood through a continuous process of creation and recreation of its meaning in the context of everyday life. Being-at-home is associated with a sense of familiarity and routine, which contributes to the creation of the feeling of continuity that connects individual's past and future.

Sociological. This approach focuses on the interpretation of home-meanings using concepts of social relations, particular the ones of family. Other sociological categories such as class, gender and tenure are also used for interpretations.

Each of these approaches emphasize certain home-meanings and downplays or neglects others, so each approach has conceptual limitations (Someville, 1997). Somerville discusses the following limitations. For instance, much of the literature from territorial/ geographical approach overlaps with the literature from psychological and social-psychological approaches, which makes the differentiation between them problematic. The psychological and social-psychological approaches are based on theories of needs, which remain weak and underdeveloped. Sociological approaches are criticised for the lack of any coherent underlying theory, with probably the only exception being Giddens' structuration theory (Giddens, 1984).

Several calls have been made to create an integrative theoretical model, exploring the processes by which home comes to have meaning for an individual (Després, 1991; Somerville, 1997). However, no such model has yet been developed. In the absence of an integrative theoretical model of home-meanings, a conceptual framework of meanings people attach to their homes is developed in the rest of the section 2.5.

2.5b. Method to develop home-meanings framework

A selective *critical literature review* strategy is adopted to identify studies, which are then used to outline a framework of meanings that people attach to their homes (Grant and Booth, 2009; Paré et al., 2015). The aim of this review strategy is to critically analyse the extant literature on a broad topic. It goes beyond a mere description and includes a degree of analysis and conceptual innovation. The product of a critical literature review is usually a theoretical or conceptual model, which might constitute a synthesis of current models, or may be a completely new interpretation of available data. The critical literature review provides an opportunity to evaluate the value of proposed conceptual innovation against the existing body of work. Critical literature review strategy has been criticised for being less systematic and comprehensive than other types of reviews, as well as for the subjective nature of the interpretation and analysis (Grant and Booth, 2009; Paré et al., 2015). To account partially for this weakness, the following paragraphs discuss how the review process has been conducted.

Relevant literature has been identified with the *Web of Science* database. An initial broad search only included the word 'home', which returned 380,000 results. Identified sources were sorted by the number of citations, and the titles were searched to identify sources that conceptualise the meanings people attach to their homes. The relevant, most cited sources were identified, and their references and citations were traced to identify more relevant literature. The choice was eventually narrowed down to fourteen sources (Table 2.6): one book, one book section, three editorial articles, three critical reviews of the literature (1991, 1997 and 2004), one qualitative metasynthesis, and five articles that investigate the concept of home from different disciplinary approaches. The latest source is a 2012 editorial for a special issue journal. All articles are published in peer-reviewed journals and cover disciplines of geography, architecture, sociology, law, psychology and housing studies. Whenever an argument presented in an article or book was based on other work, references were traced to the original sources. The framework of home-meanings is developed in the rest of the section based on these sources. The emphasis in the critical literature review is on the conceptual contribution of each new source, not the formal qualitative assessment (Grant and Booth, 2009). The fourteen sources chosen provide a rich synthesis of current literature, and the researcher made a judgement that a further detailed review of the literature will not make a significant conceptual contribution to the framework of home-meanings.

Table 2.6. Fourteen original sources used in the critical literature review

Sources	Disciplinary approach	Type	Source
Blunt (2005)	Geography	Editorial article	Progress in Human Geography
Blunt and Dowling (2006)	Geography	Book	Routledge
Blunt and Varley (2004)	Geography	Editorial article	Cultural Geographies
Coolen and Meesters (2012)	Ecological psychology	Editorial article	Journal of Housing and the Built Environment
Després (1991)	Psychology	Critical review	Journal of Architectural and Planning Research
Easthope (2004)	Geography	Review	Housing, Theory & Society
Fox (2002)	Law	Critical review	Journal of Law and Society
Heidegger (1993)	Phenomenology	Book	Routledge
Mallett (2004)	Multidisciplinary	Review	The sociological review
Manzo (2003)	Psychology	Review	Journal of Environmental Psychology
Molony (2010)	Nursing	Qualitative metasynthesis	Research in Gerontological Nursing
Moore (2000)	Environmental psychology	Review	Journal of Environmental Psychology
Saunders and Williams (1988)	Sociology	Theoretical position	Housing Studies
Somerville (1997)	Sociology	Critical review	Journal of Architectural and Planning Research

A conceptual framework is a synthesis of “the existing views in the literature concerning a given situation — both theoretical and from empirical finings” (Imenda, 2014: p. 189). The process of building a conceptual framework is inherently abductive, during which small individual pieces (in this case, concepts) are joined creatively together in a new way. The physicist and historian of science Gerald Holton describes abductive reasoning as the one that allows “a speculative leap” (Holton, 1978: p. 100), which is inevitable regardless of how small it is. However, such a leap should not be a result of random guesswork, but rather reflect a process of “disciplined imagination, where the ‘discipline’ in theorising comes from consistent application of selection criteria to trial-and-error thinking and the ‘imagination’ in theorising comes from deliberate diversity introduced into the problem statement, though trials, and selection criteria that comprise that thinking" (Weick, 1989: p. 516). This thesis makes a deliberate attempt to formalise and document the process of disciplined imagination. A step-by-step logic of development of a conceptual framework of home-meanings is presented in the rest of the section. The conceptual framework is built in a diagrammatic form. The need to summarise ideas in a diagram obliges a researcher to disaggregate a phenomenon into conceptually and functionally distinct variables and constructs and specify the interactions and interrelations between them (Miles et al., 2014). The process compels the researcher to work in a more clear, rigorous and elegant manner. Cross-tabulation of constructs derived from the literature ensures the clarity of added constructs and increases the construct validity (Yin, 2018).

The framework of home-meanings is developed around the well-established concept of *affordance* (Gibson, 1979), which helps to develop the construct validity of the developed framework. The framework is built iteratively and is informed by extant literature. Iterative tabulation was carried out for definitions and relations found in literature for each construct, which helped to sharpen construct definition and validity (Eisenhardt, 1989).

2.5c. Affordances as a way to conceptualise meanings

An ontology of the *meaning* of human perceptions is not straightforward. Inferential theories of perception argue that meanings arise inside animals, as a result of their interaction with the environment (Chemero, 2003). This approach implies that meanings are figments of the imagination of the animal that perceives them, and thus, cannot be objectively studied. In direct theories of perception, meaning is understood to be a property of the environment itself, and an animal simply gathers information from a meaning-laden environment. This approach, however, requires an ontology that postulates that the world is not just a physical world, which is at odds with today's physicalists' scientific consensus. The theory of *affordance* is a third approach that describes an ontology, in which meanings are a real aspect of the world unlike in inferential theories of perception, but they are also not direct properties of the environment unlike in direct theories of perception.

The notion of *affordance* was originally introduced by psychologist James Gibson (1979) in the field of ecological psychology. Gibson defines affordances as follows: "The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes*, either for good or ill" (Gibson, 1979: p. 127). This description is deceptively simple, and raises more questions than it answers. Several post-Gibson attempts have been made to develop a coherent theory of affordances (Chemero, 2003). This thesis follows Chemero's outline of the theory of affordances, as it provides clarity to the concept, but at the same time remains consistent with the ontology of affordances as understood by Gibson himself.

Chemero defines affordances as: "relations between the abilities of organisms and features of the environment" (Chemero, 2003: p. 189). He then explains, what he means by *abilities* and *features* (Chemero, 2001; 2003). *Features* ascribe certain characteristics of the environment without assigning them to any particular object in the environment. For instance, the phrase 'it's raining' describes the feature of the environment, but it does not assign a property to any particular object. *Properties*, on the other hand, are assigned to particular objects in the environment. For instance, a perception of a red car implies a perception that a particular entity (a car) has a particular property (being red). The perception of affordances should be understood as ascribing features, rather than perceiving properties of the environment.

Abilities are functional properties. An ability to ride a bicycle does not mean that one will not fall from the bicycle, even in the ideal conditions for cycling. In contrast, *dispositions* are guaranteed to become manifest, if enabled by the right conditions. For instance, a cube of sugar will always dissolve in water in suitable conditions. Affordances arise along with the abilities of animals to perceive these functional properties and take advantage of them. The differences between *features* and *properties*, and between *abilities* and *dispositions* underpins the following clarification of the concept of affordances:

> Affordances are neither properties of the animal alone nor properties of the environment alone. Instead, they are relations between the abilities of an animal and some feature of a situation. They are not easily localizable physically but are nonetheless perfectly real and perfectly perceivable. (Chemero, 2003: p. 191)

It follows that affordances are perfectly real entities and do not disappear, when there is no animal to perceive and take advantage of them. They do, however, depend on the existence of some animal that might take advantage of them, if the conditions are right. In this way the notion of affordances provides a reconceptualisation of the notion of meanings that are understood as real entities that do not exist in the mind of the perceiver only, but at the same time they are not just the properties of the environment itself (Chemero, 2003).

This thesis uses the concept of affordance as a stepping stone to develop a conceptual framework of home-meanings. The concept of affordances has been previously used to discuss what a dwelling can offer to an individual by Coolen and Meesters (2012). Even though the authors admitted that the concept was useful to direct the discussion, no attempt was made to develop it further into a conceptual framework of home-meanings. This thesis makes such an attempt and describes the developed home-meanings framework in the next subsection.

2.5d. Conceptual framework outline

This subsection provides an overview of the conceptual framework of home-meanings, developed in this thesis. The framework is visualised in Figure 2.9. The rest of the section describes the rationale behind the articulation of five different dimensions associated with the notion of home in the framework. The framework distinguishes five different dimensions associated with the notion of home:

(i) The home **environment** includes three elements, which afford it meaning: (a) its *physical and spatial* elements; (b) *self and social* elements; and (c) f*inancial and legal* elements.

(ii) These elements, together or separately, can offer an individual two types of **affordances**: (a) *behavioural* affordances, as home provides a platform for experiences and everyday practices; and (b) *psychological and social* affordances, as home provides a platform for establishing various psychological and social values, feelings and attributes.

(iii) Home should be understood as being created simultaneously in **real and imaginary** realms.

(iv) The **temporal** dimension is vital to understand the formation of home-meanings.

(v) It is crucial to consider various **contexts**, within which these dimensions exist, such as social, economic, political and cultural ones.

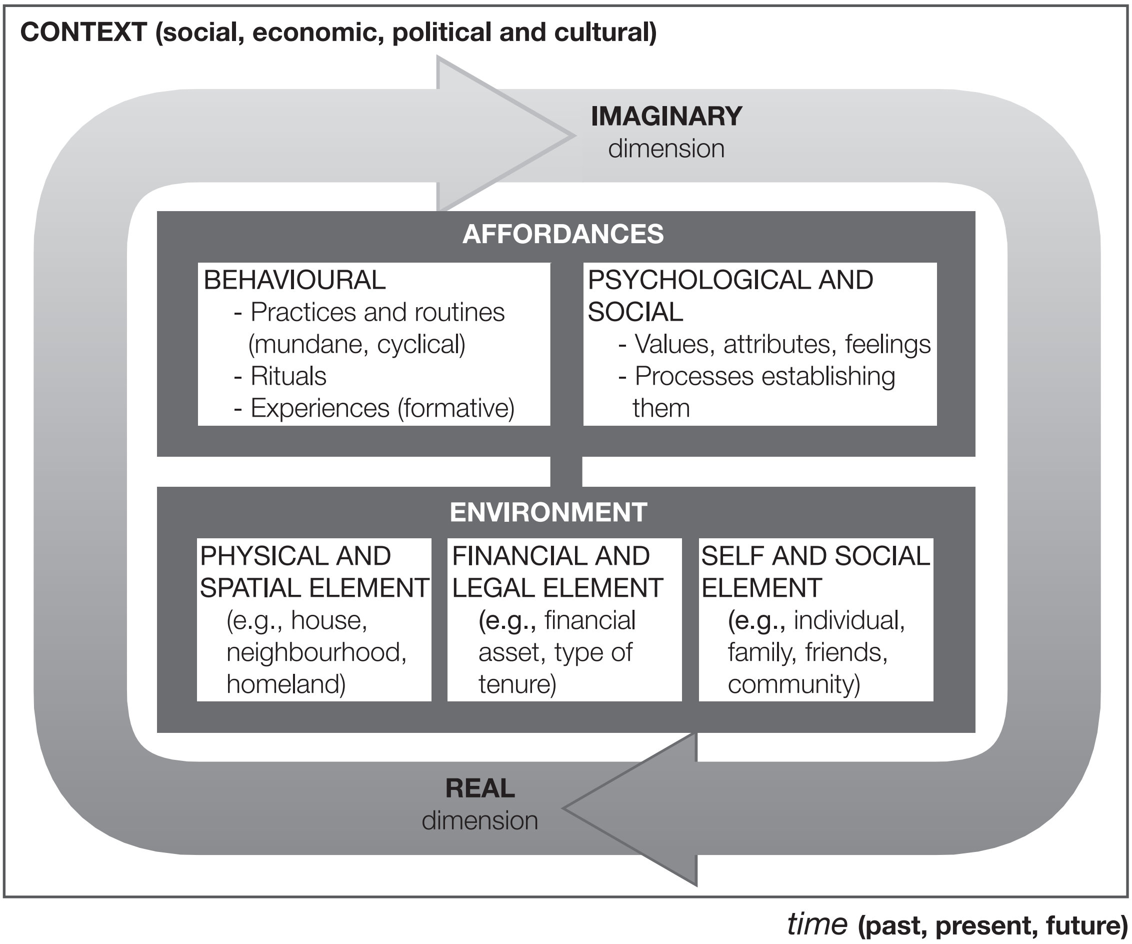

Figure 2.9. A conceptual framework of home-meanings

Environment

Affordances should be understood in relation to an animal and its environment. Gibson gives the following definition of one's environment: "The environment of any animal (and of all animals) contains substances, surfaces and their layouts, enclosures, objects, places, events, and other animals" (Gibson, 1979: p. 36). This description is very general, but it gives a good idea of the diversity of different elements in the environment, which together or separately can offer something to an animal. This thesis distinguishes three elements of the home environment, which provide affordances to an individual and have been identified previously together or separately in the literature on home-meanings:

(i) Physical and spatial elements;
(ii) Self and social elements;
(iii) Financial and legal elements.

Physical and spatial elements of the environment contain what Gibson describes as substances, surfaces and their layouts, enclosures, objects, places and events. An example Gibson gives of an event is fire (Gibson, 1979: p. 38), which is commonly associated with a fireplace, hearth, home. The physical and spatial elements of home are readily identified in the literature of home-meanings. One of the most important elements, which provides an individual with the relations associated with home is the physical structure of the house itself such as a house, yurt, truck, caravan, tent. It commonly includes the type of structure of the dwelling, its size, spatial organisation, the aesthetical characteristics, as well as the characteristics of the neighbourhood and the facilities available such as gardens and parks (Després, 1991). The spatial aspect of home is closely linked to its physicality, as the term home has been used to talk about different spatial entities such as a house, neighbourhood, town, homeland or the whole world (Mallet, 2004; Blunt and Dowling, 2006). The sense of belonging or alienation, commonly associated with home, can be constructed across different scales ranging from the body, the household, the town, nation or the whole world (Blunt and Dowling, 2006).

Self and social elements of the environment in the framework refer to what Gibson describes as animals. He notes that the richest and most elaborate affordances are provided by animals (Gibson, 1979: p. 35). Self and social elements are important to understand the meanings of home for an individual. Home is not just a physical-spatial entity, but also a societal entity and a platform for social relations, most commonly associated with one's family (Blunt and Dowling, 2006). Sixsmith captures the importance of the social relations as follows: "A place where there is love often signifies a home" (Sixsmith, 1986, p. 287). Even though home is most often considered from the perspective of a family or household, other social groups such as friends or ethnic groups may be associated with a notion of home (Coolen and Meesters, 2012). Saunders and Williams (1988: p. 83) describe home as a "socio-spatial system", as many relations associated with home arise simultaneously from a system of socio-spatial relations. The authors base their interpretation in Giddens's theory of structuration (1984) and state that both the social unit of the household and the physical unit of a house are important to structure household activities, as they both enable and constrain different actions. Based on these arguments, Saunders and Williams postulate that the home, as a socio-spatial system, is not reducible to either the social or the spatial elements, but should be considered as a fusion of the two.

Financial and legal elements of the environment are used in the framework to describe the occupant's type of tenure, such as owner-occupancy or tenancy; modes of land ownership, such as private ownership or lease; and to suggest that a house can be a financial asset. The rights associated with financial and legal elements are usually sealed in official documents. These documents refer to what Gibson describes as a very special class of artificial objects — the ones that display optical information. These objects afford knowledge at second hand or "mediated or indirect" knowledge (Gibson, 1979: p. 42). Gibson postulates that the simplest and best kind of knowledge is gained through direct perception. However, there are other kinds of knowing with "knowing by means of language" being one of them (ibid: p. 263). The disadvantage of this type of knowing, as compared to the one obtained by perceiving, is the inability to differentiate fact from fiction. For instance, a legal document that confirms the ownership of a property can be fraudulent. Nevertheless, mediated knowledge is knowledge, and an individual can anticipate various affordances associated with it, and act upon these anticipations. The type of housing tenure as well as the consideration of home as a financial asset have increasingly gained prominence in the literature of home-meanings (Fox, 2002). Many social and psychological attributes associated with home can be strengthened by these financial and legal elements. For instance, homeownership was found to enhance feelings of security and control, as well as provide a source of personal and social status (Mallett, 2004; Somerville, 1997).

Affordances

According to Gibson "*affordances* of the environment are what it *offers* the animal" (Gibson, 1979: p. 127). For instance, a surface can offer walking, a house can offer shelter. The literature of place-meanings distinguishes two components that give meaning to a place: (i) "the activities or rituals done at the place" and (ii) "an individual's internal psychological and social processes and attributes" (Smaldone et al., 2005: p. 398). Following this differentiation, this thesis distinguishes two types of affordances, which the elements of the home environment, can offer to an individual:

(i) behavioural affordances;
(ii) psychological and social affordances.

Behavioural affordances are used in the framework to describe different activities and rituals that can happen in home settings, such as eating, cooking or birthday celebrations. Home as a setting is associated with the reoccurring character of everyday activities and mundane aspects of everyday life (Manzo, 2003). Repeated activities are important for the formation of the place-meanings as they: "tend towards being performed in a fixed way, which means they begin to 'bind' you. Places and things get symbolically meaningful by this process of timebinding"

(Merloo, 1966, as cited in Westman, 1995: p. 71). Formative experiences can shape one's associations with home, such as learning to be independent or living through a stressful period (Proshansky et al., 1979 as referenced in Sixsmith, 1986: p. 287). Nevertheless, it is the "experience of happy events and general feelings of happiness [that] are an integral part of home" (Sixsmith, 1986: p. 287).

Psychological and social affordances are used in the framework to account for different psychological, social and cultural values, feelings and attributes associated with a notion of home, such as a sense of privacy and security. Every person's journey through life is unique, and so are the lived experiences and the relation one establishes with the place called home. Psychological and social values and attributes people attach to their homes are not only different for different people, but they continuously change for the same person. Feminists were the first to highlight the fluidity of the concept (Blunt and Dowling, 2006). They pointed out that it possible for home to evoke the feelings of belonging and intimacy, just as it is possible to evoke the feelings of fear, violence and alienation. The specific combination of one's home environment, such as the physical structure of the house and the people in it, might not be able to offer all the relations that an individual wants, and, thus, result in the formation of a less positive experience of the place called home (Coolen and Meesters, 2010). One might have positive, or negative emotions towards home, or even a combination of two (ibid.). Values and feelings associated with one's home were found to vary across age, gender, class and race (Després, 1991; Blunt and Dowling, 2006).

The social and psychological affordances, which home can offer to an individual, are specific to each individual. They are specific in the sense that some affordances might be possible for some individuals, but not others, or even for the same individual at different points in time. As noted previously, a list of home-meanings, and in particular a list of psychological and social affordances, is inevitably just a snapshot specific to particular places and people. Such lists, however, provide a good overview of the diversity of possible affordances. Table 2.7 provides an illustrative summary of psychological and social affordances that home environment can offer to an individual. The summary is based on three papers that provide critical reviews of empirical studies carried out in western world, where different groups of people were asked what home means to them (Després, 1991; Somerville, 1997; Mallett, 2004). Després (1991) focuses more on psychological factors, Somerville (1997) on sociological ones, and Mallett (2004) provides an overview of a combination of both. All the studies show the consistency to people's answers on the meanings of home that range from security and control to self-expression and personal status. The table provides a list for illustrative purposes only and is not intended to claim that the list of affordances is exhaustive.

Table 2.7. A list of psychological and social affordances identified by empirical research

Després (1991)	Somerville (1997)	Mallett (2004)
Physical security and control	Ontological security, root of authentic human existence	Being-in-the-world (being at home)
Reflection of one's ideas and values and indicator of personal status	Self-expression and personal status	Experience of one's (possibly fluid) identity
Refuge from the outside world	Retreat, safety and relaxation, freedom and independence	Haven: comfort, ease, intimacy, relaxation and security OR oppression, tyranny and persecution
		Belonging OR marginalisation and estrangement

Values, attributes and feelings associated with home do not simply exist, but they are made (Manzo, 2003). To account for this, the processes of establishing such values and attributes are explicitly conceptualised in the home-meanings framework.

Real and imaginative realms

In his theory of affordances Gibson makes a clear distinction between real and imaginary. He postulates that perception, including perception of affordances, can only be in relation to the real environment that accompanies the pickup of natural information (Gibson, 1979). He acknowledges that there are "noncognitive kinds of awareness — fictions, fantasies, dreams and hallucinations" (ibid.: p. 263).

The literature on home-meanings postulates that home exists not only in the real, but also in the imaginative realm and is constructed simultaneously in both as part of a single process (Somerville, 1997). Blunt and Dowling describe home as a spatial imaginary with material and imaginative geographies being relational to each other: "the material form of home is dependent on what home is imagined to be, and imaginaries of home are influenced by the physical forms of dwelling" (Blunt and Dowling, 2006: p. 22). This relationship between real and imaginary realms helps to explain the tension between a dwelling unit and one's changing objectives, aspirations and goals, which might be formalised into retrofit goals (Després, 1991). In order to be able to conceptualise this tension and remain true to the concept of affordance, the imaginative realm is theorised explicitly in the conceptual framework of home-meanings as a separate dimension.

Time

One's relations to the elements that constitute home are established not only across the sequences of space, but also along the sequences of time (Westman, 1995, p. 74). Many studies focus on the current time period. However, when talking about home, an individual might refer to the place where one was born and raised, or the place where one had happily lived, for instance, before a tragic event (Coolen and Meesters, 2012). An individual might also focus on the future when describing home. This could happen when the individual does not consider the current place of occupation as home, for instance, because of domestic violence. Then the individual is likely to speak about the desire to have home for himself/ herself one day (ibid.). The temporal dimension of home can also be seen through seasonal and cyclical evens, such as holiday celebrations or times of the season, which contribute to the formation of what home means to a particular individual (Saile, 1985 and Seamon, 1985 as referenced by Després, 1991: p. 102).

The notion of home is highly fluid and ever-changing, and is found in one's memories and nostalgia for the past, everyday life in the present, and future dreams and fears (Blunt, 2005; Blunt and Dowling, 2006). A focus on the relation between individuals and home places, as dynamic, ongoing and evolving, allows to conceptualise why and how home could mean different things at different times during one's life course (Smaldone, 2005). For these reasons, the temporal dimension is conceptualised explicitly in the home-meanings framework.

Context

It is generally recognised that the relationships associated with the notion of home should be established in varying cultural, political and historical contexts (Mallett, 2004). The notion of home is a social construct, the ideas of which are intertwined with the ideas of community, group identity and collective memory (Easthope, 2004). Some scales of home, such as the notion of homeland, is "almost always a social construction rather than a real memory" (Hobsbawm, 1993: p. 63). Home-meanings vary across different cultures and societies. The UK is representative of Anglo-Saxon culture that emphasises the household autonomy, which is represented by a physical ideal of a detached house and a legal ideal of home-ownership (Saunders and Williams, 1988). This undoubtedly has implications on UK homeowners' retrofit goals and aspirations. To highlight the importance of various contexts on the formation of individual retrofit intentions, the dimension of various contexts is conceptualised explicitly in the home-meanings framework.

This section developed a conceptual framework of home-meanings and distinguished between five different dimensions associated with a notion of home: (i) three elements of home environment, including its physical and spatial elements, self and social elements, financial and legal elements; (ii) two types of affordances home environment can offer to an individual, including behavioural and social-psychological affordances; (iii) a differentiation between real and imaginative realms; (iv) a temporal dimension; and (v) various social, economic, political and cultural contexts. The framework is assembled to bring insights into the context of retrofit decisions. The next section reiterates the gap in knowledge, outlined in the literature.

2.6. GAP IN KNOWLEDGE ON LOW-CARBON HOME RETROFIT DECISIONS AMONG UK HOMEOWNERS

Many studies have looked separately on energy retrofit motivations, decision processes, physical characteristics of low-carbon retrofits, and sustainable everyday practices. However, to date, the combined links between these components have not been directly studied in the literature. The following gap in knowledge is identified with the help of literature review:

> *There is a lack of understanding of the combined links between retrofit motivations, decision processes, post-retrofit energy consumption, as well as the influences of individual retrofit journeys on the population.*

This thesis proposes a combination of three theoretical lenses to guide the inquiry (Figure 2.10). First, the process view of *retrofit-decision process* is conceptualised in line with Rogers' innovation diffusion theory (2003). *Stages* specific to retrofit-decision process are used rather than five generic stages presented by Rogers. Second, a framework of *home-meanings* is developed to bring insights in the context of retrofit decisions. Finally, patterns and regularities revealed through analysis by first two frameworks, are noted in line with the notion of implementation difficulties. Further frameworks can be suggested to bring further insights into depicted regularities.

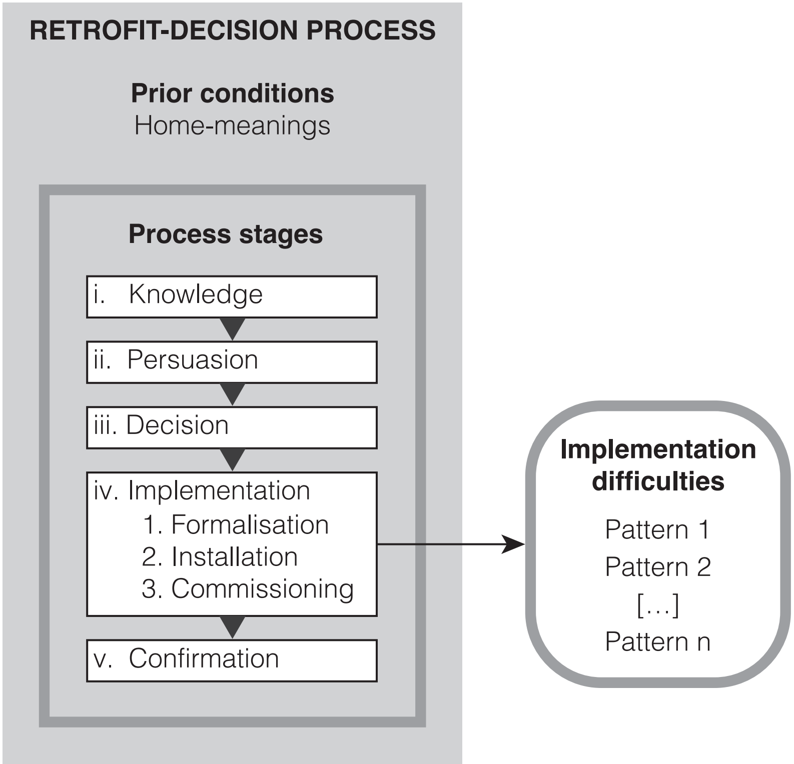

Figure 2.10. The theoretical framework used in the thesis

2.7. SUMMARY OF EVIDENCE FROM THE LITERATURE

This chapter reviews the literature, which investigates how and to what extent homeowners can be influenced to retrofit their homes to low-carbon standards. The phrase ‘low-carbon retrofit’ is used in this thesis to describe retrofit activities that resulted in at least 60% carbon reductions compared with pre-retrofit emissions. This definition is in line with the definition developed by the SuperHomes network, which is used as a source of data collection in the thesis. The chapter highlights the potential of owner-occupied housing stock to reduce operational energy use and associated carbon emissions. It subsequently draws attention to a low rate of sustainability-related retrofit, despite the availability of economically and technically effective solutions.

The chapter outlines a perception, predominant in governmental policy, that energy efficiency in building is straightforward and requires minimal investment. Subsequently, the chapter emphasises an overly narrow, technical-economic focus of such perception, and lists diverse psychological, social, contextual and other influences on low-carbon retrofit, identified in the literature. Such influences are usually analysed within a variance perspective, which frames them in terms of drivers and barriers to retrofit. The chapter critiques this approach to understand retrofit decisions and argues for a process perspective. It subsequently reviews the evidence from the process research perspective by synthesising current qualitative research on the topic. The synthesis makes it evident that the following three aspects, critical to reduction in energy consumption, should be understood as processes rather than influences, as they are formed and strengthened over time: (i) the process of aligning retrofit goals of different actors, (ii) the creation process of an overarching vision for retrofit that aligns several aims, including environmental ones; (iii) and the process of change in everyday domestic practices to accommodate lower resource consumption.

This thesis argues for a contextually embedded socio-technical systems approach to bring insights in homeowner retrofit decisions that result in low-carbon settings. The thesis proposes a combination of three theoretical lenses to guide the inquiry. First, the process view on retrofit decisions is conceptualised in line with Rogers' innovation diffusion theory (2003). Stages specific to retrofit decisions are used, which includes five generic stages presented by Rogers (2003) as well as three phases of the implementation stage presented by Owen and Mitchell (2015).

Second, a framework of home-meanings is developed around a notion of *affordance* to bring insights in the context of retrofit decisions. The notion of affordance provides a reconceptualization of the notion of meaning, in which meanings (affordances) are understood as real entities that do not exist in the mind of the perceiver only, but at the same time are not just the properties of the environment itself. This makes it possible to study them objectively. The conceptual framework of home-meanings, developed in this chapter, distinguishes between five different dimensions associated with a notion of home: (i) three elements of home environment, including its physical and spatial elements, self and social elements, financial and legal elements; (ii) two types of affordances home environment can offer to an individual, including behavioural and social-psychological affordances; (iii) a differentiation between real and imaginative realms; (iv) a temporal dimension; and (v) various social, economic, political and cultural contexts.

Finally, patterns and regularities revealed through analysis by the first two frameworks, are noted in line with the notion of implementation difficulties. The study methodology is laid out in the following chapter.

Chapter 3

Research methodology

This chapter outlines the methodological strategy adopted to address the gap in knowledge identified through the literature review in *Chapter 2*. Section 3.1 outlines the objectives this thesis addresses. Section 3.2 discusses the epistemological position adopted for the research and implications of this position for the line of inquiry. Section 3.3 presents the rationale for a combination of multiple-case study design with simulation modelling. Following this, section 3.4 details the data collection methods, which include in-depth semi-structured interviews with open and closed type questions, associative experiments and visual mapping of the eight retrofit cases used in the thesis. Section 3.5 provides details on data analysis methods. Data is analysed in two sequential steps. In the first step, case study analysis is carried out to develop insights into the retrofit context and process and reveal patterns of interest for further exploration. The theoretical framework for the analysis includes a combination between the home-meanings framework, developed in *Chapter 2* for the thesis, and retrofit-decision stages, based on Rogers' innovation diffusion theory. As a result of the case study analysis, a behavioural pattern of interest is revealed — the variation in development of retrofit-associated fatigue in the cases. In the second step, data analysis investigates further the patterns of interest revealed in the first step. A system dynamics simulation model of Hockey's motivation control theory of fatigue is developed to investigate these patterns further. Section 3.6 discusses the credibility strategies employed in the thesis, which includes concerns about validity and reliability. The chapter concludes with a summary in section 3.7.

CHAPTER CONTENTS

3.1. RESEARCH AIM AND OBJECTIVES

The literature review suggested that policies, aimed at encouraging low-carbon home retrofit among UK homeowners, can benefit from adopting a complementary approach to conceptualise retrofit decisions, through which they are understood as contextually embedded processes that unfold and strengthen over time. There is little understanding in the current literature of what are the stages in retrofit decisions, what are the feedbacks between different stages of individual retrofit-decision processes, how influences at different decisions stages and feedbacks between the stages affect the overall transition to a low-carbon housing stock, and how such understanding could be used to facilitate the uptake of low-carbon measures and technologies among UK homeowners. Motivated by the gap in knowledge outlined in *Chapter 2*, the thesis aims to improve the understanding of individual low-carbon retrofit decision journeys and explore the implications on the uptake of low-carbon measures and technologies on a population level. The thesis aims to address the following general research question (as outlined earlier in *Chapter 1*):

How can the individual retrofit decisions of UK homeowners be influenced to accelerate the rate of low-carbon retrofit in the population?

More specifically, the research addresses the following objectives through the analysis of multiple case studies:

Objective 1. Understand how home-meanings can be used to promote low-carbon home retrofit.

Objective 2. Capture the dynamics of individual retrofit-decision journeys that result in low-carbon operational energy use, and explore their implications for the transition to a low-carbon housing stock.

Objective 3. Identify patterns and regularities in retrofit implementation difficulties, captured when addressing objective 2, and explore ways to minimise them. Develop a simulation model for some of the regularities and explore different scenarios via simulation. Consider the implications for the transition to a low-carbon housing stock.

It is theorised in this study that different decision stages exist in the retrofit process and that these stages can be captured through an appropriate research design. This thesis studies how homeowner decisions can potentially be influenced and shaped by the direct and indirect influence of others, whether it is other homeowners or policy-makers. The next section outlines the epistemological and philosophical position the researcher took to inquire and for the development of knowledge about this aspect of reality.

3.2. COMMITMENT TO PRAGMATISM

It is necessary to consider at a fundamental level how the researcher understands the process of manufacturing the knowledge, before attending to the practical features of the research design. This is important to carry out the work with integrity, i.e. with soundness and consistency among values, beliefs and methodological strategies (Daly, 2007). Thus, the statement of one's epistemological position is important for others to be able to evaluate and critique the work.

The main research question, outlined in the section 3.1, is addressed from the perspective of homeowners and the mental models they hold about the retrofit adoption process. The retrofit-decision journeys of individual homeowners are understood to be subjective and independent. However, it is believed that there is a socially constructed common pattern of shared meanings of the reality, which could be captured through an appropriate research design. The captured pattern represents an objective reality. These beliefs form a basis to adopt an objectivist epistemology (Daly, 2007).

The notion of a scientific *paradigm* has been popularised by the historian and the philosopher of science Thomas Kuhn in his landmark work *The Structure of Scientific Revolutions* (1962). A paradigm is what the members of scientific community share, including their beliefs, which questions should be studied and what are the appropriate procedures to answer these questions. Kuhn highlights the incommensurability of competing paradigms. He explains that the proponents of different paradigms do research in different worlds, with different beliefs on what science is, and on what appropriate and legitimate scientific procedures are. For this reason, it is impossible to create a one-to-one correspondence between the ideas in two different paradigms. Even though such comparisons often feature in textbooks, such as in the *Handbook on Qualitative Research* (Guba and Lincoln, 1994), the authors themselves admit that such summaries are "apt as broad brush strokes" (ibid.: p. 117) and do not closely describe what a specific paradigm truly is. For this reason, it is decided in this thesis not to make a simplified, and inevitably incorrect, overview of major paradigms, but to describe the chosen paradigmatic view only.

This study is placed within a philosophical tradition of *pragmatism*. American pragmatism arose between the mid-19th and mid-20th centuries and is attributed primarily to the writings of Charles Sanders Peirce, William James, John Dewey and George Herbert Mead (Bragg, 2005; Simpson, 2009). All of these philosophers in broad terms agreed that what was true was what was the most useful (Bragg, 2005). However, they gave slightly different views of what that meant on whether there is one truth, or whether we would have to accept the plurality of truth (ibid.). This thesis follows the views outlined by C.S. Peirce, who believed that there is one truth, upon which everybody will converge at the end after a process of inquiry.

Peirce gave careful consideration on the role of scientific knowledge in general, and abstract constructs in particular. His position was that cognitive concepts and scientific knowledge should be evaluated in terms of the sensible or tangible outcomes of their use, thus, abstract knowledge that has no tangible outcome of use is considered meaningless (Peirce, 1903b). Pragmatism as a method relates meaning to consequences. The Maxim of Pragmatism, stated by Peirce, is as follows:

> Consider what effects that might conceivably have practical bearings we conceive the object of our conception to have: then, our conception of those effects is the whole of our conceptions of the object. (Peirce, 1903a: p. 135)

The meaning of a concept consists of how it might cause a person to act, in which the description of 'how' refers to one or another aim of the action (Peirce, 1903b). Thus, Peirce makes explicit a recognition between rational cognition and rational purpose (Peirce, 1905). Peirce argued that the only method to assert the meaning of concepts is an experimental one, and the only way to attain general knowledge of experiential truth is by inductive testing of theories (Peirce, 1907). Peirce understands the process of attaining knowledge to be iterative and in a state of a near approach towards provisional results, as absolute finality of the results can never be reached (ibid.). This position makes a sharp distinction between pragmatism and positivism, another philosophical tradition that views cognitive concepts and scientific endeavour in terms of the tangible outcomes of their use (Gruender, 1982).

The philosophy of pragmatism helps to cultivate a quality of mind that is focused on science that is relevant to, and informed by, human experience and practice. Pragmatism is empirical from start to finish. In line with paradigm beliefs of pragmatism, an explicit attempt is made throughout the thesis to make sure that the research is informed by and, is relevant to, human experience and practice. The methodological implications of pragmatism for this thesis are most visible in the approach taken to understand the concept of "meaning" for the development of the home-meaning framework. The framework is developed around the well-established concept of *affordance* (Gibson, 1979). The notion of 'affordance', which is discussed in detail in *Chapter 2 section 2.5*, is a way to comprehend the concept of 'meaning', that preserves a close link to human experience and practice. This strategy makes sure that the research stays true to the paradigmatic beliefs of the philosophical tradition of pragmatism. The next section outlines the rationale of the research design employed in the thesis.

3.3. RESEARCH DESIGN: MULTIPLE-CASE STUDIES AND SYSTEM DYNAMICS

3.3a. The process of scientific inquiry

Scientific inference describes the logical steps in reasoning to move from premises to consequences. Charles Sanders Peirce, a mathematician, logician and philosopher, distinguishes three types of inferences: deduction, induction and abduction (Peirce, 1903c). Peirce uses the words *hypothesis* (Peirce, 1878), *abduction* (Peirce, 1903c) and *retroduction* (Peirce, 1898) through different periods of his life to describe the same type of inference. The term *abduction* is currently widely used in academic literature to refer to this type of inference, and for this reason it is used in this thesis.

Deductive reasoning shows that a conclusion must be true as long as the premises are true, i.e. it applies a general rule to particular case and states the results. The beauty of deductive reasoning is that it is the only form of inference that guarantees its conclusions to be true. *Inductive* reasoning works in terms of probabilities rather than certainties and shows that a conclusion is probably true, if the premises are also true. It is an inference of a general rule from specific case and observed results. Induction assumes that characteristics, that are true to a number of cases taken at random, are true to the whole population these cases are coming from. Peirce calls it "statistical argument" (Peirce, 1868: p. 33), as arguments derived by inductive reasoning are based on solid empirical evidence and in the long run must generally afford correct conclusions from true premises. However, conclusions derived with inductive reasoning could easily be sound, consistent, but at the same time wrong.

Abductive reasoning, similarly to inductive reasoning, also works in terms of probabilities. Abduction explains a curious observation by the supposition that this observation is a case of a certain general rule, and thereupon it is logical to adopt this supposition. Abductive reasoning provides inference to the best explanation. It should be noted though that a conclusion derived by abductive reasoning is not a proof, but just a proposed explanation and should be supported by evidence, as an explanation derived by abductive reasoning could be built based on very few facts. However, it is plausible that a newly derived explanation with little empirical support is a better fit to describe a phenomenon than an old explanation, despite there being much empirical evidence to support it. A full cycle of scientific reasoning is pictured in Figure 3.1.

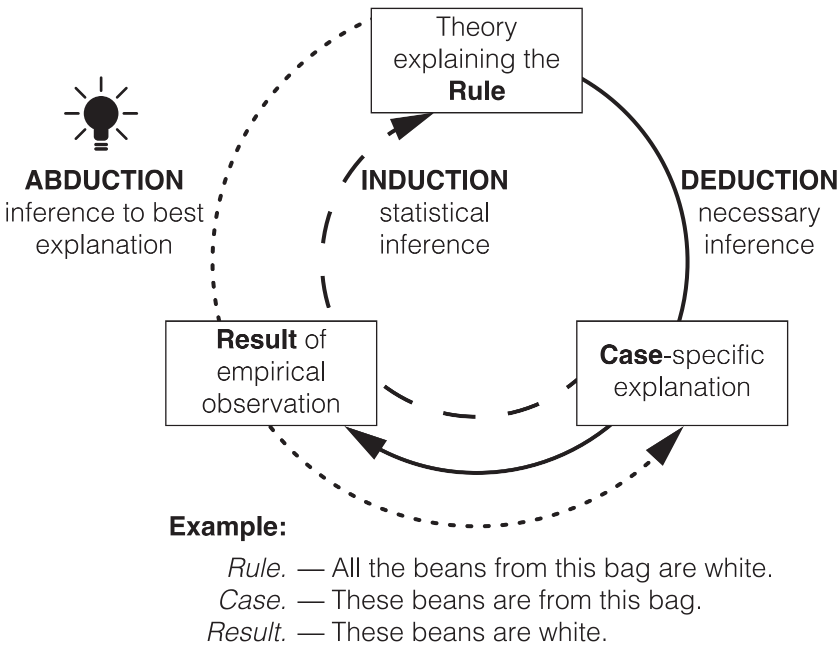

Figure 3.1. A cycle of scientific reasoning (based on Peirce, 1878: p. 188)

Abduction is the first step of scientific reasoning, it starts from the facts without having any particular theory in view, motivated purely by the feeling that a theory is needed to explain the surprising facts (Peirce, 1901). This step of inference culminates in the adoption of a hypothesis as being suggested by the facts. A hypothesis adopted by abduction can only be adopted on probation, as abduction is, after all, nothing but guessing in a process of disciplined imagination. Thus, the hypothesis must be tested. To do so one must trace its necessary and probable consequences through deductive reasoning. The concluding step of scientific inference is induction, during which empirical evidence is collected and experiments are carried out. The results are subsequently compared with predictions done by deductive reasoning. If the observations do not match with predictions, the hypothesis should be discarded and a new cycle of inference should commence. However, if empirical evidence supports the hypothesis a newly developed theory can be solidified through deductive-inductive cycle, during which the hypothesis is only slightly modified in a way that was already presumed to be possible.

3.3b. The use of an existing theoretical framework to guide the inquiry

A researcher needs to decide how much a study should be structured prior to data collection. There are some trade-offs between *tight* and *loose* designs (Miles et al., 2014). Loosely structured abductive research is particularly well suited to address 'how' and 'why' questions in unexplored research areas (Eisenhardt and Graebner, 2007). The looser the initial theoretical framework is, the more a researcher is receptive to the context of the study and local idiosyncrasies. However, the information load can be colossal, as a less selective data process means that everything looks important at the outset of the study. An experienced researcher, who explores an unfamiliar phenomenon with a highly loose designed study, might generate rich insights. However, this approach is not recommended to a novice researcher, who might only "yield a few banalities" after months of research (ibid.: p. 19). Tightly coordinated designs generate more economical and potentially generalisable findings. However, they can be less sensitive to the local context and may even entail "bending data out of contextual shape to answer a cross-case analytical question" (ibid.: p. 20).

The trade-off between tight and loose research designs touches upon the problems of *accuracy* and *generality* of theoretical findings (Langley, 1999). The degree of *accuracy* describes how closely theories follow the original data. The degree of *generality* refers to the potential range of situations to which a newly developed theory is applicable. Both qualities are desirable, but there is a trade-off between them. A newly developed theory via abductive reasoning needs to be well grounded in empirical data to strengthen its internal validity. However, a researcher should strive to generalise beyond the data as well to build insights that can be used in another context (Mintzberg, 2005).

The literature review carried out in *Chapter 2* demonstrated that the temporal aspect of retrofit decisions is still poorly understood in current research and theoretical tradition. Thus, a loose design is needed to build a rich description on 'how' and 'why' homeowners make decisions that result in low-carbon retrofit. Such explanation should be close to the original data to strengthen its internal validity. The thesis aims to develop both accurate and generalisable insights. A multiple-case study design is used to build both accuracy though in-depth description of the phenomenon, and generalisability of the results through cross-case comparison. Simulation modelling is used to strengthen the internal validity of the explanation, and ensure its accuracy. Sequential design for data collection and analysis between qualitative research and computational modelling helps to increase generalisability of the findings. Both strategies are described in the rest of the section.

3.3c. Multiple-case study design

Case studies are rich, empirical descriptions of a particular phenomenon or an instance of a phenomenon (Yin, 2018). A thorough analysis of a single-case study provides an opportunity to capture its uniqueness. However, it is difficult to separate generalisations found in a single case from idiosyncrasies associated with it. A multiple-case study design allows a clearer pattern recognition among cases, which is needed to make theoretical generalisations. Multiple-case study design has been criticised for sacrificing rich context and good story-telling in favour of generating clear theoretical constructs (Dyer and Wilkins, 1991). However, Eisenhardt (1991) highlighted that the dichotomy between good stories and good constructs is a false one. Rather the trade-off arises from the page limits in academic journals. Thus, one could have both: good stories and good constructs, when writing with less strict page limitations, for instance for a book or a thesis.

This thesis uses a holistic multiple-case study design (Yin, 2018), and considers each household's retrofit journey as a case. The unit of analysis is the stages in a household's retrofit journey (Figure 3.2), which allows a comparison of different decision stages for an individual household (within-case pattern recognition) and a comparison of decision stages between different households (cross-case comparison).

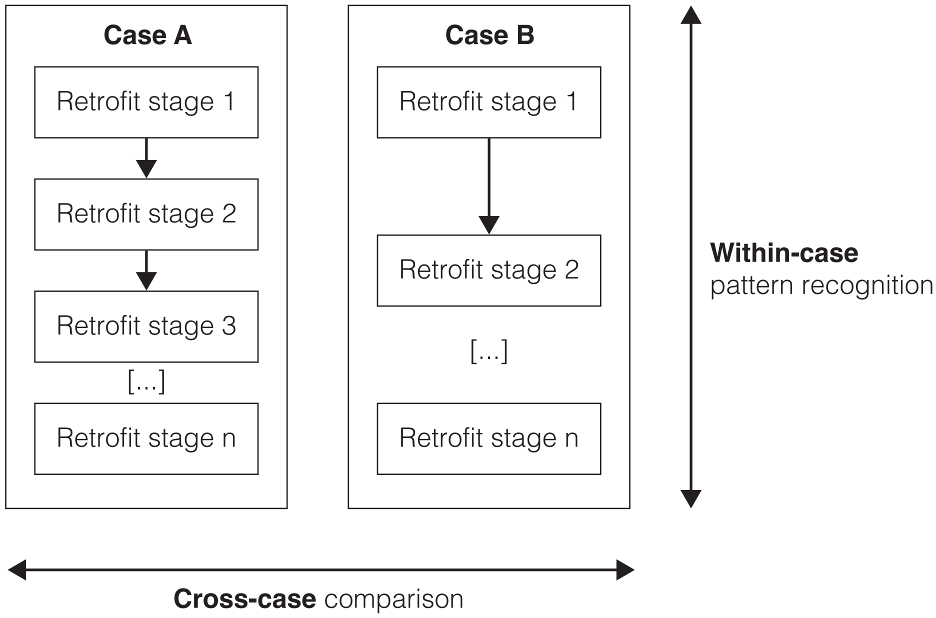

Figure 3.2. Holistic multiple-case study design

Multiple-case study design is time intensive, as the complexity increases with the number of cases. How many are needed to generate fruitful insights regarding the phenomenon depends upon how much is known about the phenomenon already, and how much information is likely to be learned from additional cases (Eisenhardt, 1991). A single case study might yield rich insights for the research in the early stages of the field development. And on the contrary, even 30 case studies might shed light only on a few banalities in a well-established field. Miles, Huberman and Saldaña (2014: p. 34) and Eisenhardt (1989: p. 545) suggest a range of 4 to 10 cases to generate enough complexity for theory development, while at the same time keeping the volume of the data manageable. This thesis analyses eight case studies.

3.3d. Sequential design: multiple-case study research and simulation modelling

A simulation model is a computer model that aims to mimic the 'real world' system, so its behaviour can be studied (Davis et al., 2007; Sterman, 1991). Simulation models offer improvements over verbal models in several aspects. First, the strength of simulation research is construct validity — an accurate specification and documentation of the constructs (Davis et al., 2007). Second, an important strength of simulation research is the internal validity of a developed explanation (ibid.). Simulation model presentation involves the precise specification of the relationships between constructs, its underlying theoretical logic, and clear boundary conditions. The process of simulation model development sharpens loose theoretical arguments that are common place in verbal theories. The developed theoretical explanation is more likely to exhibit strong internal validity. The sharp specification of a simulation model in the form of written documentation makes the logic of the explanation open for all to review (Sterman, 1991). Third, simulation models are able to interrelate many factors simultaneously, and reveal the outcomes of the interactions among multiple complex processes (ibid.). Simulation models are particularly useful when the theoretical focus is processual, longitudinal and nonlinear (Davis et al., 2007). Fourth, simulation models compute reliably the logical consequences of the modeler's assumptions, which often allows the modeler to see inconsistencies in the underlying theoretical explanation (Sterman, 1991).

This thesis conceptualises homeowner retrofit decisions as contextually embedded processes that unfold and strengthen over time. The mechanism for the transition between different stages of the process is understood to be complex with nonlinear relations. For all the reasons that outline the strength of simulation models, it is decided in this thesis to direct the development of a theoretical explanation of retrofit decisions towards a formal simulation model. However, it is not clear from the literature review what is worth formalising into a simulation model, and further clarification of the focus of the study is required. Sometimes research focus can be sharpened by intriguing observations from case study research (Davis et al., 2007). For this reason, it has been decided that this work follow a sequential design for data collection and analysis in two phases (Table 3.1). Case-study analysis was carried out in the first phase of the research. The theoretical framework developed in Chapter 2, that combines the framework of home-meanings and stages of retrofit-decision process based on Rogers' innovation diffusion theory, was used to develop insights into the phenomenon. The results of the analysis suggested a behavioural pattern of interest — different modes of development of psychological fatigue in the cases. This insight was carried into the second phase, during which a simulation model was developed to bring further insights into the pattern of interest. Hockey's motivation control theory of fatigue was identified as a suitable theoretical lens to understand the trade-offs between the work pace, fatigue and goal achievement. Further data was collected from the same interviewees to inform model development.

This thesis collects different types of data for the reason of complementarity, as different types of data produce different types of knowledge (Small, 2011). For instance, interviews are well suited to understand the sequence of events, whereas continuous associations are better suited to reveal associative structures of a single individual. Table 3.1 lists various types of data, data collection methods and data analysis methods used in this thesis. This thesis uses (i) five different types of data: continuous associations, interview transcripts, answers to close-ended questions, retrofit process maps and behaviour-over-time graphs; (ii) three data collection methods: associative experiments, in-depth semi-structured interviews and visual mapping; and (iii) two data analysis methods: case study analysis and system dynamics simulation modelling. Data collection methods are further detailed in section 3.5, and data analysis methods are further detailed in section 3.6.

Table 3.1. Sequential design for data analysis

Types of data	Data collection	Data analysis	Chapter №
Continuous associations	Associative experiments	*Phase 1*. Case study analysis	5
Interview transcripts	In-depth semi-structured interviews		
Answers to close-ended questions			
Retrofit process maps	Visual mapping	*Phase 2*. System dynamics modelling	6
Behaviour-over-time graphs			

The thesis follows a sequential three-step approach to build a simulation model. First, process research guides a multiple-case study design with qualitative data collection and analysis. Retrofit-decision stages, based on Rogers innovation diffusion theory (2003) and extended with three phases of the *implementation* stage outlined by Owen and Mitchell (2014), are used for data analysis. Data analysis reveals a behavioural pattern of interest from the case studies: a variation in the development of retrofit-associated psychological fatigue. Second, Hockey's generic theory of psychological fatigue is identified as a suitable lens to bring further insights in the phenomenon. The theory is transferred into a system dynamics model. Third, further data from the same interviewees are collected, and the simulation model is parametrised to each case. Scenarios are explored via model simulation to bring further insights into how to minimise retrofit-associated psychological fatigue.

A sequential mixed-method design for data collection helped to discover a new phenomenon (development or non-development of retrofit associated fatigue) and understand the mechanisms behind it. The combination of different methods for data collection and analysis makes it possible to go through a full cycle of scientific inquiry: inductive reasoning is used to build a theoretical explanation via multiple-case study design and thematic analysis; abductive reasoning is used to suggest Hockey's theory of psychological fatigue as a theoretical lens suitable to bring insights into the phenomenon; system dynamics computer simulation methodology is used to suggest the necessary and probable consequences via deductive reasoning and to test the suggestions via inductive reasoning.

3.3e. Sampling strategy

This thesis aims to develop reach theoretical insights into the phenomenon of interest, thus, random selection of cases "is neither necessary, nor even preferable" (Eisenhardt, 1989: p. 537). The study focuses on UK homeowners who retrofitted their houses to low-carbon standards. The cases are selected from the SuperHomes network, which is a voluntary UK network of homeowners comprised of about 200 members, who achieved at least 60% carbon reductions as a result of the retrofit activities (National Energy Foundation, 2015; SuperHomes, 2011). Carbon reductions are assessed by a representative of a SuperHomes network either on-site or remotely. Thus, the interviewees have a *narrative capability* to tell the story that enables the representation of the phenomenon of low-carbon retrofit (Daly, 2007).

Cases were selected with a convenience purposeful sampling strategy (Creswell, 1998: p. 127). A purposeful sampling strategy makes a deliberate attempt to include a range of cases that are likely to be information-rich, which is done for the most effective use of limited resources. A SuperHomes representative was approached by the researcher, who then contacted the potential participants on the researcher's behalf. Initially, ten contacts were provided, seven of which fit the selection criteria. These seven cases (B–H) together with the case A formed the thesis sample of eight cases. It should be noted that the case A in the thesis sample does not fit the selection criteria, as the homeowner rented the property out after the retrofit and does not live herself in the property. Moreover, the owner is a professional architect, and the job was carried out as part of the workload of her studio. The case was included in the thesis sample to compare and contrast the findings from her journey to the journeys of other homeowners in the sample.

The analysis of the results revealed that the choice of the work pace was crucial for several important dynamics in the cases. However, it was only possible to sample one case study which adopted an emergent retrofit strategy over time (case H). The researcher approached the SuperHomes representative again a year later to see if it is possible to find more participants who retrofitted their homes over time. However, the researcher was advised that SuperHomes network is not being funded any longer and it is no longer possible to help with the research project and arrange more interviews (Mallett, 2018). Nevertheless, the sampling strategy allows the capturing of a diverse range of experiences. It should be noted, however, that the sample is not representative, neither of the SuperHomes population nor of the UK homeowner population as this is not the aim of the sampling strategy. A comparison of time profiles of retrofits and energy-related building performance goals before the retrofit between the thesis sample and the SuperHomes owner population can be found in *Appendix CA. Sample/ population comparison*.

This section explained the rationale of the research design employed in the thesis: sequential approach for multiple-case studies design with system dynamics simulation modelling. The section also justified the choice for a convenience purposeful sampling strategy. The next section describes data collection methods employed in this thesis.

3.4. DATA COLLECTION

The thesis employs three methods for data collection: (i) in-depth semi-structured interviews; (ii) associative experiments and (iii) visual mapping. The rest of the section looks into these methods in more detail. The study has been approved by the Bartlett Ethics Committee. Details on data protection, risk assessment and ethics approval can be found in *Appendix BA. Ethics approval confirmation*.

3.4a. In-depth semi-structured interviews with open and closed type questions

Interviews is the most straightforward way to generate data on lived experience (Daly, 2007). For this reason, semi-structured interviews with the homeowners is the main method for empirical data collection in this thesis. The semi-structured style of interviews allows to maintain the interview focus on the research questions, and ensure a coherent process of data collection and analysis (Daly, 2007). At the same time, the flexibility of semi-structured interviews allows interviewees enough freedom to talk about their lived experience. As a result, new theoretical concepts and relations can emerge from the data through analysis.

15 interviews were carried out for the thesis for eight case studies during two rounds

of interviews with a difference of about a year between the first and a second interview (Table 3.2). It was only possible to have a second round of interviews for seven out of eight cases. An interview was usually carried out with one of the owners, normally the one who was more involved in the retrofit project. In case H both owners participated in the interviews. The interviews lasted between 50 and 90 minutes and took place at interviewees' homes. Interviews incorporated a walk-through procedure, which is spatial-visual technique that allows to evoke interviewee's memories about the retrofit experience (Lowe et al., 2017). Photographs of different aspects of the retrofit were taken, which allowed visual information to be retained for future analysis.

Table 3.2. Characteristics of the interviewees

Case	Interviewee	The role of the owners in the project	Interviews 1st	Interviews 2nd
A	One of the two owners	One of the owners is an architect, who led the project. The role of the second owner in the retrofit is unknown.	✓	✓
B	One of the two owners	DIY project done by the interviewed owner. The second owner had minimum involvement in the retrofit.	✓	✓
C	One of the two owners	DIY project led by the interviewed owner. The second owner was actively involved in the retrofit.	✓	✓
D	The only owner	The owner led the project by coordinating different tradespeople.	✓	✓
E	One of the two owners	The interviewed owner quit her job to supervise construction and led the project by managing a professional builder. The second owner was also involved in the project.	✓	✓
F	One of the two owners	DIY project done by the interviewed owner together with a builder friend. The second owner had minimal involvement in the retrofit.	✓	✗
G	One of the two owners	The interviewed owner became a Passivhaus certifier during the retrofit. Both owners were actively involved in the project, being involved in both DIY work and managing builders.	✓	✓
H	Both owners	Both owners were involved in the project, which was carried out by different builders and tradespeople.	✓	✓

Interviewees volunteered their participation. They were notified in advance of the upcoming visit of the researcher, which was carried out at the time and day of their convenience. All interviewees were given an information sheet with written information about the project and contact details (see *Appendix BB. Information sheet*). In line with ethics protocol, all interviewees signed an informed consent declaration, which ensured that the participants understood their right to withdraw from the study at any time without consequences (see *Appendix BC. Informed consent form*).

Interviews had a pre-structured element with the interview guides developed ahead of the interviews (see *Appendix BD. Interview guides*). The approach ensured that the same questions are asked to all interviewees using prompts, which afforded a convergence of topics across the cases. Besides the briefing and the closing sections, both round of interviews included three topics (Table 3.3).

During the first round of interviews, information was collected on general household characteristics, dwelling characteristics prior and post retrofit, and the retrofit process itself. Sustainability related measures are more likely to be considered as part of a broader retrofit project which includes amenity-based improvements, rather than being conducted separately (Wilson et al., 2013a). In order to contextualise the rationale behind the choice of sustainability related measures, they should be considered together with the rationale for non-sustainability related ones. The homeowners were asked about the works they carried out on their dwellings irrespective of whether these works were sustainability-related or not. The owners were asked why they made their choices and what they planned to achieve. The interviewees were asked about the rationale behind their retrofit actions and were prompted to elaborate on their answers for the researcher to get a more comprehensive picture of their intensions. The owners were also asked to identify stages in their retrofit decisions, if possible, as well as drivers and barriers of each of identified stage. They were also asked to reflect on their pre- and post-retrofit living experiences and how these were shaped and changed as the result of the retrofit activities.

During the second round of interviews, feedback was gained on the preliminary results; information was collected on the retrofit-related fatigue experience, if there was any; and associative experiments were carried out. Data needed to parameterise the system dynamics model was also collected at this stage, which included both open-ended questions and closed-ended questions with a 7-point Likert scale. All interviews were digitally recorded and transcribed verbatim for analysis. An exemplary excerpt from an interview transcript can be found in *Appendix CC. Example of an interview transcript.*

Table 3.3. Question topics for semi-structured interviews with homeowners

#	Topic	Sub-topic	Purpose of the topic
	1st round of interviews		
1	General household information	▪ Contact information ▪ Household characteristics	▪ Depict changes in the household characterises in the period of retrofit activities. ▪ Establish preferred contact method.
2	Retrofit process. Sit-down session	▪ Retrofit goals ▪ Dwelling characteristics before the retrofit ▪ Dwelling characteristics after the retrofit ▪ Timing of the retrofit process ▪ Stages in retrofit-related decisions ▪ Post-retrofit living experience	▪ Get the information about the reasons for participants' intentions to live in low-carbon houses. ▪ Get information on house configuration, structure type, internal and external conditions prior and post retrofit. ▪ Get a chronological order of the retrofit process. ▪ Identify stages in retrofit decisions. ▪ Get information about lived-in experienced, associated with low-carbon dwellings.
3	Retrofit experience. Walk-through	▪ Retrofit-related stories	▪ A prompt for the participants to recall more memories regarding the retrofit as they see the measures.
	2nd round of interviews		
1	Confirmation of preliminary results	Present an interviewee with the diagrams on: ▪ Retrofit timeline ▪ Stages of retrofit-decision process ▪ A causal map of retrofit activities	▪ Get feedback from the participants on how well the researcher understood their experience. ▪ Increase the external validity of the derived explanation.
2	Retrofit-related fatigue experience	Gather information on: ▪ Initial goals completion ▪ Goals erosion ▪ Perceived benefits of the retrofit ▪ The level of related knowledge prior retrofit ▪ The level of control over the activity ▪ The level of retrofit-related feeling of fatigue	▪ Gather information on a household's experience of the retrofit process, necessary to explain why some homeowners developed retrofit-associated fatigue and consequently formed a negative impression of their retrofit experience, while others did not. ▪ Gather input parameters for system dynamics model.
3	Associative experiments	Continuous associations for words: ▪ Home ▪ Low-carbon home	▪ Gather information on similarities and difference between the idea of 'home' and 'low-carbon home' for the participants.

3.4b. Associative experiments

An *association task* is a data collection method, during which the participants are asked to produce responses in association with a specific word or phrase (Nelson et al., 2000). The task is considered finished when a participant decides that all associations are produced. The associative experiment method has been developed and used for more than a hundred years (Dallett, 1968). The initial theorisation can be seen in the works of Galton (1879) and Jung (1907). Regularities that can be found in word association data, such as order and meaning apparent in association responses, have been used to cast new light on the meanings of words (Dallett, 1968), to identify responders' knowledge in a specific area of studies (Verplanck, 1992), to make generalised statements regarding collective semantic understanding of particular cultural phenomena (Lazutkina, 2015) and others (Nelson et al., 2000).

Association responses are most commonly elicited by words (Dallett, 1968). Association procedures could be differentiated between (i) discrete association tasks, in which participants are asked to produce a definite number of responses for each cue; and (ii) continuous association tasks, in which participants are encouraged to produce as many responses as possible for each cue (Nelson et al., 2000). A standard discrete association task is based on a single response (ibid.). The distribution of such responses for a population of individuals is commonly used to reveal associative structures shared collectively that arise from similar individual experiences (ibid.). Such structures might, however, not be representative of an experience of a single individual. Continuous association tasks are better shaped to reveal the associative structures of a single individual.

As part of the data collection for this thesis the homeowners were asked to say as many words as possible in association with the word 'home' and the words 'low-carbon home'. This approach allowed to elicit most vivid associative structures specific for each homeowner. The associative experiments were introduced as part of the in-depth interviews. The data was subsequently analysed via multiple-case study approach. The coding themes were derived from the home-meaning framework developed in *Chapter 2*. Data analysis methods are discussed in section 3.5. The results of the analysis are presented in *Chapter 5*.

3.4c. Visual mapping

It was decided to also use graphical forms for data collection in this thesis to depict the retrofit process for individual cases. Interviewees were asked to draw retrofit timelines together with the researcher during the first interview. Graphical forms of data presentation have several advantages over narrative approaches (Langley, 1999). A large quantity of information can be presented in a condensed manner on a single graph, which lets the audience see all the relevant information at once and instantly assess the completeness of the information provided. It also provides a necessary break from sometimes monotonous interview experience. Retrofit timelines for each case can be found in the next chapter together with a short description of each case.

During the second interview, the homeowners were asked to draw behaviour-over-time graphs of their experience for certain variables related to the process of development of retrofit-associated fatigue. A behaviour-over-time graph is a simple graphical representation that focuses on the pattern of behaviour over time of a given variable. The construction of such graphs can lead to a rich discussion on why something is changing. An example of a graph drawn by one of the participants can be found in *Appendix BE. Example of a behaviour-over-time graph*.

This section described the three data collection methods used in the thesis: (i) in-depth semi-structured interviews; (ii) associative experiments and (iii) visual mapping. The next section describes the data analysis methods used.

3.5. DATA ANALYSIS

The thesis employs two methods of data analysis: (i) case-study analysis with thematic coding and (ii) system dynamics modelling. It should be noted that these methods are not mutually exclusive and are combined to address the objectives of the thesis.

The first of the three objectives in this thesis is to understand how home-meanings can be used to promote low-carbon retrofit. The second objective of the thesis is to capture the dynamics of individual retrofit-decision journeys that result in low-carbon operational energy use and explore the implication for the transition to a low-carbon housing stock. The analysis method employed to address these two objectives is a holistic multiple case study analysis, which includes (i) detailed reports of individual cases to gain familiarity with the cases, and thematic coding of interview transcripts; (ii) cross case comparison, which implies a comparison of the variables of interest across the cases, keeping in mind particularities and context of individual cases (Box 3.2).

Box 3.1. 1st and 2nd research objectives and methods used

Objective 1. Understand how home-meanings can be used to promote low-carbon home retrofit.

Objective 2. Capture the dynamics of individual retrofit-decision journeys that result in low-carbon operational energy use, and explore the implications for the transition to a low-carbon housing stock.

Step 1. Collect empirical data. 1st round.

a. Collect empirical data on retrofit goals, decision processes and post-retrofit living experiences via in-depth interviews.
b. Collect individual associative structures for the notions of 'home' and 'low-carbon home' via associative experiments.
c. Capture retrofit timelines in the process of visual mapping with the participants.

Step 2. Analyse empirical data.

a. Write case-by-case reports in the process of familiarisation with the case studies.
b. Carry out case-by-case analysis: use the themes derived both deductively from the theoretical framework adopted in the thesis and inductively with codes arising from the data.
c. Make cross-case comparisons to identify common themes associated low-carbon dwellings and associated retrofit processes.

Step 3. Further data collection and data analysis.

a. Conduct a second set of interviews to confirm preliminary findings.
b. Repeat the process of case-by-case and cross-case analysis.

Result. A demonstration of existence of stages in contextually-rich retrofit decisions. Articulation of how governmental policies can diversify their efforts, targeting households at different stages of the process.

The third objective of the thesis is to identify patterns and regularities, captured when addressing objective 2, and explore ways to minimise them. Retrofit-associated fatigue has been suggested as one of the implementation difficulties, as a result of the analysis carried out in *Chapter 5*. Thus, the third objective focuses on the development of a generic simulation model of retrofit-associated fatigue to explore how the development of fatigue can be neutralised. The analysis methods employed to address this objective are: (i) thematic coding of rich textual description of Hockey's motivation control theory of fatigue to build a causal structure of the theory, as well as to develop a formal simulation model; (ii) system dynamics model building and exploration of the theory (Box 3.2).

Box 3.2. 3rd research objective and methods used

Objective 3. Develop a generic simulation model of retrofit-associated fatigue. Explore via the simulation how the development of fatigue can be neutralised to ensure an overall positive experience of low-carbon retrofit by the homeowners.

Step 1. Justify the use of Hockey's motivation control theory of fatigue as a suitable theoretical lens for further analysis.

a. Identify a pattern of interest in retrofit-related implementation difficulties, revealed when addressing the 2nd objective. Suggest abductively a theoretical lens suitable to bring further insights into the phenomenon (a generic model of psychological fatigue is suggested).

b. Evaluate the use of Hockey's theory in favour of a widely accepted work-fatigue hypothesis.

Step 2. Develop a system dynamics model

a. Develop a causal structure of the model in the process of thematic coding of Hockey's article (1997) and book (2013).

b. Develop a formal computer simulation model.

c. Test and validate the model.

Step 3. Collect additional empirical data.

a. Collect additional empirical data tailored specifically to understand the process of fatigue development associated with retrofit via in-depth interviews with open-ended and close-ended questions and visual mapping by the participants of behaviour-over-time graphs of the variables of interest.

b. Parametrise the model to the case studies in the sample.

Step 4. Explore scenarios

a. Explore scenarios for step-by-step retrofit approach: (i) small breaks, equivalent to weekend breaks; (ii) big breaks, equivalent to annual breaks; (iii) a combination of small and big breaks.

b. Explore scenarios via computer simulation to identify the ones capable of neutralising fatigue development in the process of low-carbon retrofit.

Result. A demonstration of different retrofit approaches, as a result of which the development of retrofit-related fatigue is minimised. Articulation of how governmental policies can diversify their efforts to promote a step-by-step and DIY retrofit approaches.

3.5a. Case study analysis

Data analysis for case study research differentiates between *within-case* analysis and *cross-case* pattern recognition (Eisenhardt, 1989). *Within-case* analysis typically involves detailed case study descriptive reports, which help to gain familiarity with individual cases (ibid.). The goal for within-case analysis is to retain the integrity of the entire case, before proceeding to compare cross-case patterns (Yin, 2018). In this sense, the case-study approach contrasts with the data aggregation approach of variable type of research, which is intended to make conclusions about variables, but not necessarily about the cases (ibid.). The interview transcripts and corresponding photographs and timelines were sorted into cases and reviewed. A report was written for each case and included the household description, the state of the house before and after the retrofit and the retrofit process itself. Notes and memos taken during the interviews, as well as the interview reports were retained as the basis for further analysis. All eight case study reports can be found in *Appendix CB. Cases reports*.

Cross-case analysis obliges the researcher to look beyond idiosyncrasies of individual cases and see evidence across multiple cases (Eisenhardt, 1989). Two primary ways for textual data analysis are a narrative description and visual display methods (Miles et al., 2014). Visual display methods enable to see the data in fresh perspectives. In this thesis the visual display methods used are matrices, retrofit-decision process diagrams and causal loop diagrams. A *matrix* essentially represents a cross-tabulation of material in a condensed form. An example of an analytical matrix, used in the process of data analysis, can be found in *Appendix CD. Example of an analytical matrix*.

Cases were analysed with themes derived deductively from the theoretical framework used in the thesis. Retrofit-decision process diagrams were drawn for each of eight cases. A *process diagram* is essentially a visual representation of a particular process. The stages of the retrofit-decision process in this thesis are conceptualised in line with the stages of the innovation-decision process outlined by Rogers (2003). The detailed analysis of this conceptualisation is presented in *Chapter 5.* Retrofit-decision process diagrams for all eight cases can be found in *Appendix CF. Retrofit-decision process diagrams*.

The cases were analysed inductively to further uncover the variety of patterns arising from the data. Causal loop diagrams were used for visual display. A *causal loop diagram* (CLD) is a diagram that intends to aid to the visualisation of the causal interrelation of different variables (Sterman, 2000). The CLD convention used in this thesis is described later in subsection *3.5b. System dynamics modelling*. First, CLDs were created for each of the eight cases separately. Afterwards, a CLD was developed based on the common patterns across the cases. This consolidated CLD, which depicts the pattern across the cases, can be found in *Appendix CE. Example of an analytical causal diagram*.

Case reports, matrices, process and causal diagrams together with analytic text provide a systematic way to display the information and go through the iterative process of building a theoretical explanation from case studies (Eisenhardt, 1989).

Thematic analysis

Thematic coding is used in the thesis to make sense of textual information, including interview transcripts and theoretical frameworks, such as Hockey's motivation control theory of fatigue. Thematic coding formed a large part of the within-case and cross-case analysis. This section describes the process of thematic coding of interview data only; the same logic was applied for thematic analysis of theoretical frameworks. The method of thematic analysis is "essentially independent of theory and epistemology" (Braun and Clarke, 2006: p. 5), and, thus, can be adapted to specific research needs, which is done in the thesis.

All interview transcripts, as well as corresponding analytic notes, were transferred into NVivo 11, a computer-assisted qualitative data analysis software (CAQDAS) package. The researcher read all the transcripts before the coding process, in order to refresh the overall feeling of the interview. Data analysis begins with the process of coding. *Codes* are essentially labels that are attached to the excerpts of descriptive information (Miles et al., 2014). Coding can be divided into two major stages: first cycle of coding and second cycle of coding (ibid.). During the first cycle of coding, the codes are assigned to the data itself. This stage of analysis includes the immersion in the data through the process of fracturing it, and a repeated comparison and sorting of the codes. The codes are systematically compared and contrasted to identify similar notions that can be represented by the same code. In the second cycle of coding, the codes from the first cycle are grouped into categories and themes. The categories are compared and contrasted. In the process, some categories are reconfirmed, the existence of others is contested and new categories emerge.

Themes for coding can be derived inductively from the data or deductively from an existing theoretical framework. Both approaches were used in the process of case study analysis. There are various views on how extant literature should be used to inform the process of qualitative data analysis, if at all (Dunne, 2011). The disadvantages of using pre-existing theoretical frameworks in the process of data analysis are that: such frameworks impose theoretical constructs and assumptions that are not relevant to the study; force data into an existing framework;

or are unable to uncover evidence that contradict an existing framework. The advantages of using pre-existing theoretical frameworks are that: such frameworks provide theoretical sensitivity; help the researcher to become aware of existing methodological and conceptual pitfalls; and clarify the process of inquiry (Daly, 2007; Dunne, 2011). Some methodologies such as grounded theory (Strauss and Corbin, 1990) argue explicitly for a researcher to suspend all his/ her past knowledge and experience in order to allow for a deeper understanding of the phenomenon. However, it is argued that compete suspension of one's knowledge and beliefs is simply not possible (Daly, 2007). A researcher brings his/ her beliefs, understandings, and previous academic knowledge, into the data analysis process, regardless of whether such beliefs are stated or not.

In this thesis, carefully-chosen pre-existing theoretical frameworks are used to guide the process of data analysis. The choice is done sequentially. Stages of retrofit-decision process, based on Rogers' innovation diffusion theory, combined with home-meanings framework developed in *Chapter 2*, are used during the first phase of data analysis (see Table 3.1). Hockey's motivation control theory of fatigue is used during the second phase of the analysis.

3.5b. System dynamics modelling

System dynamics is a simulation method suitable for capturing dynamic changes over time by simulating the evolving behaviour of interrelated variables (Sterman, 2000). It has been used to understand a number of social processes including industrial dynamics (Forrester, 1961), urban dynamics (Forrester, 1969), limits to world population growth with finite resource supplies (Forrester, 1971), organizational dynamics (Sastry, 1997), and management dynamics (Repenning and Sterman, 2002).

In this thesis system dynamics modelling is used to address objective 3: develop a generic simulation model of retrofit-associated fatigue and explore via simulation how the development of fatigue can be neutralised. Insights regarding a step-by-step approach versus a single-step in-depth retrofit approach and associated patterns of fatigue development become clear only after the second objective of the thesis is addressed in *Chapter 5.* The rationale for choosing Hockey's motivation control theory of fatigue to address the third objective is presented in *Chapter 6*. The following paragraphs discuss why system dynamics is a suitable methodology to formalise and explore Hockey's theory, acknowledging that the reader may not be familiar with the theory. The reader is advised to come back to this subsection when he/ she reaches the

Chapter 6.

Several characteristics of system dynamics methodology make it a suitable choice to model Hockey's motivation control theory of fatigue. First, system dynamics as a formal modelling methodology captures feedback processes or circular causal relationships between state variables (stocks or levels), and variables that represent rates of change (flows) (Richardson, 2011). The distinction is important, because state variables accumulate over time and cannot be changed instantaneously. In the retrofit process one of the state variables is the feeling of fatigue. It takes time to develop such a feeling, as well as to recover from it. The stock and flow structure in system dynamics allows the explicit modelling of process delays, such as the delays in fatigue accumulation. Second, the information that arises from the state variables is used to trigger the behaviour of the system. Indeed, the performance regulation mechanism that Hockey conceptualised in his theory is triggered based on various information, including information about the feeling of fatigue. Third, Vensim software, used for system dynamics modelling in this thesis, approximates continuous-time processes, which allows the simultaneous capturing of ongoing processes that influence each other.

The first methodological step to formalise Hockey's theory of fatigue is to identify all the theoretical constructs and their relations as specified in the theory, and is described in section 6.2. Hockey (1997, 2013) provides a rich textual description from which to derive the causal structure. The system dynamics modelling process utilises different techniques to assist the development of a causal structure. This research followed Sastry's (1997) paper on modelling punctuated organisational change as a process template to develop a simulation model from a textual theory. A thematic analysis of Hockey's paper (1997) and book (2013) was conducted to identify and code statements relevant for model conceptualisation and simulation. Four types of statements were identified: (i) definition of constructs, (ii) explications of the relationships between other constructs that underpin the structure of a given construct, (iii) description of behaviour over time specific for a particular construct, and (iv) a conceptualisation of how each construct could be measured. The explicit theorisation of possible units, in which different constructs can be measured, ensured that variables derived from these constructs are meaningful as well as distinct from each other.

The relationships between the constructs served as the base to develop the causal structure of the process of fatigue development into a *causal loop diagram* (CLD). In CLDs arrows are used to represent the relationship between two variables. The standard CLD convention of positive and negative signs was used to indicate the type of influence one variable had on another (Sterman, 2000). A positive sign indicates that a change in one variable causes a change in an affected variable in the same direction. A negative sign indicates that a change in one variable causes a change in affected variable in the opposite direction. The polarity of the causal loops is then identified as reinforcing or balancing, depending on the net change effect in reference to the initial change in the variable chosen as a starting point. Reinforcing loops indicate a change in the net effect in the loop in the same direction and are denoted by **R** in the CLD. Balancing loops indicate a change in the net effect in the loop in the opposite direction and are denoted by **B** in the CLD.

The second methodological step is to move from a CLD to a formal description of the model, the implementation of which is described in section 6.3. This step facilitates the testing of the dynamic patterns proposed in the theory. State variables are identified and provide the starting point for model formalisation. The challenge of model specification is to capture accurately the elements of the original theory and the relations between them. The endogenous explanations of fatigue development in the theory is reflected in the model formulation. Special attention is given to ensure that formulations are consistent with different aspects of the written verbal theory provided by Hockey.

The structure of the formal model was visualised via a *stock and flow diagram* (SFD), a standard system dynamics diagram (Sterman, 2000). The diagramming notation followed in this work is shown in Figure 3.3. Stocks are represented by rectangles. Flows that change the level in the stock variables are represented by arrows pointing in and out of the stocks and refer to the boundaries of the model. Valves control the stocks. Clouds represent the sources and sinks of the stocks. The names for the flow variables are written in lowercase. The names for constants — variables that represent exogenous input to the model — are written in UPPERCASE. The names of all other variables Capitalise Each Word. Some of the endogenous variables are direct representations of the constructs described in Hockey's theory. There is no background colour behind the names of such variables. Other variables represent the effects of one construct on another construct, or a normalised value of a variable. Such variable names start with the word 'Effect' or 'Normalised' and have their names written on a light grey background. Shadow variables are instances of variables that are formulated elsewhere in the model and are used for model clarity and convenience. The names of these variables are written in light grey colour and surrounded by angle brackets. Black arrows represent the connections between different variables with one exception. The variables that represent initial stock values are connected to the corresponding stocks with light grey arrows.

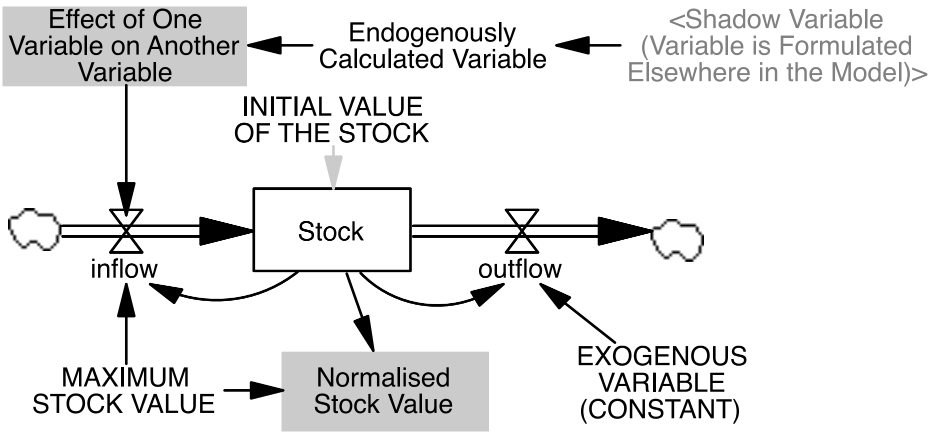

Figure 3.3. Stock and flow diagramming notation

The third methodological step is validation of model's formulation and output and is described in detail in section 6.4. The fourth methodological step is exploration of model behaviour, which is carried out in section 6.5. Hockey gives a rich description of different coping strategies or work management modes, which his theory is designed to explain. The model is used to reproduce these modes endogenously based on the variables and relations discussed by Hockey. The model is also applied in eight empirical case studies of low-carbon home retrofit processes to explore the associated fatigue experiences of homeowners. For these runs, the parameter values for initial conditions for the simulation runs are derived from empirical cases carried out as part of this research. For some variables the initial values are derived from participants answers to closed-end questions using a 7-point Likert scale. For other variables the values were derived via coding of interviews with the participants. The participants drew behaviour over time graphs for the variables associated with the development of fatigue, including the feeling of fatigue itself, which were used to validate the model output (Ford and Sterman, 1998). Finally, various scenarios aimed at reducing the development of the feeling of fatigue in the process of low-carbon home retrofit are discussed in detail in section 6.6.

This section described the two data analysis methods used in the thesis: (i) case-study analysis with thematic coding and (ii) system dynamics modelling. The next section describes the credibility strategies employed.

3.6. CREDIBILITY STRATEGIES

For a researcher it is important to work and present results with integrity, which is understood as being true to the assumptions, beliefs and practices held by a chosen epistemological position, paradigm, theories and methodology (Daly, 2007). Adherence to underlying principles and procedures, routed in one's epistemological position, paradigm beliefs, theoretical understandings and methodological strategies, gives the audience the necessary cues to position the research on the landscape of scientific work, and provides an important set of cues as to how the research could be assessed. Different initial assumptions and beliefs shape the course of inquiry and evoke different kinds of arguments and rationale and require an appropriate set of evaluating criteria to assess credibility and trustworthiness of the research output.

Credibility is concerned with two key issues — *credibility of procedures* and *credibility of outcome*s (Daly, 2007). *Credibility of procedures* has to do with how informed, transparent and accountable are the methodological strategies and techniques used in the research. From the objectivist point of view, which is adopted in this thesis, credibility of procedures is rooted in the notions of methodological rigour, efforts to minimise personal bias, and a concern with research *validity* and *reliability*. In this thesis an attempt is made to minimise bias during empirical data collection via in-depth interviews, by making sure that the participants are asked non-leading questions and the researcher displays a neutral attitude to the phenomenon (Daly, 2007).

Validity evaluates whether the research product actually portrays the phenomenon it is set to explain and how well the conclusions are grounded in the data (Daly, 2007). General strategies used in this thesis to strengthen its validity include: (i) the use of data to support statements; (ii) the provision of a full account of data collection and analysis strategies; (iii) the use of visual display tools to provide clarity (Daly, 2007; Davis et al., 2007). A rich "thick" description of the cases is provided, which further helps to strengthen the research validity (Geertz, 1973).

There are various types of validity evidence. For this thesis it is useful to distinguish the notion of *construct validity*, which evaluates the degree to which a measure of a construct reflects the concept it intends to measure; and the notion of *internal validity*, which evaluates how well a causal relation between the variables is demonstrated (Yin, 2018). Cross-tabulation and pattern matching help to improve both internal and construct validity during the data analysis (Eisenhardt, 1989; Yin, 2018). Other strategies to increase internal validity included temporal analysis of retrofit decisions and overall journeys, as well as a cross-case synthesis and explanation building (Yin, 2018).

Reliability concerns how sustainable the results are (Daly, 2007). It is accepted that the phenomenon and, thus, the results, are situated within a specific time and context and, therefore, cannot be replicated under different conditions. It is more common to talk about internal reliability, which deals with generating confidence in data interpretation. The strategies to increase internal reliability used in this thesis include: (i) the use of a case study protocol; (ii) a development of a case study database; (iii) the maintenance of the chain of evidence (Yin, 2018) and (iv) computer simulation.

Credibility of outcomes looks into the quality and trustworthiness of the research results (Daly, 2007). In social sciences the credibility of outcomes is not determined from the credibility of the procedures. It is accepted that the results cannot be proven, and thus, absolute truth cannot be established. Thus, the credibility of the outcomes cannot be established, but can only be deepened. One of the strategies to deepen the credibility of the outcomes is *triangulation*, which describes a process of using multiple standpoints to understand the phenomenon under investigation (Creswell, 1998; Daly, 2007). Several triangulation strategies are used in the thesis. Data triangulation includes gathering data from participants with different experience of low-carbon retrofit, in terms of time profiles of the retrofits and the kind of energy-related building performance goals prior the retrofit. This diversity helps the researcher to understand the commonalities of the phenomenon of low-carbon retrofit across the cases. Method triangulation included using two distinct methods: case study analysis and system dynamics modelling, to bring insights into the implication of a step-by-step retrofit approach versus a one-step in-depth retrofit approach. Another strategy employed to deepen the credibility of the outcomes is member checking (Creswell, 1998), during which the preliminary results on low-carbon retrofit decisions were taken back to the interviewees for them to judge the credibility and accuracy of the findings. Their feedback and comments are incorporated in further analysis.

One of the of the intended outputs of this research is generalisability of its results. *External validity* evaluates to which extend the findings of the study can be generalised to other people and situations (Yin, 2018). A general strategy used in this thesis to strengthen both internal and external validity is to position the research findings in the extant literatures (Eisenhardt, 1989). The use of an already externally valid Rogers' innovation diffusion theory further increased the external validity of the outcomes (Yin, 2018).

The questions of *paradigmatic integrity* deal with the aspects of reality that are meant to be communicated to the audience (Daly, 2007). The present research is done within the pragmatism philosophical tradition. A discussion of the relevance of findings to human practice is given at length in this thesis. An overview of the credibility strategies employed in the thesis is presented in Table 3.4.

Table 3.4. Credibility strategies employed in the thesis

Definitions	Strategies employed in the thesis
Credibility of procedures — evaluates how informed, transparent and accountable are methodological strategies and techniques used in the research.	
Validity — evaluates how well the conclusions are grounded in the data.	Data collection: ▪ Non-leading interview questions. ▪ Researcher displays neutral attitude to the phenomenon. Data analysis: ▪ A thick description of the phenomenon. ▪ The use of data to support statements. ▪ A provision of a full account of data collection and analysis strategies. ▪ The use of visual display tools to provide clarity. Tests specific to system dynamics modelling: ▪ Boundary definition and boundary adequacy tests, including time horizon tests. ▪ Numerical sensitivity to simulation time step.
Construct validity — evaluates whether a measure of a concept really reflects the concept it intends to be measuring.	▪ Iterative tabulation of evidence for each construct. ▪ The use of constructs well-established in the literature. Tests specific to system dynamics: ▪ Dimensional analysis of the model equations.
Internal validity — evaluates how well a causal relation between the variables is demonstrated.	▪ Pattern-matching across cases and cross-case synthesis. ▪ Explanation building. ▪ Temporal analysis. ▪ The use of existing valid theory to guide the inquiry. ▪ Computer simulation. Tests specific to system dynamics modelling: ▪ Extreme conditions test. ▪ Behaviour exploration tests.
Reliability — evaluates the level of confidence in data interpretation.	▪ The use of a case study protocol. ▪ A development of a case study database. ▪ The maintenance of the chain of evidence. ▪ Computer simulation. Tests specific to system dynamics modelling: ▪ Model documentation

(continued)

Table 3.4. Credibility strategies employed in the thesis *(continued)*

Definitions	Strategies employed in the thesis
Credibility of outcomes — looks into quality and trustworthiness of the research results. Credibility of the results are not deterministic from the credibility of procedures, as it is accepted that the results cannot be absolutely proved.	
Deepening the credibility of the outcomes. Absolute truth and, thus, credibility of the outcomes cannot be established, but can only be deepened.	▪ *Triangulation* — a process of using multiple standpoints to understand the phenomenon under investigation. ▪ *Data triangulation*, as data is collected from participants with different experience of the phenomenon. ▪ *Method triangulation*, as two methods: case study analysis and system dynamics modelling, are used to bring insights into the implications of a step-by-step retrofit approach. ▪ *Member checking strategy*, during which the research findings are taken back to the participants.
Paradigmatic integrity — deals with what is meant to be communicated to the audience.	In line with *pragmatism* philosophical tradition, an explicit attempt is made to make sure that the research is informed by and, is relevant to, human experience and practice.
External validity — evaluates to which extend the research findings can be generalised.	▪ Multiple-case study design. ▪ Positioning the research findings in the extant literature. ▪ Validation of the theoretical results obtained through simulation modelling with empirical results.

This section described general credibility strategies employed in this thesis, as well as credibility strategies specific to case study design. Credibility strategies used specifically for system dynamics modelling are discussed in detail in *Chapter 6*. The next section concludes the chapter with a brief summary.

3.7. SUMMARY OF THE STUDY METHODOLOGY

The aim of the work described in thesis thesis is to investigate individual low-carbon retrofit journeys and explore their implications on the uptake of low-carbon retrofit measures and technologies on a population level. The background literature review for the thesis revealed that retrofit decisions should be understood as processes that evolve and strengthen over time, however, there is little understanding of what are the stages of the retrofit decisions, what are the feedbacks between different stages, and how influences at different stages of the decision processes can affect the overall transition to a low-carbon housing stock.

The thesis adopts a multiple-case study design coupled with system dynamics simulation modelling to develop theoretical insights into a process of low-carbon retrofit decisions. This approach helps to obtain rich data to build a theoretical explanation. A combination of various types of data used, as well as methods for data collection and analysis include:

(i) five types of data: interview transcripts, answers to closed-ended questions, continuous associations, retrofit process maps, and behaviour-over-time graphs;
(ii) three types of data collection: in-depth semi-structured interviews, associative experiments, and visual mapping;
(iii) two types of data analysis: case study analysis with thematic coding, and system dynamics modelling.

Eight case-studies are selected with a convenience purposeful sampling strategy from the SuperHomes network, a UK-based voluntarily network of homeowners, who achieved at least 60% carbon reductions as a result of retrofit activities. The primary method of data collection is in-depth semi-structured interviews, and is collected sequentially with two sets of interviews with a gap of about a year between them. The preliminary results from the first set of interviews served as a basis to develop a data collection strategy for the second set of interviews. The preliminary results from the first set of interviews are also verified by the participants at this point.

A multiple-case study design is used to understand how low-carbon retrofit goals can be encouraged among UK homeowners and capture the dynamics of individual retrofit decision journeys that result in low-carbon energy use, and explore the implications for the transition to a low-carbon housing stock. The theoretical framework for the analysis, developed in *Chapter 2*, includes the combined framework of home-meanings together with stages of retrofit decisions, based on Rogers' innovation diffusion theory. A sequential approach for data collection and analysis is used to reveal a pattern of interest, which is used as a starting point for simulation model development. The pattern is the variation in the development of psychological fatigue in the cases. Finally, a system dynamics model of Hockey's motivation control theory of fatigue is developed to bring further insights into the dynamics of the development of retrofit-associated fatigue. Scenarios are explored via simulation on how fatigue development can be neutralised, ensuring an overall positive experience of low-carbon retrofit by homeowners.

The study is positioned within the research tradition of pragmatism and makes an explicit attempt to ensure that the research is informed by, and is relevant to, human experience and practices. Several strategies are used to increase credibility of procedures, including general concerns about reliability and validity, specifically construct validity and internal validity. Several strategies are employed to deepen credibility of outcomes of the research, which include data and method triangulation, and member check strategy. Several strategies are also implemented to increase generalisability of the research findings.

Chapter 4

Analysis context: Low-carbon retrofit cases

The chapter provides summary descriptions of all low-carbon retrofit case studies, carried out for this thesis, in section 4.1, and prepares the reader for the cross-case analysis carried out in the subsequent *Chapters 5* and *6*. This chapter then provides a rich description of individual cases in section 4.2, necessary to familiarise the reader with them. It should be noted that it is rather a condensed description of each case. Detailed reports for each case can be found in *Appendix CB. Case reports*.

CHAPTER CONTENTS

4.1. OVERVIEW OF EMPIRICAL CASES

4.1a. Key characteristics of the case study dwellings and households

The thesis features eight low-carbon retrofit cases, which are located in London, Hertfordshire and Buckinghamshire (Figure 4.1).

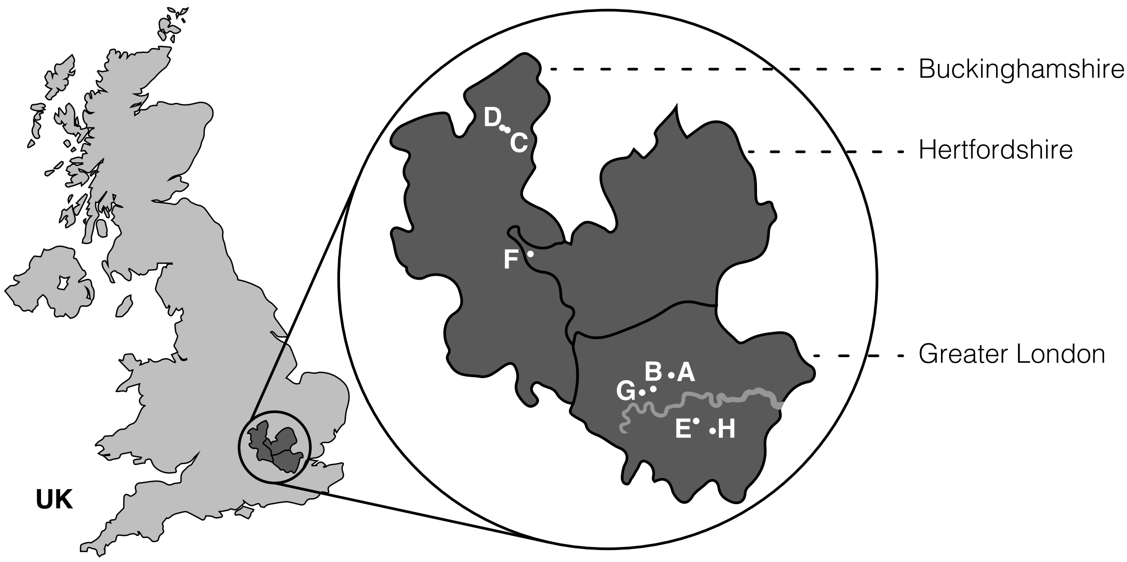

Figure 4.1. Geographical location of the cases

The cases range from Victorian terraced houses, through an early-20th-century terraced and semi-detached houses, to a mid-20th-century detached house (Table 4.1). Half of the houses are in conservation areas. The households in the study range from a couple to a family of five. Where there are children, they range from very young to late teenagers. Two out of eight households have tenants living in their houses. Most adult occupants in the sample are economically active. The sample households can be separated into three groups based on the professional background of at least one of the owners. In cases A and B at least one of the owners is a professional architect/ builder; in cases C, D and E at least one of the owners works or worked in an area related to sustainable construction; in cases F and G at least one of the owners has non-construction specific engineering background; both owners in case H have non-technical background.

Table 4.1. Profile of sample households

Case	House age/ type	Location	Conservation area	Occupants	Professional background
A	Victorian, four-bed, former mews house	London	Yes	Four adult tenants	Professional architect
B	1920, three-bed, mid-terrace	London	Yes	Family of four	Professional builder
C	1930s, three-bed, semi-detached	Buckinghamshire	No	Young couple	Sustainable-construction-related
D	Edwardian, three-bed, mid-terrace	Buckinghamshire	Yes	One adult, one child	Sustainable-construction-related
E	Victorian, five-bed, mid-terrace	London	No	Family of four and an au pair	Sustainable-construction-related
F	1967, five-bed, detached	Hertfordshire	Yes	Family of five	IT-engineer
G	1925, three-bed, semi-detached	London	No	Family of four	IT-engineers
H	1933, three-bed, semi-detached	London	No	Retired couple, one tenant	Non-technical

4.1b. Key characteristics of the cases in relation to the sampling strategy

The cases are chosen with a convenience purposeful sampling strategy (discussed in *Chapter 3* section 3.3e). Here the sample diversity is reported in terms of (i) time profile of retrofits, and (ii) explicit energy-related building performance goals before retrofit.

The retrofit cases fall in three categories, consistent with the cases observed by Fawcett and Killip (2014). First, those where the retrofit was planned from the outset and took place largely at one time: cases A, E, F, G. Retrofit works for these cases took up to a year to complete. Second, cases where the retrofit was planned at the start, but the works took place as separate pockets of intense activity over a period of time: cases B, C, D. The works spanned 2–4 years for these cases. Third, it was only possible to sample one case (H), in which the overall retrofit works were not planned from the beginning, but rather emerged over time and resulted in a low-energy house. The overall retrofit works in this case spanned over three decades. The researcher made an attempt to sample more cases with emergent retrofit design strategy, however, the SuperHomes network representative advised that no more assistance can be provided due to a lack of funding for the network (Mallett, 2018). Figure 4.2 provides an overview of time profiles of cases retrofits.

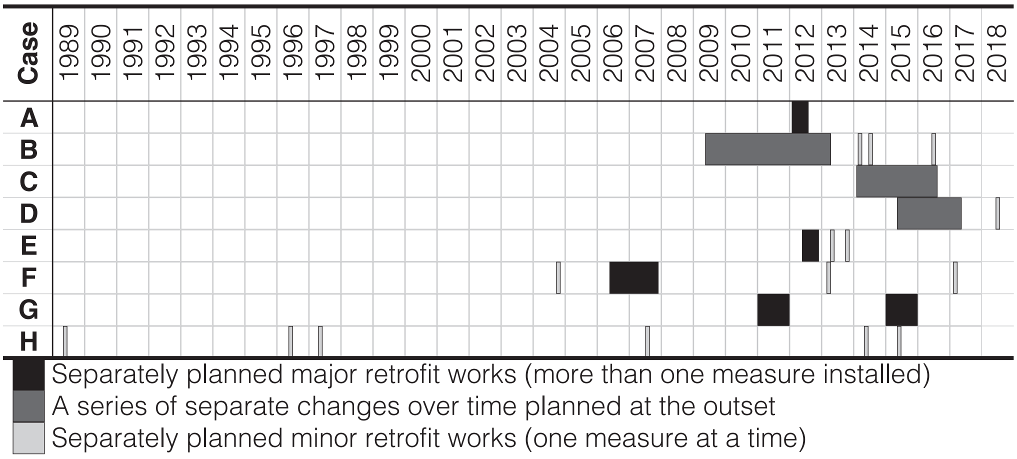

Figure 4.2. Summary of the convenience purposeful sampling strategy: retrofit timelines

Building performance goals in the sample ranged from no explicit goals to a desire to achieve carbon neutral living (Table 4.2). The retrofit cases can be grouped in three categories. First, where specific measurable targets for building performance were set before construction: (a) in case A the target was set to achieve the Level 4 of Code of Sustainable Homes; (b) in case B the target was set to achieve carbon-neutral living; (c) in case G the target was set to achieve Passivhaus standard. Second, cases where non-measurable targets for building performance were set before construction: (a) in case C the aim was to install all energy efficiency measures with short return on investment; (b) in case F the target was set to minimise the use of non-renewable resources such as energy and water; (c) in case H the household has a long-term goal to eventually achieve independence from the grid. The remaining two households had no explicit building performance goals from the outset: cases D and E.

All the households achieved more then 60% of carbon reductions as the result of the retrofit activities. Carbon reductions savings are assessed by a representative of a SuperHomes network either on-site or remotely. If assessed on-line, the representative gathers the data required in person, which include necessary measures, notes and pictures regarding the state of the house before and after the retrofit. If assessed remotely, a SuperHomes owner is asked to gather the required information and email it to the representative of the network. The data collected serves as an input for an energy assessment tool. SuperHomes network used to make such assessment with National Home Energy Rating (NHER) (National Home Energy Rating, 2016), but have recently switched to Standard Assessment Procedure (SAP) (GB. BEIS, 2014). It should be noted that in both cases the data is collected at one point in time post-retrofit, rather than in two points in time, before and after the retrofit.

Table 4.2. Retrofit goals and carbon reductions achieved by the homeowners in the sample

Case	Households' building performance goals	Carbon reductions achieved*
A	Code of Sustainable Homes Level 4	75% assessed on-site
B	Achieve carbon neutral living	67% assessed remotely
C	All energy efficiency measures with short return on investment	70% assessed remotely
D	No explicit building performance goals from the outset	78% assessed remotely
E	No explicit building performance goals from the outset	68% assessed remotely
F	Minimise use of non-renewable resources	92% assessed remotely
G	Passivhaus	80% assessed remotely
H	A long-term goal to achieve independence from the grid	90% assessed remotely

Measurable targets for building performance goals
Non-measurable targets for building performance goals
No explicit building performance goals before retrofit

Note: Carbon reductions savings are assessed by a representative of a SuperHomes network either on-site or remotely.

4.1c. Physical characteristics of the dwellings before retrofit

Six out eight dwellings, with the exception of cases B and F, are of solid wall construction. Case B features composite wall construction and case F features cavity wall construction. Seven out of eight cases, with the exception of case F, features suspended timber floor. Case F features solid floor construction. All cases featured single glazing before construction. In cases D and F the glazing prior to retrofit can be described as a combination of double and single. The dwellings in cases C, E and G were in general state of disrepair before the retrofit works. It was not possible to heat the dwellings to comfortable heating conditions in cases C, F and H. The dwellings in cases C and H had problems with mould and condensation before the retrofit. A summary of physical characteristics of the dwelling before the retrofit can be found in Table 4.3.

Table 4.3. Physical characteristics of the dwellings before retrofit

Case	Fabric	Floor	Glazing	State of repair	Specific problems
A	Solid brick wall	Suspended timber floor	Single	Habitable conditions	no
B	Composite wall: cavity brick outside, light concrete inside	Suspended timber floor	Single	Habitable conditions	no
C	Solid brick wall	Suspended timber floor	Single	Disrepair	Not possible to heat the house to comfort level, mould, condensation
D	Solid brick wall	Suspended timber with solid floor extension	Combination of single and double	Habitable conditions	no
E	Solid brick wall	Suspended timber floor	Single	Disrepair	no
F	Cavity wall	Solid floor	Combination of single and double	Habitable conditions	Not possible to heat the house to comfort level
G	Solid brick wall	Suspended timber floor	Single	Disrepair	no
H	Solid brick wall	Suspended timber floor	Single	Habitable conditions	Not possible to heat the house to comfort level, mould, condensation

4.1d. Physical characteristics of the dwellings after retrofit

In all cases fabric insulation measures have been installed throughout: floor, celling and/ or loft and walls. The households opted for internal wall insulation either because they were constrained by the location of their houses in conservation areas and corresponding building regulations, or because they wanted to preserve the fabric of the building for aesthetic reasons. Three out of eight households had original sash windows and decided to keep them: cases A, E, F. In case A the owners restored the original windows and made them double glazed. The owners noticed that this option provided the desired level of thermal comfort, while being aesthetically pleasing, however it was also the costliest option.

Seven out of eight households made improvements to increase airtightness, with the exception of case H. It was not possible to make technical assessment of the airtightness of the properties; thus, an impressionistic assessment was done by the researcher herself. The airtightness in cases B, D, E can be described as allowing for intermediate leakage. Notably, these are also the households, which opted for natural ventilation strategies. As a result, intermediate leakage allowed for sufficient ventilation through infiltration for all of these households, while it still ensured comfortable living conditions without draughts. The airtightness in cases A, C, F, G can be described as low leakage. Cases A, F, G also installed mechanical ventilation, thus the low leakage ventilation strategy ensured maximum efficiency of the systems, while maintaining the good quality of indoor air. Case C, which improved the airtightness of the dwelling to a low leakage level, relied on natural ventilation for the ventilation strategy. The owners in this case are aware of possible problems and are "sensible about the moisture [they] generate". The owners found that air becomes stuffy in the house by morning. No improvements were made to the airtightness in case H. The owners still find the dwelling draughty.

All the households installed low energy lighting and appliances throughout. Seven out of eight households installed some renewable energy generation technologies, thus, decarbonising their energy supply. The household in case C did not install any renewable energy technologies. Such an investment was not economically reasonable, as the owners only planned a short-term stay in the property.

All of the households considered environmentally friendly materials and six out of eight households used them during construction. Three households made an effort to re-use, re-cycle or restore materials present in the building prior to the retrofit: cases A, B, D. The owners in case F had active consideration for sourcing the materials locally. The owners in case B made sure they did the minimum works necessary to minimise carbon footprint associated with the construction process. This household also planned in advance a behavioural adaptation as a strategy to reduce energy use. Seven out of eight households also installed measures to reduce water usage. A consideration for materials as well as reducing mains water use shows an interest in broader environmental issues by the households. A summary of the sustainability-related characteristics of the dwellings across the cases after the retrofit can be found in Table 4.4.

This section provided an overview across all the cases. The next section provides a condensed case-by-case description.

Table 4.4. Sustainability-related characteristics of the dwellings after the retrofit

Case	Wall insulation*	High performance windows	Air-tightness **	Lighting	Ventilation system	Heating system	Energy generation	Water saving measures
A	All internal	Double and triple	Low leakage	Low energy	MVHR	Condensing boiler	Solar thermal	Low flow shower heads and taps
B	All internal	Double	Intermediate leakage	LED	Natural, bathroom extractor fan	Air-source heat pump and underfloor heating	Solar PV, battery tank	Instantaneous water heater
C	Front internal, back external	Double	Low leakage	CFL/ LED	PVHR, bathroom extractor fan	Condensing boiler	No	No
D	Original house internal, extension uninsulated	Double and single	Intermediate leakage	CFL/ LED	Natural, bathroom extractor fan	Condensing boiler, multi-fuel stove	Solar PV, solar thermal	Water storage with solar immersion controller
E	House internal, extension external	Double and restored single	Intermediate leakage	Low energy	Natural, bathroom extractor fan	Condensing boiler	Solar PV, solar thermal	Rainwater harvesting for the garden
F	Cavity wall	Double	Low leakage	CFL phased out by LED	MVHR (heating switched off)	Wood pellet boiler, wood burning stove, underfloor heating	Solar PV, solar thermal	Rainwater harvesting for the garden, rainwater recovering for the washing machine, low-flow taps and flush toilets
G	External envelop	Passivhaus certified	Low leakage	LED	MVHR	Condensing boiler	Solar PV, solar thermal	Rainwater harvesting for the garden
H	External envelop	Double and triple	High leakage	Not known	Natural, bathroom extractor fan, air cabinet	Condensing boiler, wood burning stove, underfloor heating	Solar PV	Unvented water storage

Note: LED = light-emitting diode; CFL = compact fluorescent lamp; MVHR = mechanical ventilation heat recovery; PVHR = passive ventilation heat recovery; PV = photovoltaics. * floor insulation and loft/ ceiling insulation is installed in all cases. ** An impressionistic assessment of the airtightness of the properties was done by the researcher herself.

4.2. CASE-BY-CASE DESCRIPTION

4.2a. Case A

The owner in case A is a professional architect, who owns her own architectural studio. She carried out the project during normal working hours in her studio. She does not live in the house, but rather rents all four bedrooms to four independent individuals. Thus, four different households live in the property.

The house is an end-of-terrace Victorian Mews House located in a conservation area in Camden, London. The original building, built in late 19th century, consisted of a home and a hay store. The property retained many of the original features, which appealed to the owner. She wanted to preserve the original fabric as much as possible while bringing the building closer to the modern standards of sustainability and energy efficiency.

The house was not energy-efficient, but it was not in a bad state of repair and was perfectly habitable. The property featured solid brick walls and single glazed sash windows. There was no insulation throughout and there was no heating on the ground floor. There were no problems with mould or condensation.

The retrofit works were carried out during the first half of February 2012. A detailed timeline is shown in Figure 4.3. The layout was changed significantly during the retrofit: the upper two floors of the house were converted into a four-bedroom, two-bathroom maisonette. The bedrooms and bathrooms were located on the first floor and the third floor was converted into an open-plan kitchen and living room. Apart from the layout, the structural changes included the introduction of an additional dormer upstairs. Original Victorian features were reused and upgraded to higher thermal performance criteria. Draught-proofing was carried out throughout. Thin double-glazed units were fitted for the windows, doors were insulated with vacuum-based insulation materials. All external walls and roof were internally insulated with foil-sided polystyrene insulation, which improved not only the level of insulation, but also the level of airtightness. The new mechanical service included solar thermal and two MVHR units. Energy-efficient fluorescent lighting and A-rated appliances were introduced throughout. All the works were completed in August 2012, at which point the first new tenants moved in.

Th building achieved Level 4 standard for the Code for Sustainable Homes post-retrofit. 75% of carbon savings has been achieved as a result of the retrofit. This value has been assessed by a representative of a SuperHomes network, who visited the house to confirm the measurements.

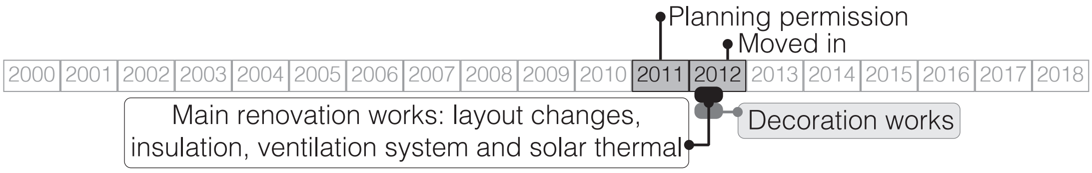

Figure 4.3. Timeline of retrofit works for case A

4.2b. Case B

The household in case B consists of a couple in their late 30s early 40s and their two children under the age of ten. One of the owners is a professional builder and used to supervise the building of high-quality energy-efficient homes in mainland Europe. The project was carried out DIY.

The property is a mid-terrace house, located in the conservation area in Hammersmith and Fulham, London. It is a 1920 brick cottage style dwelling, typical of the area. The owners were fond of the original features throughout the house such as fire places, which helped to preserve the unique character of the place. The house was in a good condition when the family moved in and was perfectly habitable. The property features composite walls: cavity brick on the outside and light concrete on the inside. The windows were single glazed. The house had no insulation when the owners bought it, except of some insignificant roof insulation. The property was heated with gas.

The owners carried out several retrofit works between 2012 and 2014. The detailed timeline is shown in Figure 4.4. First, the owners built the conservatory over a period of three months. Afterwards, they installed the internal wall, ceiling, roof and loft insulation. Consideration was taken for draught proofing. As the owners insulated the floor, they also installed energy-efficient underfloor heating. The system is zoned and has a separate control in every room. The wood burning stove in the living room was installed for decoration purposes only. The owners also took steps to minimise water use and installed a 10kW instantaneous water heater, which regulated the temperature with water flow. The owners also installed a 3.34 kW PV system, which was financed through a Feed-in Tariff scheme. They subsequently installed an air-to-air source heat pump, which is used not only for heating in the winter, but as an air conditioning unit in the summer as well. Window films were originally installed on the original single-glazed windows for insulation purposes. All windows were subsequently changed to double-glazed ones to improve acoustic insulation. Finally, in May 2016, a 5 kW/h battery tank for the PV system was installed.

The owners achieved practically a zero net energy living through a combination of good insulation, passive heat gains via conservatory, energy-efficient lighting and appliances, efficient electrical underfloor heating system, solar PV system, air source heat pump and behavioural adjustments. The necessary behavioural changes include being thoughtful of the thermostat setting during the winter and taking shorter showers. 67% of carbon savings were reported by a representative of a SuperHomes network, who assessed the house remotely.

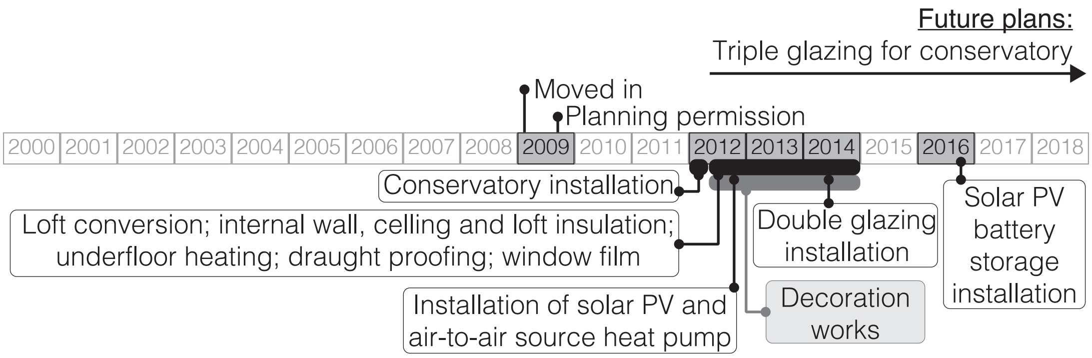

Figure 4.4. Timeline of retrofit works for case B

4.2c. Case C

The household in case C is a couple in their 30s. The husband is an architectural technologist and a principal energy specialist in an energy charity, which specialises on energy use improvements in buildings. The owners decided to carry out retrofit DIY, for which they had no previous experience.

The house is a semi-detached house located in Buckinghamshire, England, built around 1930s. It is a two-storey building typical for the time period, featuring 3 bedrooms upstairs and 2 reception rooms and a kitchen downstairs. The house was in a state of neglect at the time the owners purchased it. The property featured solid brick walls, timber suspended floors, single glazed windows. Some of the window panes were broken, which undermined the overall security of the place. There was no insulation throughout the property, except for some insignificant loft insulation of 15mm. There was no central heating system, and the boiler, that was installed at the time, did not have enough capacity to adequately heat the whole house. The property felt cold and uncomfortable. There were problems with mould and condensation.

The owners carried out the retrofit over a span of two years from mid 2014 to mid 2016. A detailed timeline is shown in Figure 4.5. The owners first installed double glazed windows and composite external doors. Afterwards, the primary pipework was re-routed and a condensing combination boiler was installed. Later, floor insulation was installed for the suspended floors. From summer 2014 to summer 2015 the owners refurbished and internally insulated all the rooms in their house. They made sure that newly insulated fabric is as airtight as possible. At some point the owners readjusted their ventilation strategy to include chimney stack passive heat recover ventilation alongside upstairs trickle vents and wet room extracts. In summer 2016, the owners additionally insulated the external floor perimeter.

The house became warmer post-retrofit. The owners are sensible about the moisture they produce in the house and they do not dry clothes indoors. 70% of carbon savings were reported by a representative of a SuperHomes network, who assessed the house remotely.

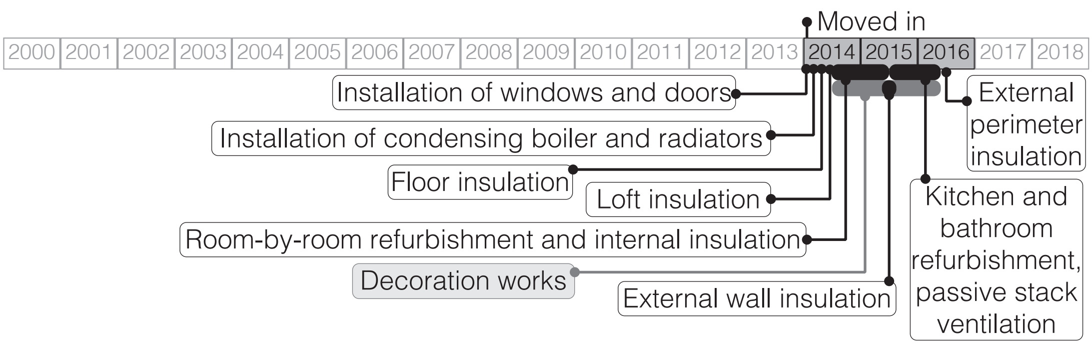

Figure 4.5. Timeline of retrofit works for case C

4.2d. Case D

The household in case D has two members: a mother in her 40s and her son in his early teens. The owner works as a manager in an organisation, which focuses on improving the use of energy in buildings. The owner hired different tradespeople to carry out the works and supervised the construction.

The property is a mid-terraced house, located in a conservation area in a small town in Buckinghamshire. Built in 1907 the building is an Edwardian two-storey high house, and features 3 bedrooms upstairs and living/ kitchen areas downstairs. The house was dated, however, the overall physical condition of the house was satisfactory when the owner purchased it. The house featured brick solid walls, original single glazed sash windows in the front and double-glazed windows in the back. The house had originally some insignificant loft insulation, but was otherwise uninsulated. The property was heated with an old-fashioned wall mounted gas fire.

The family moved in the property in February 2015 and did several renovations and improvements on the property over a course of two years. A detailed retrofit timeline is shown in Figure 4.6. First, the non-functional remaining chimney breasts were removed. Subsequently, internal insulation was installed throughout the property. In order to insulate properly the area around the boiler it had to be taken out and the pipes had to be extended. The owner took this opportunity to replace the boiler altogether with a more energy-efficient one. Later, loft and floor insulation works were carried out. Solar PV was installed in September 2015 and a wood burning stove in November the same year.

The house became warmer post-retrofit. The owner constantly monitors the amount of electricity generated by the renewables. She reports a feeling of satisfaction in taking the bath in water that had been heated by solar electricity. 78% of carbon savings were reported by a representative of a SuperHomes network, who assessed the house remotely.

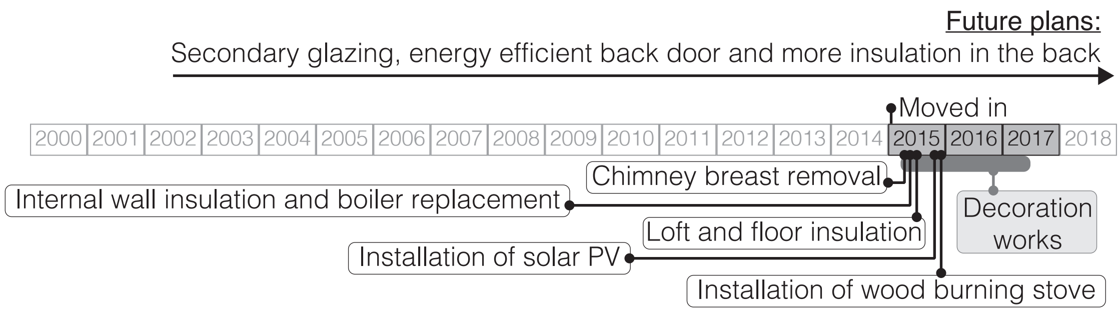

Figure 4.6. Timeline of retrofit works for case D

4.2e. Case E

The household in case E consists of a working couple in their 40s with three children in their mid and late teens. One of the owners used to work as a sustainability consultant in the built environment for more than 7 years, collaborating with developers, planners and local authorities on both new built and retrofit projects. This owner quit her job to supervise the construction. The owners hired a professional builder to carry out an in-depth retrofit of the property. The household lived elsewhere during construction.

The house is a mid-terraced house in Lambeth, London. The property is Victorian, built in 1890s. It has three split-level storeys, featuring a reception room and a kitchen on the ground floor and five bedrooms upstairs. The house was in need of a major refurbishment when the owners purchased it. The house featured solid brick walls, which were in poor physical conditions and some of them had cracks. The leaky roof needed to be replaced altogether. There were otherwise no structural issues. The house featured suspended wooden floors. There was no insulation in the property. It had single sash windows throughout and some of them were broken. Every room had a gas heater. The wiring was old and needed to be redone.

The main renovation project lasted for half a year from June to December 2012. A detailed retrofit timeline is shown in Figure 4.7. As part of the project some walls have been knocked down or moved in order to adjust the layout of the property to the family's taste and needs. The roof, ceiling and floors were insulated. Exposed walls have been insulated internally. Draught proofing was installed around all windows, the front door and below skirting boards on the ground floor. The central heating system was installed, which featured condensing boiler and radiators. The owners also installed solar PV panels and solar water heating. They also installed rainwater harvesting and use this water for watering the garden. Water saving taps were installed in the bathrooms as well. In 2013 the family carried out works to redesign the garden and build a patio. At the end of 2013 the owners also installed secondary glazing on the windows facing the road.

The improvement in the building fabric increased the thermal comfort of the place. 68% of carbon savings were reported by a representative of a SuperHomes network, who assessed the house remotely.

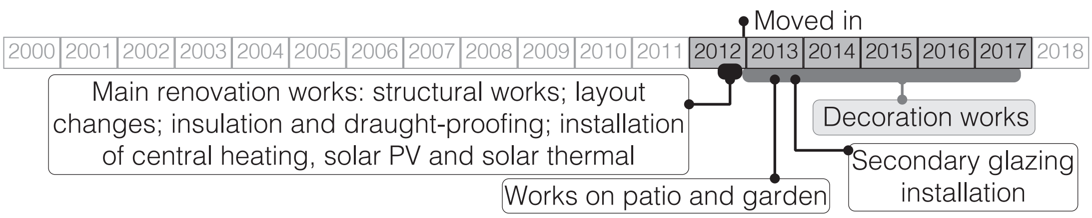

Figure 4.7. Timeline of retrofit works for case E

4.2f. Case F

The household in case F consists of two adults in their 40s and three children 10 to 12 years old. The husband has a degree in IT engineering and computer science. The retrofit was carried by him together with his builder-friend.

The house is a detached house, located in a conservation area in a village on the border between Hertfordshire and Buckinghamshire. It was built around 1967. The house was not in a bad state of repair when the owners moved in. The house had cavity brick walls and a combination of single- and double- glazed windows. Overall, the house was very cold. It had no insulation throughout. The heating system featured a very old boiler and some central heating. The fire tank was only 6 or 7 kW (62% efficiency after being serviced), which was too small to heat a house of that size. The house also had an open fire place. The heating system was inadequate and unsafe, as the old fire tank would not have passed the fire regulations, and electrical wiring was unsafe at places.

The owners moved in the house in June 2004 but they did not start the retrofit works immediately. They wanted to live in the house for some time and understand what they really needed. Over the years they did several renovations and improvements on the property. The main works were carried out in one go over 14 months from September 2006 till December 2007. A detailed retrofit timeline is shown in Figure 4.8. Several works were carried out outside the main retrofit activity. The only thing the owners did before main renovation works began was the cavity and loft insulation. The main retrofit works included major layout changes, and the new layout comprised 14 rooms. Internal walls, and ceilings were stripped down and completely rebuilt, a kitchen extension was added and the garage extended. The owners installed multi-layered thermal and acoustic insulation throughout the whole fabric: loft, cavity walls, underfloor and ceilings, they also installed double glazed windows and doors. The owners installed two wood-burning stoves and chimneys. They also installed solar thermal and biomass wood pellet boiler, both of which feed a large well insulated thermal storage. It was decided to install underfloor heating throughout the ground floor in 8 zones. The owners put heat recovery ventilation system throughout the house with a heating option switched off. The whole property had new wiring and plumbing. In 2007 the husband built a DIY pergola with solar panels.

The owners enjoy post-retrofit indoor environment. 92% of carbon savings were reported by a representative of a SuperHomes network, who assessed the house remotely.

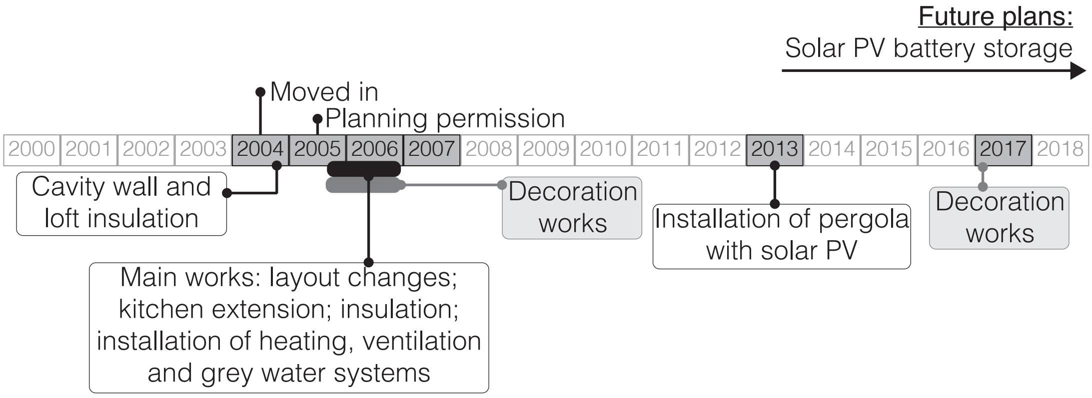

Figure 4.8. Timeline of retrofit works for case F

4.2g. Case G

The household in case G comprises of a young couple in their 30s with two small children. Both owners are IT engineers. One of the owners became a Passivhaus certifier during the retrofit project. The owners hired builders, who had no previous experience of Passivhaus construction.

The original house was a semi-detached council house in Ealing, London, built around 1926. It was a typical two floor three-bedroom building, and featured a reception room and a kitchen on the ground floor and three bedrooms upstairs. The dwelling was in a need of major refurbishment. The property had single glazing throughout and featured solid walls with no insulation. The heating system of the house included a gas-powered boiler and radiators.

The owners bought the property in 2010. Since then they did several renovations, which they carried out in two major stages. A detailed retrofit timeline is shown in Figure 4.9. The first stage was carried out in 2011 over a period of around one year. During this time a two-storey extension was added on one side, extending the property to 125 m^2. The house was split into two self-contained flats. The whole property was retrofitted to a Passivhaus standard. The following measures have been installed: external wall insulation, floor and loft insulation, triple glazed windows and doors. The house has been sealed to be very airtight. The heating system consisted of gas-fired central boiler and radiators. The overall setup includes mechanical heat recovery ventilation, solar thermal and solar PV systems. A rainwater harvesting system was installed and used to water the garden. In 2015 they did a back extension to the ground floor property, building it to Passivhaus standard.

Thermal comfort improved significantly. No heating was required in the last four years, even during winter months. 80% of carbon savings were reported by a representative of a Super-Homes network, who assessed the house remotely.

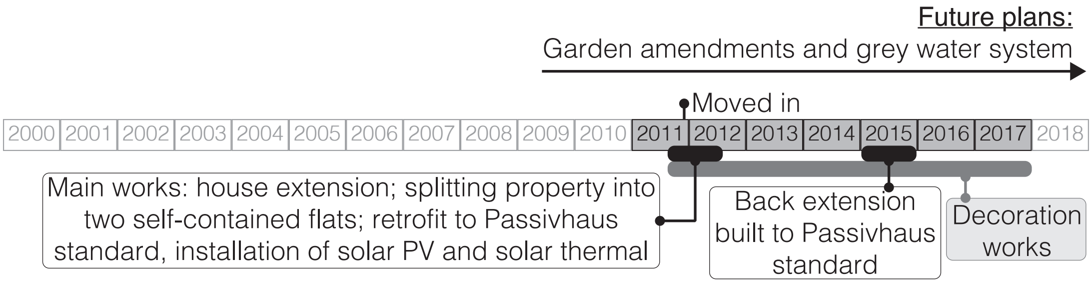

Figure 4.9. Timeline of retrofit works for case G

4.2h. Case H

The household in case H consists of a retired self-employed couple (the owners) and a tenant. The owners have no background in energy or civil engineering.

The house is a semi-detached house in Lewisham, London. It was originally built as a summer holiday house in 1933 for railway workers and it was never designed to be occupied all-year-round. It was a typical two floor three-bedroom building, with 2 reception rooms, a kitchen on the ground floor, three bedrooms, and a separate bathroom upstairs. The house was not in a bad state of repair when the owners moved in and was perfectly habitable. The house featured solid brick walls, uninsulated loft and uninsulated wooden floors. The windows were single glazed with wooden frames. The frames were rotten, and there was a condensation problem, with mould growing everywhere. Each reception room had a gas fire located in an old fire place, each bedroom and bathroom had a radiator, there was no heating in the hallway or landing. The house is located on a hill with the side of the property exposed to wind. The house was very draughty and a cold breeze used to come up from the floor, making it impossible to heat the house. The thermal discomfort even prevented the household members from enjoying sedentary activities indoors.

The owners moved in the property in 1989 and carried out retrofit works over almost three decades. A detailed retrofit timeline is shown in Figure 4.10. The owners first installed insulation curtains shortly after they moved in. However, the house became very dark as a result, and there was mould growing under the curtains. The curtains were removed. The owners later installed underfloor heating system and insulated the floor. At the time the boiler was changed to a condensing one. Loft conversion was carried out in 2007 and insulated to building standards at the time. Simultaneously, the bathrooms were changed to wet rooms and the air cabinets were installed. External wall insulation was installed in 2014. A pergola in the garden with solar PV panels on it was installed in 2015.

Indoor thermal comfort had been improving over the years after each retrofit. Nowadays, the couple finds living in the house a much more relaxing experience. 90% of carbon savings were reported by a representative of a SuperHomes network, who assessed the house remotely.

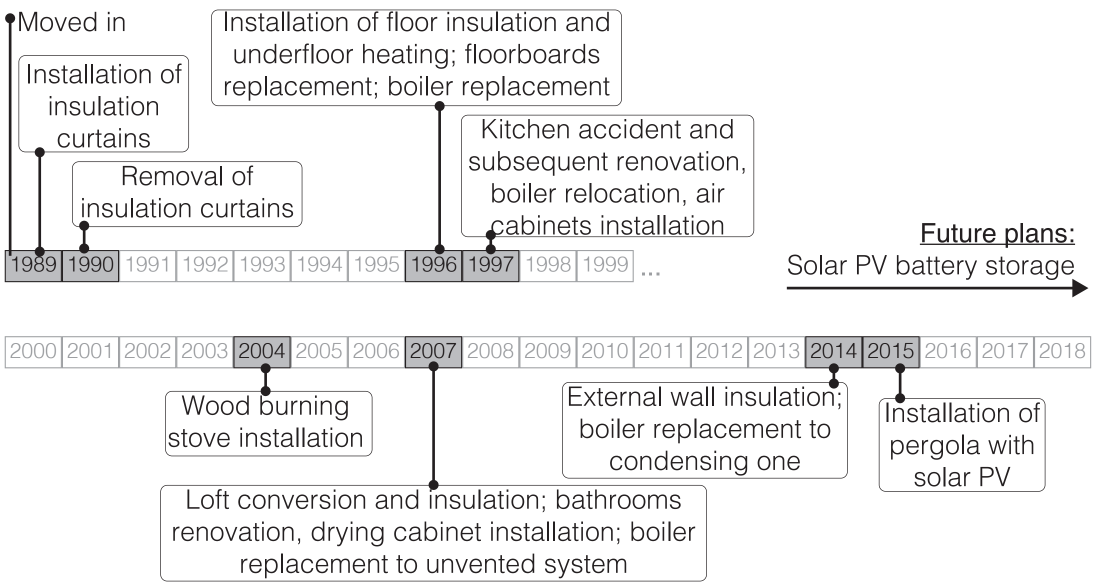

Figure 4.10. Timeline of retrofit works for case H

Chapter 5

Individual retrofit decisions as contextually embedded processes

Previous research suggests that low-carbon retrofit should be understood not as a decision taken at a single point in time, but as a process that develops over time and is socially shaped (Wilson et al., 2015). It has also been suggested that meanings of home help to explain why homeowners decide to renovate in general, and renovate energy-efficiently in particular. This chapter uses a conceptual framework of home-meanings, an understanding of a building as a socio-technical system, Rogers' innovation diffusion theory and an idea of implementation difficulties to conceptualise low-carbon retrofit decisions as contextually embedded processes. This theoretical conceptualisation is used to develop further insights in the nature of these processes. Section 5.1 uses a framework of home-meanings developed in *Chapter 2* to analyse contextual heterogeneity in relation to low-carbon dwellings. Section 5.2 uses a notion of a socio-technical system to look at different combinations of technological improvements and behaviour adaptation used in the cases to minimise operational energy use. Section 5.3 clarifies the meaning of an 'innovation' in the context of low-carbon retrofit. It then proceeds to provide evidence for the existence of stages in a low-carbon retrofit process. The section also provides evidence on the implementation difficulties associated with low-carbon home retrofit. Section 5.4 examines the effect of different approaches to the pace of retrofit work (one-step vs step-by-step) on the associated implementation burden. Section 5.5 concludes the chapter with a brief summary.

CHAPTER CONTENTS

5.1. THE CONTEXTUAL HETEROGENEITY OF LOW-CARBON DWELLINGS

Chapter 2 provides evidence of the lack of understanding of contextual heterogeneity in homeowner goals and intentions that result in low-carbon home retrofit. The framework of home-meanings developed in *Chapter 2* is used to develop insights into the heterogeneity of living experiences associated with low-carbon dwellings. The insights can be used to develop a variety of messages aimed at encouraging low-carbon retrofit. This section identifies re-occurring themes in empirical cases related to homeowners':

(i) retrofit goals;
(ii) post-retrofit living experiences;
(iii) associations with low-carbon dwellings.

The data on retrofit goals and post-retrofit living experiences was collected through in-depth interviews, and the data on homeowners' associations was collected through continuous associative tasks as described in *Chapter 3*. This subsection presents results in detail. Previous research suggests that the emergence of low-carbon retrofit decisions should be understood through the meanings people attach to their homes (Wilson et al., 2015). In line with this suggestion, the home-meanings framework is used to group the re-occurring themes in the process of thematic coding of the homeowner interviews. Themes, the origins of which cannot be traced to the meanings people attach to their homes, are grouped separately with inductive reasoning.

Several themes are identified during the thematic analysis of interviewees' retrofit goals, living experiences and associative tasks. Themes that can be traced to the meanings people attach to their homes include: (i) the *physical structure* of the house; (ii) various *behavioural affordances* accommodated by the physical structure of the house; (iii) as well as various *social and psychological affordances*, including the feelings of safety, control and comfort (thermal comfort, the quality of indoor air, light and acoustics), as well as the associations between personal or professional identity of a homeowner, and the place identity of a dwelling. A summary of themes mentioned by the homeowners in the empirical cases is given in Table 5.1.

The theme titled 'financially-related considerations' incorporates homeowners' concerns, which cannot be traced to the meanings people attach to their homes. Such concerns include aspirations to reduce energy bills or achieve low-carbon retrofit on a small budget. As the origins of the theme 'financially-related considerations' cannot be traced to the meanings people attach to their homes, no further analysis on the theme was done. In the rest of the section, the themes that can be traced to home-meanings are looked in more detail, which include: (i) feelings of comfort, safety, security and control; (ii) accommodation of behavioural affordances by the physical structure of a low-carbon house; (iii) personal identity in relation to a low-carbon dwelling and place identity of such dwelling.

Table 5.1. Themes related to low-carbon retrofit derived from empirical cases

Themes	Cases							
	A	B	C	D	E	F	G	H
Themes associated with home-meanings								
Affordances								
Social and psychological affordances								
Comfort								
- Thermal comfort	✓	✓	✓	✓	✓	✓	✓	✓
- Indoor air quality	✓	✗	✓	✗	✗	✓	✓	✗
- Acoustics	✗	✓	✓	✗	✗	✓	✓	✗
- Light	✓	✓	✗	✗	✗	✗	✗	✗
Safety/ Security	✗	✓	✓	✗	✗	✓	✗	✗
Control	✗	✓	✗	✗	✗	✓	✓	✗
Identity								
- Personal identity	✓	✓	✓	✓	✓	✓	✓	✓
- Place identity	✓	✓	✓	✓	✓	✓	✓	✓
Accommodation of behavioural affordances by the structure of a house	✓	✓	✓	✓	✓	✓	✓	✓
Physical structure of a house, maintenance	✓	✓	✗	✗	✓	✓	✓	✗
Financially related considerations	✓	✓	✓	✓	✓	✓	✓	✓

Note: ✓ denotes that the theme that was mentioned by the interviewee; ✗ denotes that the theme that was not mentioned by the interviewee.

5.1a. Feelings of comfort, safety, security and control

The notion of comfort was mentioned by all interviewees, primarily in relation to **thermal comfort**. All the interviewees mentioned that their houses are warmer post-retrofit during cold months. One of the owners in case H described cold as a "brain-numbing experience". The owners in this case mentioned that before the retrofit they "were beginning to get a bit desperate about the house being cold in winter" and remember their experiences as being "physically uncomfortable". After the retrofit, the owners found their living experience to be "so relaxing", due to improved thermal comfort. The interviewed homeowners in cases C and G mentioned the pleasant experience of living in an energy-efficient house, afforded by the uniform indoor temperature. For instance, the interviewed homeowner in case G explained that a possibility to "have a constant 20–22ºC… it's a part of feeling cosy, for me at least". The interviewed homeowners in cases A and E explicitly talked about their homes being cool during warmer months, which they attributed to the installed energy efficiency measures.

The interviewed homeowners in cases F and G stressed the importance of a good **indoor air quality** to be comfortable at home. The owners in these cases gave special considerations to ventilation strategies, and opted for mechanical ventilation. The owners in case G had previously lived in mouldy places and they wanted "to make sure that the air quality is good and that [they] don't have mould". The interviewed owner in this case stated that, after the retrofit, "the air quality is probably just something we absolutely love".

Thermal comfort and indoor air quality were often mentioned by the interviewees when they talked about their retrofit goals and motivations. Improved **acoustics** was revealed as another dimension of comfort, which was experienced by the owners in cases C and G as a result of living in their homes post-retrofit. For instance, the interviewed homeowner in case C mentioned that their home provides a quieter environment post-retrofit and described their experience as:

> Another benefit of the rock mineral is that it really dampens the external noises well. That, combined with double glazing, was a big step improvement on acoustics. You used to hear trains every now and then. So, we went from being able to hear them in the house to not at all. (case C, interview 1)

Some interviewees mentioned improved **daylight** conditions after the retrofit. Such improvements were more often associated with layout changes rather than energy efficiency retrofit per se. However, in case B, the improvement in daylight conditions is closely linked to energy efficiency retrofit. The owners in this case built a glass conservatory that not only trapped solar gains, but also made the space much brighter, which proved to make a "big difference".

In some cases, the owners mentioned the feelings of **safety** and **security** associated with living in low-carbon dwellings. Energy-efficient services and appliances were, in general, considered to be safer options compared to traditional non-energy-efficient ones. For instance, the interviewed homeowners in cases B and F emphasised that appliances and services, such as LED lights, induction cooker, or an underfloor heating system are safer for the little children to be around, as “you don’t have any risks of children getting burned by hot radiators” (case F), or getting burned from a cooker or a hot light bulb (case B).

The interviewed homeowners in cases B and G mentioned a newly achieved feeling of **control** over their environment, afforded to them by the energy-efficient retrofit. For instance, the interviewed homeowners in case G highlighted that “it’s really up to me”, what the indoor temperature is. However, the perception of control was not uniform throughout the cases. The interviewed homeowner in case F found the thermostat controls not very good, and found herself “turning on and off the radiators, because it is either too hot or too cold”, which proved to be “a bit of a disappointment”.

5.1b. Physical structure of the house and behavioural affordances

Several themes emerged in relation to **the physical structure of a house**. The interviewed homeowners in cases A and G described the retrofit outcome as a substantial improvement to the material structure of their homes. The interviewed homeowner in case G described the quality of retrofit as long-lasting. The interviewed homeowner in case A mentioned that “the house is wearing very well”. She hopes that the quality of construction means that there will be no need “to do anything new with [the property] for another generation”.

The interviewed homeowners in cases A and F mentioned the physical structure of their homes in relation to required **maintenance**. The interviewed homeowner in case A highlighted that the house is very easy to maintain. The interviewed homeowner is case F described the house maintenance needs as “very little” compared to non-energy-efficient alternatives. For instance, he mentioned that during very cold weather they only need to fill up their wood pellet hopper once a week, whereas during a milder weather it can last up to two weeks. He recalled that the appliance his family had in his childhood used anthracite coal grains, and required daily maintenance. He and his father used to “empty out all of the ash, de-clinker it, and then fill it with two new buckets of coal”.

Finally, all interviewees talked about their low-carbon homes in terms of a **structure**, which provides a better platform for everyday life, as compared to non-energy-efficient houses. For instance, the owners in case H explained that the physical configuration associated with a low-carbon dwelling, especially stable indoor temperatures, is a necessary framework to carry out household activities:

> Once the house is all structured, then we could start doing things in it. Like, I can start painting in it, cause it's warm… It is a kind of framework for all the other stuff we can do. (case H, interview 1)

The structure of a low-carbon home was mentioned not only in relation to mundane **behavioural affordances**, but also in relation to more distinct activities whether daily, weekly or more seasonal ones. The interviewed homeowners in case F and H highlighted that their extended family loves being around during Christmas, because their home is a "nice, warm and comfortable environment", as described by the interviewed homeowner in case F. The interviewed homeowners in cases B and F talked explicitly about the notion of a low-carbon dwelling as a positive formative experience for their children. They mentioned how taking care of on-site energy and water systems teaches their children a good lesson of responsibility, while, simultaneously, provides a bonding experience with them. For the owners in case H, a warmer, nicer environment meant a more "relaxed state of mind" and, consequently, less arguing that comes from being in a "physically uncomfortable" environment.

5.1c. Sustainability, place identity and personal identity

All interviewees talked about their **broader sustainability interests**, which were underpinned by their personal attitudes and, sometimes, by their professional image. Such interests helped the owners to be determined to initiate and carry out their retrofits. As of the owners in case H stated: "you, kind of, have to be in tune with the whole idea of making your house warmer, or generating electricity, or whatever it is". Indeed, what was the idea the interviewed homeowners were in tune with was different.

The interviewed homeowners in cases D, F and H talked about the acquired feeling of self-sufficiency and independency in terms of energy use. The owner in case D referred to solar thermal panels, which allow her to have hot water heated by renewable energy during summer months. She also mentioned that her solar PV panels generate more electricity annually than the household uses in a year, which gives her "great sense of satisfaction". The heating configuration of the house in case F allows the owners to have some independence from the outside world. The interviewed homeowner mentioned that even in the coldest day the family can heat the whole house "with the power cut for three days in the snow". The owners in case H talked about "being sustainable in [their] old age", referring to the ability to pay energy bills after retirement, when their income gets fixed.

The interviewees often mentioned an idea to help the environment in one or another capacity. For the owners in case H "it makes sense" to help the environment, if they can afford it. They also grow their own vegetables. The interviewed homeowner in case F always wanted an opportunity to have his own "environmentally friendly home". The owners in case G aim to achieve "low [carbon] footprint" for their household. They cycle instead of using a car, choose to fly no more than once per year, do groceries locally and buy less things altogether. Thus, they wanted a house that does not need much energy to operate. The interviewed homeowner in case B wanted his home to be "carbon neutral". The household in this case also opts to use car sharing, instead of owning their own vehicle. The interviewed homeowner in case E tries to make more sustainable choices in everyday life: buys organic food, buys better quality clothes that last longer, and chooses to fly less often. The interviewee in case C spoke about him and his wife being "naturally frugal" in relation to energy use. They also do little things to live a more sustainable life, such as grow their own vegetables. The interviewed homeowner in case A finds appealing an idea to get some energy for free through renewable sources, even if on-site energy generation does not cover all of the household's needs.

Some interesting results were obtained from the analysis of homeowners' narratives regarding the **place identity** of their houses. The interviewed homeowners in cases A, B, C, D, E and F talked about period features of their homes, when prompted to describe what they liked in their homes prior to retrofit. The interviewees highlighted that such features grant their homes a certain character. The interviewed homeowner in case C even said that he and his wife "were of very strong view that [they] don't want a new build". The interviewed homeowner in case A elaborated on her feelings more explicitly, stating that she is proud that she managed to preserve the character of the property during the retrofit. When prompted to talk about the features she liked in the property prior to retrofit, she stated:

> Well, I think, what we liked, was the sense that it hadn't changed a lot since its original inception. So, that you could still see that it was an open space here… And you could imagine the hay… And, certainly, downstairs you could see that there were horses. There are still hoops for the horses for tying… The character that it retained… and that it hadn't been, actually, messed about by anybody, properly, for at least 30, 40, 50 years… It was rather untouched… It was very much a witness of its time. (case A, interview 1).

For interviewees in cases A, B, C and D low-carbon retrofit was an important part of their **professional identity**, as these interviewees work in construction or in sustainability-related construction industry. For instance, the interviewee in case D mentioned that she can now talk to her customers about low-carbon retrofit from “personal experience”, which gives her “more credibility”.

Some noteworthy insights were obtained as a result of analysis of homeowners’ associations. The interviewees were asked to name all the words that come to their minds in an association with the word ‘home’ and the phrase ‘low-carbon home’, as described in *Chapter 3* (Table 5.2). When a full integration between an individual and its environment is achieved, words such as *warmth*, *harmony* and *joy* are used to describe one’s home (Molony, 2010). The results of the associative tasks indicate that home is associated with a comfortable, joyful place and an overall positive experience for the interviewees in each case. An interesting difference is noted between the interviewee’s associations with the word ‘home’ and the phrase ‘low-carbon home’. The difference is in the scale of understanding of a societal entity. The idea of home has connotations to a **personal** and family **identity**, whereas the idea of low-carbon home has a broader connotation of a societal and **national identity**. When asked to give associations with the word ‘home’, the interviewees talked about themselves, their family and friends. When asked to give associations with the phrase ‘low-carbon home’, the interviewees talked about their responsibilities to the wider society, future generations and the Earth.

Table 5.2. Results of the associative tasks

Case	Home	Low-carbon home
A	**calm**, inspiring, **comfortable**, open, **practical**, **easy to maintain**, coherent	careful, engaged, understanding, concerned, open-minded, *forward-looking, environment-conscious, long-term*, simplicity on all levels, sign of the time
B	**comfort**, **retreat**, energy, beauty, love, care, oasis, paradise, garden of Eden	**comfort**, **retreat**, energy, beauty, love, care, oasis, paradise, garden of Eden*
C	**family**, **comfortable**, **warm**, **homely**, **rest**, **sleep**, **food**, **shelter**	**comfortable**, **low cost to run**, **healthy**, **warm**, **quiet**, **peaceful**, *considerate, sustainable*
D	**peace**, **relaxation**, **comfort**, **identity**, **cosy**, **calm**	**inexpensive to run**, quite modern, minimalistic, Passivhaus, sterile, Grand Design, modern architecture, not cosy, airtight with mechanical ventilation
E	**comfort**, **cosy**, space, **work**, **chores**, **reflecting my personality**	**efficient**, **low energy consumption**, **comfortable**, *sustainable*, resilient. *It's where the money is put where it doesn't get seen. So, people can't notice the difference. But it's put where it should be*.
F	**family**, **comfort**, **place to relax**	*n/a
G	fun, joy, **peaceful**, **warm**, **cosy**, **comfortable**, **healthy**, **family**, **friends**, **garden**, **kitchen**, **cooking**	**very comfortable, good air quality, health**, *sustainable*, proud to have one
H	1: **family**, **safe**, **comfort**, responsibility, DIY 2: **warm**, **safe**, **food**, fun, workshop, **children**, **friends**, **Christmas**, **pension**, something about old age, continuity	1: sensible, efficiency. *It's a thing to do. There is no reason not to be efficient*. 2: *responsibility, citizenship, neighbourly The whole world is safe, protected. It's much more national and global than just us*.

Note: * The interviewee explicitly said that the associations must be the same as with a word 'home'.

Words in bold denote associations that tend to be understood on the scale of an individual or immediate family and friends; *words with shading* denote associations that tend to be understood on the scale of a society, nation and human kind.

5.1d. Home-meanings and low-carbon dwellings

The analysis presented in this section reveals that low-carbon dwellings are associated with enhanced feelings of comfort, safety, security and control, as well as an extra-domestic identity of broader social responsibility. The feelings of comfort, safety, security and control, as well as the notion of identity, are part of social and psychological affordances in the framework of home-meanings described in *Chapter 2*. This thesis makes no attempt to suggest an integrated theoretical model to explain the emergence of different affordances. Rather, it explores the relationships between different dimensions that give home meaning, which are already identified in the literature. The literature is used in the rest of the section to bring together the dominant and re-occurring ideas on how home settings can offer a platform to:

(i) develop a feeling of comfort;
(ii) develop a feeling of safety and security;
(iii) develop a feeling of control;
(iv) establish one's identity.

It has been suggested that colloquial idioms of home reflect qualities associated with home environments (Porteous, 1976). For instance, the common expression 'my house is my castle' reflects the importance of home to establish the feelings of privacy and refuge, evidence for which are widely found in empirical research (Smith, 1994). The idioms related to the notions of comfort, safety, security, control and identity in relation to one's home are presented in Table 5.3, and provide evidence that such psychological and social affordances can be provided to an individual in home settings.

Table 5.3. Colloquial idioms about social and psychological affordances provided by one's home

Affordance	Colloquial idiom	Source
Comfort	East or west, home is best.	Bohn, 1888: p. 347
	Home is home, be it never so homely.	Bohn, 1888: p. 408
	Ah! there is nothing like staying at home, for real comfort.	Austen, 1816: p. 264
Safety/ Security	My house is my castle.	Bohn, 1888: p. 456
Control	Every dog is a lion at home.	Bohn, 1888: p. 349
	None but cats and dogs are allowed to quarrel in my house.	Bohn, 1888: p. 463
Identity	It is a shame to steal, but a worse to carry home.	Bohn, 1888: p. 428

A vast amount of literature talks about feelings of comfort, safety, security and control, afforded by one's home (for an overview see Blunt and Dowling, 2006; Després, 1991; Mallett, 2004; Somerville, 1997). Home is a place of **comfort**, a place of privacy, a place where one could withdraw to and regenerate, a place where one can relax and be oneself, a place of refuge, a haven (Mallett, 2004; Molony, 2010; Saunders and Williams, 1988). Home provides shelter for its inhabitants, a setting where one feels **safe** and **secure** (Blunt and Dowling, 2006). At the same time, home is a sole area of **control** for an individual (Després, 1991).

Several features of one's environment and processes that one engages in, were found to enhance the feelings of comfort, safety, security and control. Several sources suggested that reoccurring nature of everyday life can enhance all of these feelings. For instance, domestic practices and routines were found to enhance the feeling of control over one's environment (Taylor and Brower, 1985, as referenced in Després, 1991: p. 99). Some elements of the feelings of safety and security in one's home can be explained with an idea of *ontological security* (Somerville, 1997), which originates in the work of Anthony Giddens (1984) and was introduced to the literature on home-meanings by Saunders and Williams (1988). Giddens defines ontological security as "confidence or trust that the natural and social worlds are as they appear to be" (Giddens, 1984: p. 375). He theorises that ontological security is maintained by the predictability of routinised, taken-for-granted, ordinary activities of day-to-day life.

Some elements of the feeling of comfort can be explained with the idea of home as a state of *being-in-the-world*. A stream of phenomenological research describes this state as being in peace and comfortable with oneself and the world (Mallett, 2004). These ideas originate in Heidegger's essay *Building Dwelling Thinking* (1959). Heidegger traces the origin of the word *to build* to the word *to dwell*, and highlights that its original meaning was *to be* and *to remain in peace*. Other research has highlighted that the experience of being-at-home is shaped via a sense of familiarity and routine that arises from the experience of taken-for-granted routines (Després, 1991). These insights are reminiscent of the findings from empirical cases. The reoccurring nature of everyday activities carried out in one's home is difficult to verbalise. However, all the interviewees mentioned how the structure of the house post-retrofit provides a better platform for everyday life. For instance, the interviewed homeowner in case C said: "it sounds a little cliché, but [it is a] much more comfortable, generally better, nicer environment to live in".

The notions of home and personal **identity** are closely linked. Home is a place, where an individual's self is important (Després, 1991; Molony, 2010). Home could be a symbol of self-expression, an active statement of how one would want to be seen by others on one hand, and a symbol of social status of its inhabitants on the other hand (Somerville, 1997). Several features of the environment and processes in it contribute to an establishment of one's identity. One of the core processes for the inhabitants to express themselves is a process of personalisation of one's place through the choice of furniture, decorations and a choice of meaningful objects and possessions (Després, 1991; Porteous, 1976). Indeed, all the interviewees talked about a personalisation process. For instance, the owners in case F wanted to "make [their] mark on it". The owner in case D even mentioned that a personalisation process is of a crucial importance to her:

> I am not someone who is just interested to kind of just walk into a house, which is kind of brand new and everything is done. I want to put my own personal taste and stamp on it. (Case D, interview 2)

During the second interview, interviewees were asked to show the researcher around their homes and talk about the features of their houses they like and are proud of. Many interviewees talked about their choice of furniture and decoration, showing the researcher the meaningful objects around the property. The interviewees sometimes even apologised in front of the researcher that they talk about aesthetics, rather than energy efficiency and low-carbon measures. For instance, when talking about her choice of tiles in the hall and stained glass in the front door, the owner in case D noted: "So, it is nothing to do with the energy efficiency. It's just that I am proud of them. It's just I love it". This discrepancy, yet again, highlights that the notion of 'low-carbon home' is associated with a different identity, as compared to the notion of 'home'. In relation to one's identity, the literature on home-meanings highlights that multiple identities, such as the ones of gender, race, class and sexuality, are shaped and reproduced in home settings, as multiple social processes shape simultaneously the meanings of home (Blunt and Dowling, 2006). Such identities do not oppose each other, but rather are simultaneously shaped in an organic manner. Similar logic is implied here, and it is assumed an identity of one's 'home' is not in an opposition to an identity of a 'low-carbon home'.

This section looked into re-occurring themes identified in empirical cases, with themes derived deductively from the home-meanings framework. Different dimensions arose from the analysis of interviewees retrofit goals, post-retrofit living experiences and associative tasks. Low-carbon dwellings were found to be associated with a broader notion of comfort, security and control, as well as an extra-domestic identity of a broader social responsibility. The section also looked into the current literature to identify relationships that shape the identified home-meanings. The next section looks into links between identified themes, decision processes and post-retrofit energy use.

5.2. LOW-CARBON DWELLINGS AS SOCIO-TECHNICAL SYSTEMS

5.2a. Operational energy use in a house

A building should not be perceived merely as a physical artefact, as without occupants there will not be any operational energy use either. A building should be understood as a system that "involves interactions between natural laws, biophysical systems and the actions of their human occupants" (du Plessis and Cole, 2011: p. 438). Operational energy use should be understood as a result of the "adaptive process" in this socio-technical system (Cole et al., 2013: p. 245). Low energy consumption cannot be solely attributed to the physical structure of the house and its components, or solely to the occupant behaviour. Occupants do not consume energy, they consume services that energy makes possible (Wilhite et al., 2000). It follows that a different level of behavioural adaptation is required to achieve low energy use in different buildings. For instance, occupant behaviour has little influence on heating needs in a Passivhaus, whereas in a leaky house a substantial behavioural adjustment from the occupants is needed to achieve low energy use associated with heating.

This section looks at low-carbon dwellings in the case studies as socio-technical systems. An attempt is made to understand the processes, by which the owners in case studies transitioned to low-carbon use in their dwellings.

5.2b. Socio-technical configurations exhibited in the case studies in the process of low-carbon energy use: similarities and differences

The owners in the sample chose different combinations of technological improvements and behavioural adaptations to minimise operational energy use. In some cases, carbon reductions were achieved primarily through technological means, in other cases behavioural adaptation played a major role (Table 5.4).

Table 5.4. Modelled carbon reductions via technological means and further estimated reductions with a help of behavioural adjustments

Case	Socio-technical combinations	Carbon reductions via technological means only*	Carbon reductions with a help of behavioural adjustments
A	Whole house retrofit with mechanical ventilation. No behavioural changes.	75% (on-site)	No added difference
B	Insulate and generate approach with planned behavioural changes.	67% (remote)	Carbon-neutral living (the household uses as much electricity per year as it produces)
C	Fabric first approach substantially improved airtightness. No behavioural changes.	70% (remote)	No added difference
D	Insulate and generate approach with sensible behavioural adjustments.	78% (remote)	No gas used to heat water during summer months.
E	Insulate and generate approach with sensible behavioural adjustments.	68% (remote)	The heating is not switched on until late into the heating season.
F	Whole house retrofit with planned behavioural involvement in the home operation.	92% (remote)	Some practices are changed not to use energy, such as a choice not to use tumble dryer.
G	Passivhaus retrofit. No behavioural changes.	80% (remote)	No added difference
H	Insulate and generate approach with planned behavioural changes.	90% (remote)	No added difference

Note: * carbon reductions savings are assessed by a representative of a SuperHomes network

The chosen combinations do not directly correspond with broader sustainability considerations of the households, which are described in more detail in section 5.1c. For instance, the interviewed homeowners in cases B and G both talked about their interest in energy sensible living. The interviewed homeowner in case B articulated his interest in “carbon neutral living”, and the interviewed homeowner in case G talked about her intention to achieve “low-carbon footprint” for the household. Despite this similarity, the chosen socio-technical combination for their buildings was drastically different. The owners in case G retrofitted their house to Passivhaus standard. The interviewee in this case reported that the household has “zero” behavioural adaptation to minimise energy use associated with heating and, instead, relies solely on the structure and technology to provide for low-energy use. The interviewee in case B, on the other hand, believes that one should not “go too crazy about anything” when it comes to retrofit. In order to meet Passivhaus requirements, it is likely that a thick level of insulation is needed, which the interviewee in this case finds “a bit silly”. The interviewed homeowner in this case believes that besides a technological change to the building and its services, a household should also “change [their] attitude a little bit”. The interviewed homeowner talked about “ample usage”, when describing operational energy use patterns in the household. The phrase means that in order to live on a very minimum electricity supply, the household makes sure that they don’t use several appliances at the same time.

A similar mismatch between an executed socio-technical approach and homeowners’ broader sustainability interests can be observed, when comparing cases A and H. In both cases a substantial improvement to the building envelope and services has been carried out. In both cases the owners do very little behavioural adjustment to further reduce operational energy use. One of the owners in case H makes sure that the lights are switched off when not in use. However, it is not part of habitual practice of another owner. The difference in the cases is noticeable when comparing broader sustainability interests. The owners in case H make an effort to help the environment, whenever they can. In case A, the owner feels that she did plenty in retrofit, and when it comes to ensuring low-energy use, she prefers to rely on the physical structure and technology to provide for it. She jokingly referred to this attitude as being a “champagne socialist”.

The dissimilarities in cases C, D, E and F are less obvious. All of the owners in these cases made significant improvements to the physical structure of their houses and their components. All of the owners exhibited sensible, or naturally frugal behaviour in relation to energy use. Their broader sustainability-related interests were somewhat different. The interviewees in cases C and E talked about an overall effort to live more sustainable life, whereas the interviewees in cases D and F talked about the feelings of independence and self-sufficiency in relation to energy use.

A striking similarity across all the cases was the level of knowledge the interviewees showed regarding the complexity behind the technological solutions of their low-carbon dwellings. The interviewees in cases B, C, F and E described their theoretical knowledge regarding low-carbon retrofit before the actual works as ‘good’ or ‘expert’. However, the owners in cases A, G and H stated that even though they might have had some knowledge on the subject before the actual works, most of the learning occurred during the retrofit process. The owner in case G explained that “a different relationship to your house” is shaped in the process of retrofit, during which the house becomes “your baby” as you grow to “know every corner” in it.

Interestingly, it seems that the retrofit-decision process the owners go through, if successful, results not only in high levels of knowledge regarding the technological solutions of their dwellings, but also helps the owners to accept and adapt to the suboptimal outcomes of their retrofit choices. With the exception of case A, in which the homeowner is a professional architect, in all other cases some unintended consequences or suboptimal solutions have been reported, whether they were energy or non-energy-related ones. For example, the owners in case C, who adopted a fabric first approach, reported a low ventilation rate. The final retrofit solution in case B allows for carbon-neutral living, which homeowners were aspiring to, but there is a slight discomfort to everyday life as the house overheats slightly during the summer. Moreover, the water tank, which is heated via solar energy, does not reach desired temperatures in winter, which means the household has to take cold showers. The owners are considering options to improve the situation.

The interviewed homeowners in cases D, E and H reported problems with the thermal regulation of the house, such as leaky doors or windows (cases D and E), or persistent draughts (case H). The owners in case G, who retrofitted the house to Passivhaus standard, found that some parts of the house lack daylight accessibility. The owners in case F, who did a whole house retrofit in one go, adopted several heating technologies with overlapping functions in order to secure that the needs of the family are met. Heating technologies included solar thermal; underfloor heating system that relies on a thermal storage, which in its turn is heated by a wood pellet boiler; two wood burning stoves and a mechanical ventilation heat recovery system. In retrospect, the interviewed homeowner found that so much technology was not needed. Nevertheless, none of the interviewed homeowners thought that these issues are of major concern. Thus, it can be suggested that a successful retrofit-decision process helps the owners to tolerate possible drawbacks, and successfully operate their building in a low-carbon manner.

This section discussed low energy use as an ongoing process in a socio-technical system of a low-carbon dwelling. The section looked at the similarities and differences in socio-technical combinations found in the cases studies. It was concluded that a successful retrofit-decision process is paramount for achieving low-carbon operational energy use post-retrofit. The next section analyses what makes a retrofit-decision process successful.

5.3. LOW-CARBON RETROFIT AS AN INNOVATION-DIFFUSION PROCESS

5.3a. Meaning of an 'innovation' in the context of low-carbon home retrofit: Clarification of the unit of analysis

The innovation diffusion literature focuses predominantly on diffusion of particular products or services. In the canonical case, Rogers (2003) looked into diffusion of a 2,4-D weed spray in an Iowa farm neighbourhood, rather than the spread of herbicides in general. Owen and Mitchell (2015) showed that the home retrofit-decision process does not necessarily imply a particular product from the outset. Instead, the process often starts from an identification of a design option before it moves to an identification of a particular product. This differentiation is visible in the case-studies as well. For instance, the owner in case D was determined to install solar PV panels (a design option). She then went through a formal tendering process and got quotes from three different companies, and, subsequently, made a choice which particular product to purchase.

The analysis of the case studies revealed yet another notable difference: the owners were implicitly or explicitly aware of the socio-technical system they were operating in. Sometimes, the choice of such system was done explicitly before the choice of particular design options. For instance, the owners in case G first decided to go for a Passivhaus, a choice that implies a particular socio-technical system. They subsequently went on to identify, whether they should do a lightweight or heavyweight type of construction for their extension (design option). More often the choice was implicit and was realised over a period of time.

It is argued in this thesis that an innovation-diffusion process of a low-carbon home retrofit implies three imbedded aspects: (i) a diffusion of an idea of a particular *socio-technical system*; (ii) a diffusion of an idea of different *design options* to realise this socio-technical system; and (iii) a diffusion of a particular *product* in mind. See Box 5.1 for the definitions of these three aspects.

Box 5.1. Three aspects of a low-carbon home retrofit as an innovation
(based on Cambridge Dictionary, 2018; du Plessis and Cole, 2011)

Socio-technical system. A socio-technical system of a low-carbon building involves interactions between natural laws, technological characteristics of a building structure and its components, and the action of its occupants, which in combination result in low-carbon operational energy use.

Design option. A design option is a solution for a particular design problem. For instance, internal or external wall insulation represent two design options to solve a problem of heat loss through walls.

Product. A product is something that is made to be sold, usually something that is produced by an industrial process or, less commonly, something that is grown or obtained through farming.

The analysis showed a difference in the diffusion of a design option and a particular product. The interviewees in cases B, C, D and E highlighted that they were aware of the design options before starting the retrofit, but took their time to familiarise themselves with new products on the market. For instance, the interviewed homeowner in case C explained that he did not learn anything new about design solutions during the retrofit project, however, he "learnt a bit about the products […] available at that time". Some owners talked about the short temporal dimension associated with innovation of particular products:

> It's such an evolution, as you know, with anything to do with energy sector… Products change so quickly… If I would now retrofit it again, I wouldn't even be able to buy the same products anymore. (case B, interview 2)

The owners talked readily about specific products and the manufacturing companies and/ or retailers they got these products from. However, they often talked about design solutions rather than particular products. Interestingly, in the situations where the owners grew dissatisfied with the retrofit outcomes, they tended to put the blame on a specific product, a manufacturing company or an installer, rather than the design solution itself. The owners would often still be convinced that the design solution is the right one, but they thought, they could have done a better job by choosing a different product. For instance, the interviewee in case B installed the battery tank for his solar PV and he still considers it a good decision. However, during the SuperHomes Open Day event he recommended others to go for a different product: "I would never recommend it [this product]. What I would recommend, is to go for a good one. Go for Tesla".

Several owners talked about dependencies between design options that exist in the system of a low-carbon dwelling, such as dependencies between the choice of insulation strategy and the choice of ventilation strategy. For instance, the interviewed homeowner in case G mentioned that "they didn't understand [such] dependencies" before retrofit. However, without an understanding of such dependencies there is a greater chance to deliver a solution that compromises the building integrity of thermal envelop or indoor air quality. Subsequently, there is a greater chance of unintended consequences such as thermal bridges and low ventilation rates. The interviewed homeowners in cases C and D emphasised that the tradespeople often cannot advise on an overarching vision for a socio-technical system of a low-carbon dwelling, as they are often concerned only with their particular trades they specialised in, and are not interested in delivering the best overall solution for the house:

> Try to have a conversation with a plumber about your plans to do insulation and install internal wall insulation, where you want radiators… They just want to stick radiators on the wall, and then get out of there… (case C, interview 1)

The interviewee in case C noted that even though there are places to learn about particular products and design options, there are almost no places for potential adopters to learn about socio-technical combinations and interdependencies that should be taken into account, when carrying out low-carbon retrofit:

> It, kind of, became even cleared to me, at the end of the retrofit, how few places there are, for an average householder to turn to for an energy advice… Yeah, I couldn't even begin to imagine, where you would start, if you had a knowledge base of zero in energy efficiency… If you don't really have a general grasp of building physics, and the importance of air tightness, and the continuity of insulation around the whole envelope, and that kind of thing… Yeah, I suppose, it's kind of a difficult thing to grasp…
> (case C, interview 1)

In summary, the interview analysis made it clear that a low-carbon home retrofit as an innovation diffusion process incorporates three imbedded aspects: (i) diffusion of particular products, (ii) diffusion of various design options, (iii) diffusion of an idea of a particular socio-technical system necessary to achieve low-carbon living.

5.3b. Evidence of retrofit-decision stages for different design options in the process of low-carbon retrofit

One of the most essential elements of Rogers' innovation diffusion theory is the conceptualisation of diffusion as a process of communication, where the innovation-decision process is an "information-seeking and information-processing activity" with various stages (Rogers, 2003: p. 14). It is possible for an individual to use the same communication channels to obtain information at each stage of the decision-making process. Nevertheless, the differentiation of information sources and channels by stage can serve as an indication of different stages in the innovation-decision processes. The interviews were analysed for evidence of different communication channels that homeowners used to obtain information at different stages of their retrofit decisions. The evidence is used to confirm the existence of stages in retrofit-decision process, both generic ones proposed by Rogers (2003) and specific ones proposed by Owen and Mitchell (2015).

None of the owners reported that they retrofitted to low-carbon standards immediately after they became aware of the possibility to do so. The transition of households through the decision process stages required a period of time that spanned months or years. The households received information from different sources and channels at different stages of the decision process, such as non-specialised newspapers and magazines, specialised sustainable construction events, interpersonal communication within professional network, tradespeople, specialised publications and interest groups or networks to name a few (Table 5.5).

Table 5.5. Sources and channels of information at different stages of retrofit-decision process

		Stages of the retrofit-decision process				
	Case	**Knowledge**	**Persuasion**	**Decision**	**Implementation***	**Confirmation**
Exp*	**A B**	Cosmopolitan professional network	Cosmopolitan professional network	Tradespeople, own judgement	National tradespeople and builders	SuperHomes network
Sust*	**C**	Nation-wide professional network	Local professional network	Tradespeople, own judgement, internet forums	Internet forums, YouTube videos, specialised publications	SuperHomes network
Sust*	**D E**	Nation-wide professional network	Local professional network	Tradespeople, builders they knew	Local tradespeople and builders, experts known through the workplace	SuperHomes network
Tech*	**F**	Publicly accessible information	Home Building & Renovation Show, builder-friend	Builder-friend, tradespeople	Local tradespeople and builder-friend	SuperHomes network
Tech*	**G**	Non-specialised public media	Passivhaus Exhibition and network	Passivhaus network	Local builders, cosmopolitan experts from Passivhaus network	SuperHomes and Passivhaus networks
Non-t*	**H**	Non-specialised journals, magazines and TV programs	Excel Ecobuild Exhibition, neighbours	Tradespeople, builders they trusted	Local tradespeople and builders	SuperHomes network

Note: Implementation stage includes three phases: option formalisation, installation and commissioning.

Exp – experts: professional builder or architect; **Sust** – professional background related to sustainable construction; **Tech** – non-construction specific engineering background; **Non-t** – non-technical background.

The distinction between the **knowledge and persuasion stages** was less pronounced for homeowners, whose professional background related in some way to sustainable construction (cases A, B, C, D, E). These homeowners became aware of different measures and technologies for low-carbon retrofit through their extended professional networks. Favourable or unfavourable attitudes towards different measures were also shaped by their immediate peers in their professional networks. The distinction between knowledge and persuasion stages was much clearer for the homeowners with non-construction or sustainability-related background (cases F, G, H). They were first exposed to the idea of low-carbon retrofit through non-specialised publicly accessible sources. The interviewed homeowner in case F first became aware about sustainable construction at high school, where he was asked to design his own environmentally friendly house as part of the school project. This owner found the school project so interesting, that since then, he always wanted to do an environmentally friendly house in real life. The homeowners in case H got their initial information from non-specialised journals and magazines, as well as TV programs. They continue to monitor these sources in an attempt to stay informed of the latest developments.

In cases F, G and H, homeowners did not have a construction or sustainability-related background, so they went to specialised industry events to obtain further information about different options, which signifies information-seeking behaviour during the **persuasion stage**. The owners in case F went to the Home Building & Renovation Show, the owners in case G went to one of the Passivhaus shows, the owners in case H went several times to the Excel Ecobuild Exhibition. They used these events to talk with experts, obtain further information and form their opinion about different measures and technologies. The owners in case H did several interventions over a period of time and they reported a clear distinction in information sources between knowledge and persuasion stages:

> We read papers. We read the *Times*, we read the *Observer*. They all have sections on homes. We read what people have done, and if we think we can do it, then we seek out an expert. (case H, interview 1)

The interview data analysis suggests that two kinds of interpersonal channels are used to form an opinion about a particular retrofit option at the persuasion stage: construction experts and other homeowners, who already did similar works. Low-carbon retrofit is a complex technical solution and appropriate technical advice from experts is essential to make an informed decision. The homeowners in all the cases sought such advice. Nevertheless, all the homeowners in the sample recognised that expert advice is not enough to form an opinion, it is also important to see what other people like them have done to their homes. The owners in case H got initial information from other owners, who did similar retrofit. Sometimes, it was their neighbours, sometimes they got such stories from public journals and magazines. The owners in case H highlighted that “it is a big incentive to see that other people are doing it and it worked for them”. Not all the owners mentioned explicitly the use of such information channels, but all of them joined the SuperHomes network as they felt that their experience could benefit others.

As homeowners make their **decision** to go ahead with particular design options, they proceed to gather further information on particular products. One of the homeowners in case H made a clear distinction between the two phases:

> So, what we are saying is, even if you got a plan to do it, you still are only half way there. Because lot of the people, who are selling you something, it isn't appropriate. And then you still have to consider if you getting the best deal. (Case H, interview 1)

The owners with a professional background in construction (cases A, B) tended to make the final choice based on their personal judgement. The owners with no such background (cases C, D, E, D, F, G and H) were more prone to look for reassurance from other channels, such as professional networks, product or company's reviews, internet forums etc.

It can take a significant amount of time between an inception of an idea about a design option to the actual installation of a product. Case H provides a good illustrative example of the length of different stages, as the owners in this case took their time to form their *decisions* before proceeding to the *implementation* stage, thus, the decision stages unfolded in a relatively linear fashion. As one of the owners said it takes time to "mature your decision". Homeowners in case H completed the low-carbon retrofit in six independent retrofit steps, which took them about 25 years to complete. The owners recalled: "I think we have done things little by little… and also each renovation then lets us know what else is needed". The *decision* and *persuasion* stages in each step took much longer than the *implementation* stage (Figure 5.1). For some installed measures the owners in case H were able to recall quite precisely how long it took them from the moment they got an initial idea until the moment they implemented it, which was about three years for external wall insulation, two years for the loft conversion and insulation, and five years for the solar PV. For each of these measures the actual construction works ranged from a couple of days to a couple of weeks. The owners recalled that it took less time to decide on the loft, compared to the decision on the external wall insulation, because some of their neighbours already had their loft done, so they went around people's houses and got inspired. It took longer to decide on the solar PV as the owners were initially advised that they are not eligible for the governmental support scheme because of the roof orientation.

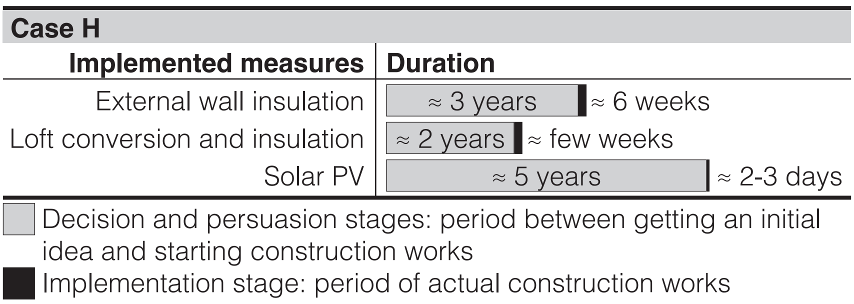

Figure 5.1. Length of first three stages of retrofit-decision process in case H

The **implementation stage** of low-carbon retrofit is easily distinguishable, as it is the period when the retrofit works are carried out. All three phases of the implementation stage, outlined by Owen and Mitchell (2015), are visible in the case studies. *Option formalisation* is characterised by the need to acquire planning permission for some works. All the owners had to acquire planning permission from their local planning authority either for all works, or part of the works. This phase is also characterised by a formal tendering process. For instance, when changing their windows to double-glazed ones, the owners in case C went to get six quotes from different companies about their specific products, and made their final decision based on the information they obtained.

Installation works can take from a few days to a few months, depending on the scale of the project. At the time of construction, further information is gathered as required from tradespeople, internet forums or experts. The information sources are very different at this stage. The owners in case C carried out the works as a do-it-yourself (DIY) project. It was the first time they did such works, and the owners spent a lot of time on the Internet watching videos, reading forums and magazines or even "looking at the conventional way of doing things and then putting an energy efficiency twist on it". The owners in case F relied heavily on the opinion of the builder, in whom they had great trust, as he was a long-term family friend. The interviewed owner in case E, who manged the retrofit project, hired a local builder with no previous experience in low-carbon retrofit. She then hired a sustainability consultant through the recommendation from the previous workplace, who transferred practical knowledge regarding low-carbon retrofit to the builder on site. The *commissioning* phase of the implementation stage was the least visible in the case studies. The only notable example was case G, in which the house got officially accredited and received a Passivhaus label, after passing a pressure test.

The **confirmation stage** is easily distinguished for the homeowners in the sample. They all joined the SuperHomes network after the retrofit, in order to share their experience with other people who may consider a home retrofit to low-carbon standards. Some owners also sought validation for the decisions they made. The interviewed homeowner in case F had no idea of the level of carbon reductions achieved as a result of retrofit. He decided to join the SuperHomes network partly to acquire this information. A representative from the SuperHomes network made an evaluation of the carbon reduction achieved as part of the process of granting a SuperHomes label to the house. The homeowner was very pleased, literally "blown away", to find out that they achieved 92% of carbon reductions.

During the second set of interviews the researcher shared preliminary results with the participants, which included the evidence of five retrofit decision stages for each case. All of the interviewed homeowners agreed with the staging evidence presented to them. This confirmation strengthens external validity of the results.

In summary, the different information sources and channels the homeowners used can readily indicate different stages of the retrofit decision-making process. Several networks can play a role at different stages of the innovation-decision process, starting from family and friends in the beginning of the process to expert opinion towards the end of the process. The sources tend to be more media-based during the initial stage of acquiring knowledge and becoming aware of a particular technology. Interpersonal networks tend to play a greater role at the persuasion and confirmation stages. At the implementation stage information sources include internet reviews, technical documentation for various products as well as information from the construction team.

5.3c. Implementation difficulties in the process of low-carbon home retrofit

The interview analysis showed that a successful retrofit-decision process helps the owners to use their buildings in a technologically optimal manner, accept and adapt to shortcomings, if any. In line with this observation, the interviews were analysed to understand homeowners' experience of going through the retrofit process itself. The interview analysis provided evidence that retrofit can be an unpleasant experience for a household (Table 5.6).

Table 5.6. Experience related to retrofit process

	Case	Length of main retrofit works	Time when works are carried out	Retrofit strategy in relation to dwelling occupation	Intensity of the experience	Finishing on time, within planned scope and budget
Exp*	A	6 months	during working hours	void	a bit easier than expected	success
	B	4 years	after work, weekends	in situ	a bit tiring	success
Sust*	C	3 years	after work, weekends	in situ	a bit tiring	success
	D	2 years	after work, weekends	in situ	a bit tiring	moderately unsuccessful
	E	6 months	during working hours	void	neutral	success
Tech*	F	1 year	after work, weekends	in situ	very tiring	hugely unsuccessful
	G	1 year	after work, weekends	first void, then in-situ	completely unbearable	hugely unsuccessful
Non-t*	H	2–3 weeks	after work, weekends	in situ	neutral	success

Note: [grey box] Experiences with negative connotations regarding retrofit process

Exp – experts: professional builder or architect; **Sust** – professional background related to sustainable construction; **Tech** – non-construction specific engineering background; **Non-t** – non-technical background.

First, there were concerns about project duration. For most cases the main retrofit works lasted from six months to four years (case A, B, C, D, E, F and G). The interviewed owner in case F reports: “It was just a long project. And lots of, lots of work”. Second, most of the owners in the sample did their retrofit projects after working hours, on the weekends and during their holidays (cases B, C, D, F, G and H). As the interviewed homeowner in case C recalls: “We did that ourselves over the weekends…” The interviewed homeowner in case B mentioned working “16 hours on the weekend”. As the owner in case D summarised it: “Life is pretty full on doing it [retrofit] and working”. Third, most of the owners in the sample lived in the property during the retrofit process, which was a challenging experience (cases B, C, D, F, G and H). As the interviewed owner in case G noted “we lived within building works, we couldn’t leave the house…” The owner in case D reflects on her experience:

> This is living in chaos. Yeah, dust everywhere. And, as I said, cooking on camping stove. My son’s bedroom in pieces [laughing] and he is sleeping on a mattress on the floor in another room. That kind of stage. (case D, interview 2)

Fourth, most of the owners reported the experience being somewhat tiring (cases B, C, D, F, G and H). The interviewed homeowner in case G reported the most overwhelming retrofit experience in the sample, recalling: "Going this way, I think it [project] probably would have broken a few marriages, I think". Other homeowners did not put it in such strong words, but still reported being tired and overwhelmed:

> Consistently a bit tired and overwhelmed… Yeah, never at a breaking point and completely unbearable… It becomes quite draining at some point. You come in from work, change into your work clothes and start… And then you are always tired and it gets overwhelming… It was never easy or plain sailing at any stretch… (case C, interview 2)

Fifth, some negative messages were concerned with finishing the project on time, and within the agreed scope and budget. Some cases were not successful in this. In case D not all the planned works were carried out, as some project phases were more expensive than initially anticipated, and the owner simply ran out of money. In cases F and G the projects grew out of scope, and, as the interviewed homeowner in case F reported, "took longer and cost more money" than originally anticipated.

This section analysed what makes a retrofit-decision process successful. First, the meaning of an 'innovation' in the context of low-carbon home retrofit was clarified. This thesis argues that an innovation-diffusion process of a low-carbon home retrofit implies not one, but three units of analysis: a product, a design option and a socio-technical system. The section then proceeded to show evidence of stages in the process of retrofit decisions. Finally, interviews were analysed for the evidence of implementation difficulties associated with low-carbon home retrofit. The interview analysis provided evidence that retrofit has a potential to cause a serious disruption to a household life. The next section describes how different retrofit strategies affected homeowners' retrofit experience, helping to ease implementation burden associated with such retrofit in some cases.

5.4. EFFECT OF A RETROFIT APPROACH ON IMPLEMENTATION BURDEN

A negative experience of a low-carbon retrofit could result in homeowners' negative impression of the installed measures themselves. However, even a difficult retrofit project does not have to result in the formation of a negative experience by the homeowners. Some interviewees in the case studies reported being tired and overwhelmed with the retrofit, while others did not. This section looks at the effect of different variables, in particular retrofit strategies, on the formation of a positive or negative experience regarding retrofit.

The need to work for long hours is the most widely assumed cause of persistent fatigue (Hockey, 2013). However, there is less evidence that working hours and time allocated to meet desired goals per se are responsible for development of the feeling of fatigue (ibid.). This corresponds with findings in the case studies carried out as part of this research, where no immediate link was visible between the length of retrofit works and associated post-retrofit feelings of fatigue (Table 5.7).

The cases differed in terms of retrofit timing. In cases A, E, F and G the works were planned from the outset and carried out in one go. However, in cases A and E no feeling of fatigue has been reported, whereas in cases F and G the owners described the experience as very tiring and even completely unbearable. In cases B, C, D the owners carried out the works as separate work packages over time, which were planned altogether from the outset. The whole journey to meet the initial goals took them from two to four years. The interviewees in cases B, C, D described their retrofit experience as a bit tiring. The difference in their experience became visible, when they were asked whether they would do such work again. The interviewees in cases B and D were very enthusiastic about going through the experience again, whereas the interviewee in case C said that it is possible that his wife would not be happy to do such a challenging project again in her life. Case H is the only case study in the sample that represents a retrofit strategy, in which the owners did not plan the whole retrofit from the outset, but rather made a series of separate changes over time, each of which was planned and carried out individually. Such works could be described as minor and each of such works were carried out within 2–3 weeks. The owners did not report the feeling of fatigue.

Table 5.7. Effect of retrofit length and strategy on retrofit experience

Cases	Strategy of carrying out retrofit	Length of main retrofit works	Reported maximum feeling of fatigue
A	Separately planned major retrofit works	1 year	It was a bit easier than she thought
B	A series of separate changes, planned from the outset and carried out over time	4 years	A bit tired
C	A series of separate changes, planned from the outset and carried out over time	3 years	A bit tired, might not do it again
D	A series of separate changes, planned from the outset and carried out over time	2 years	A bit tired
E	Separately planned major retrofit works	1 year	Neutral
F	Separately planned major retrofit works	1 year	Very tired
G	Separately planned major retrofit works	1 year	Completely unbearable
H	Separately planned minor retrofit works	2–3 weeks	Neutral

The development of the feeling of fatigue cannot be attributed solely to the project duration, but should be understood together with the retrofit timing strategy; previous experience with similar projects; retrofit strategy in relation to dwelling occupation; the physical condition of the house, especially if the household lived in the property during construction work; the level of involvement of the household in the retrofit activities and the associated burden and stress; and the success of the project management, i.e. whether the project was finished in time, within planned scope and budget (Table 5.8). The rest of the section explains the development or non-development of the feeling of fatigue observed in the cases.

Table 5.8. Effect of different retrofit strategies on retrofit experience

Cases	Reported maximum feeling of fatigue	Previous experience of similar projects	Retrofit strategy in relation to dwelling occupation	State of repair before retrofit	Retrofit team structure	Finishing on time, within planned scope and budget
A	It was a bit easier than she thought	Professional architect, no sustainability-specific experience	Void	Habitable conditions	Builders managed by owner	Success
B	A bit tired	Expert knowledge	In situ	Habitable conditions	DIY	Success
C	A bit tired	Expert theoretical knowledge, no practical knowledge of construction	In situ	Disrepair	DIY	Success
D	A bit tired	Expert theoretical knowledge, some useful practical knowledge of construction	In situ	Habitable conditions	Builders managed by owner	Moderately unsuccessful
E	Neutral	Good theoretical knowledge, some useful practical knowledge of construction	Void	Disrepair	Builders managed by owner	Success
F	n/a	Some theoretical knowledge, no specific knowledge on construction	In situ	Habitable conditions	Owner alongside a builder-friend	Hugely unsuccessful
G	Completely unbearable	Some incorrect theoretical and practical knowledge on low-carbon construction	First void, then in-situ	Disrepair	Builders managed by owner	Hugely unsuccessful
H	Neutral	Some incorrect theoretical and practical knowledge on low-carbon construction	In situ	Habitable conditions	Builders managed by owner	Success

Note: [white] Separately planned major retrofit works (case A, E, F, G)
[light grey] A series of separate changes, planned from the outset and carried out over time (case B, C, D)
[dark grey] Separately planned minor retrofit works (case H)

5.4a. Planned in-depth retrofit in-one-step. Cases A and E

The interviewees in cases A and E did not report any feeling of fatigue. The interviewed owner in case A is a professional architect, thus, she had good theoretical knowledge about construction, as well as good practical experience of carrying out projects of similar size and scope. Even though she had no previous low-carbon-specific knowledge, her experience allowed her to make a good estimate of required effort needed before commencing on a project. She also lived elsewhere during the project and carried out the project during normal working hours as part of the normal job of the architectural studio she owns. No feeling of fatigue has been reported.

One of the owners in case E worked previously in sustainability construction consultancy. She hired a builder with no previous experience in low-carbon retrofit to do the job. She hired subsequently a sustainability consultant, who transferred practical knowledge regarding low-carbon retrofit to the builder on site. Even though she had enough theoretical knowledge to supervise the works, in hindsight she would have preferred to hire a builder with previous experience in low-carbon construction. This owner also quit her job to supervise the construction. The household did not live in the property during construction. Thus, for the household the retrofit experience did not overshadow the rest of their lives. The interviewed owner recalls:

> So, I'd probably say, [I spent] maybe four hours [per day on retrofit activities]. And that was a luxury. It's because I wasn't working. I had all the time I needed… I had my children, I had a few other things. (case E, interview 1)

5.4b. Planned step-by-step retrofit. Cases B, C and D

The interviewees in cases B, C and D reported being only moderately tired with the retrofit, despite having full-time jobs during retrofit works. The households in these cases lived in their properties during the retrofit works, which helps to explain the feelings of being tired and overwhelmed with the retrofit. One of the owners in case B worked in sustainability construction in mainland Europe. He had an extensive theoretical and practical knowledge of carrying out works of similar type and scope. The project took about four years, and the project duration meant that their living experience was significantly shaped by the retrofit, as the owners had to compromise other aspects of their lives for this period. Thus, the experience was draining at times. Nevertheless, the owners did the works DIY at a comfortable pace and carried out the works in "the most logical order to make it comfortable to live in". Doing retrofit themselves also meant that they could take a break or a holiday whenever they felt it was needed:

> Well, it was really few occasions when it was really bad. We literally just went on holidays, just took a weekend off. Just do not see the building site, because that really helps. We just had to be physically removed from the building site, just going away. Just went for a week in Cornwall, or for a weekend in the Cotswolds. Just to be away, just to be physically removed a bit… that kept us both going, kept me going, absolutely. (case B, interview 2)

The owner in case D worked as a project manager in sustainability construction consultancy. Thus, she had expert theoretical knowledge regarding low-carbon construction and some useful knowledge regarding project implementation. The owner divided the project into smaller works, to manage it easily and control the work quality. The owner hired different tradespeople with experience in sustainability-related retrofit for their specific trades to carry out the works. She had sufficient theoretical knowledge to supervise the construction. The house was in a habitable condition, and allowed them a reasonable comfort of living during retrofit works. The owner worked as a project manager in sustainability construction consultancy and felt obliged to use the products and builders that she recommends to others as part of her daily job. Nevertheless, she was not always satisfied with the choice of the builders and the retrofit options. This might have affected the formation of a moderately negative impression of the retrofit experience.

One of the owners in case C worked as an architectural technologist in sustainability construction consultancy. Thus, the household had an extensive theoretical knowledge about low-carbon construction. They decided to do retrofit DIY, while living in the house. They had no previous experience of neither construction works nor managing projects of similar size and scope. The owners took their time to learn how things should be done properly, building in confidence in their retrofit-related decisions. The owners misjudged the amount of learning required to get appropriate practical knowledge regarding construction. The owner recalled that they "didn't probably anticipate [the learning to be] the hardest part of it". It was a really steep learning curve that required considerable time to research and get the necessary information. The owners did the works themselves and had no exogenous time constrains in doing the research to obtain the necessary knowledge. Nevertheless, the house was in major state of disrepair before the retrofit and the conditions were far from habitable or even safe. It took time until the conditions reached a state, when the owners could live reasonably comfortably in the house, and continue with the project. This means that before this state was reached, the owners did not have the opportunity to recover at home from the daily work or retrofit-associated stress.

5.4c. Planned in-depth retrofit in-one-step with no prior experience. Cases F and G

The interviewees in cases F and G reported being overwhelmed with their retrofit experiences. The implementation difficulty of low-carbon retrofit solutions is associated with the level of the team's practical knowledge of sustainability-related construction. One of the owners in case F has a non-construction-specific engineering background in IT engineering. This owner was an active member of the project team alongside a builder-friend and was involved in technical design and construction. The builder-friend had no previous knowledge in low-carbon construction, and neither did the owner. The owner decided to learn by doing. The household lived in the house during construction works and decided not to rush things and take their time to gain sufficient practical knowledge and find the best solution. The fact that the builder was a long-term friend of one of the owners helped to establish a close, trusting relation during construction works:

> The builder is a long-term friend of mine and he is very experienced at property renovation. He is very open and honest about what he could and couldn't achieve, and open to ideas. We worked closely throughout the whole project, and it was extremely useful. Because I've chosen him as the builder, he was a lot easier and more comfortable on my basis. And rather than me going out to tendering, and fully specifying, we knew we could build it and run the journey that way. So that was a lot easier. We probably spent more money as a result of that. If we had done it through a different supplier, we'd have to be much more rigorous in this, and know exactly what we want. But we'd probably then finished up with a compromised solution, because we wouldn't have ended up getting what we really wanted. (case F, interview 1)

Despite this positive experience, the project management was not successful in case F, and the project grew out of scope and budget and was not finished on time with some of the planned works not being implemented at all. For instance, the owners "had aspirations to build the conservatory, but the money was gone, so [they] put some decking there and had the decking ever since". As a result, the post-completion satisfaction with the overall journey was reduced.

The owners in case G had non-construction-specific engineering background in IT engineering. The interviewed homeowner highlighted that their background in IT engineering allowed them to quickly grasp the principles of building physics. The owners decided to retrofit to

Passivhaus standard, which allowed them to do intermediate quality checks to Passivhaus standard to ensure the quality of construction. Nevertheless, none of the members of the construction team had any previous knowledge of Passivhaus construction, and one of the owners became a Passivhaus certifier in the process of obtaining practical construction knowledge. The idea to retrofit to Passivhaus standard came two months before the construction works began. The house required major layout changes, and the owners hired builders to do the retrofit and were interested to finish their projects as soon as possible, so they did not have to pay for the extra time. Thus, the owners did not have the luxury to take their time to do the research at a comfortable pace. The interviewed owner in case G recalls the difficulty of project planning, logistics and being actively involved in the construction process under conditions of limited time:

> We were building the house in the day, and we were trying to plan for the next week in the night, so we didn't sleep. We just tried to be ahead a little bit for the works to happen. (case G, interview 1)

What enabled the owners to overcome the retrofit-related difficulties was the excellent level of communication, respect and trust between the owners and the builders, which was crucial to deliver high quality work. As an interviewed owner in case G reported they had to be "hands-in-hands with the builders" and "it had to be a real teamwork". Both owners in case G were self-employed at the time of retrofit works, which allowed them to be flexible with their time and reallocate their time to the project as required. The owners moved to the house before it was finished, thus, they had limited opportunities to recover from daily stress. The retrofit was such an exhausting experience, that the interviewed homeowner described it as being absolutely unbearable at times. The owners disengaged from further retrofit activity such as decoration, as soon as the house was in habitable condition. They took about a year to restore before they were willing to engage in any further effortful activity. The project management was also not a success, as the process took longer and cost more than initially planned.

5.4d. Emergent step-by-step retrofit. Case H

Interesting dynamics were observed in case H. The owners in this case lived in the house during retrofit, thus, had little opportunity for daily recovery from stress. The owners had no background in architecture or engineering, or any other technical background. The husband in the household is a guitar teacher, the wife does acupuncture, medical research and recently started painting. As a result of lack of the relevant theoretical knowledge, they never eliminated the uncertainty that works that were carried out during the retrofit would result in what the owners initially envisioned they would, or even that the works were carried out correctly altogether. This remaining uncertainty is visible in one of the owner's description of their PV roof:

> It's only been two years, we've still got plenty of time, it [solar PV] could still collapse at some point. (case H, interview 1)

The owners also did not have previous experience of carrying out projects of similar size and scope. They felt that they could not trust tradespeople completely as they received conflicting information and "bad advice", which made it necessary for them to make their own judgement, which advice to follow. The owners reported that, if they had followed some bad advice they received, the overall project "could've gone pear shaped".

Overall, all these circumstances provide perfect conditions to develop a feeling of fatigue and an overall negative impression of the retrofit process. Nevertheless, the owners did not report feelings of fatigue. This can partly be explained by the length and the nature of construction works themselves, which are best described as measure-by-measure retrofit without an overarching vision of the final solution. Each individual measure was installed within few days or few weeks. It is theorised here that as all of the works were small in size, the time required to finish them was not enough for the feeling of fatigue to develop up to a level that would make owners form a negative impression of the retrofit process.

In summary, different circumstances played a role in the process of fatigue development in the case studies: the length of the project; the retrofit timing strategy; previous experience with similar projects; retrofit strategy in relation to dwelling occupation; the physical condition of the house, especially if the household lived in the property during construction works; the level of involvement of the household in the retrofit activities and associated burden and stress; and the success of the project management, i.e. whether the project was finished in time, within planned scope and budget. Nevertheless, as observed in case H, even under most unfavourable conditions, the feeling of fatigue might not develop during the project, if the project is carried out step-by-step to allow comfortable time for building confidence in retrofit solutions, as well as time to recover from disruptions to everyday life associated with retrofit works. The next section summarises the findings presented in the chapter.

5.5. SUMMARY OF THE FINDINGS ON INDIVIDUAL RETROFIT-DECISION PROCESSES

This chapter used a conceptual framework of home-meanings, an understanding of a building as a socio-technical system, Rogers' innovation diffusion theory and the idea of implementation difficulties to conceptualise low-carbon retrofit decisions as contextually embedded processes. This theoretical conceptualisation was used to develop further insights in the nature of these processes.

To understand the context of retrofit decision the chapter identified re-occurring themes in retrofit goals, post-retrofit experiences and associative experiments of eight homeowners in the thesis sample, who achieved at least 60% carbon reductions as a result of retrofit activates. The themes were derived deductively from the framework of home-meanings developed in *Chapter 2*. Low-carbon dwellings were found to be associated with a broader notion of comfort, safety, security and control, as well as an extra-domestic identity of a broader social responsibility. The chapter delved further into the home-meanings literature to bring together ideas about the notions of comfort, safety, security, control and identity in relation to one's home. The reoccurring character of everyday mundane activities was found to contribute to the establishment of all of these feelings. The home environment was identified as an important setting to establish various identities, such as the ones of gender or sexuality, which are simultaneously shaped in the context of one's home. It was suggested that a newly identified extra-domestic identity of a broader social responsibility is not in contrast to other identities supported by one's home environment.

The chapter than proceeded to view low-carbon operational energy use as an ongoing process in a socio-technical system of a low-carbon dwelling. A variety of technological improvements and behavioural adaptations, which together resulted in a minimisation of operational energy use, were observed in the case studies. It was concluded that a successful retrofit-decision process is paramount for a successful post-retrofit energy use. The chapter then proceeded to analyse what makes a retrofit-decision process successful.

The meaning of an 'innovation' in the context of low-carbon home retrofit was clarified. This thesis argues that an innovation-diffusion process of a low-carbon home retrofit implies not one, but three units of analysis: (i) an idea of a particular socio-technical system; (ii) different design options that can help to realise envisioned system; and (iii) particular products that are used in the retrofit. The evidence was gathered for the existence of different communication channels and sources of information at different stages of retrofit-decision processes, which justifies the appropriateness of the use of Rogers' innovation diffusion theory to conceptualise retrofit decisions. The interview analysis distinguished two types of interpersonal communication networks used by the homeowners during the *persuasion* stage: sustainability experts and other homeowners, who did similar works. The analysis suggested that the type of information received from the homeowners is not equivalent to the type of information received from the experts, and thus cannot be fully substituted by it. Thus, provision of access to social networks, where homeowners can exchange the information on different products and construction experts, can help to shorten the *persuasion* period of individual actors.

Finally, interviews were analysed for evidence of implementation difficulties associated with low-carbon home retrofit. The analysis provided evidence that retrofit has the potential to cause serious disruption to household life. Such potential disruption was associated in the case studies with: (i) the length of the project, which lasted up to four years in some cases; (ii) the timing of retrofit works, which for many homeowners in the sample took place after working hours, on the weekends and during their holidays, as many homeowners were in full time occupation during the works; (iii) an inability to relax and restore during retrofit works, as many households lived in the property during construction period; (iv) extra pressure associated with retrofit-related responsibilities, as many owners were active members of construction teams, managed their projects, ordered materials and liaised with authorities; and (v) the possibility of not finishing the project on time, within the planned scope and budget, which increased the amount of stress related to retrofit. A detailed case-by-case analysis of retrofit journeys allowed to suggest that a step-by-step retrofit approach can ease implementation burden associated with retrofit, regardless of the level of homeowner prior theoretical and practical knowledge regarding low-carbon construction, or their retrofit strategy in relation to dwelling occupation.

This chapter looked at the overall decision process related to low-carbon retrofit. The next chapter looks at the implementation stage, specifically at the implementation burden associated with low-carbon retrofit process.

Chapter 6

A system dynamics model of retrofit-related psychological fatigue

The results from *Chapter 5* reveal that tiredness related to retrofit process is one of the reasons why homeowners form a negative impression regarding low-carbon home retrofit. The results further highlight that a positive experience about the retrofit process is important to generate a positive word of mouth spread that can help to persuade other homeowners to retrofit their homes, which in turn can accelerate the transition to a low-carbon housing stock. Homeowners identify the inconvenience and disruption to everyday household activities associated with low-carbon retrofit as a reason not to engage in retrofit. Nevertheless, the results presented in *Chapter 5* show that the formation of a negative experience associated with low-carbon retrofit process is not inevitable, regardless of the disruption it brings to occupiers' everyday life. To investigate further the formation of fatigue during retrofit, this chapter develops a system dynamics model of psychological fatigue and uses it to suggest policy interventions to minimise fatigue development in the process of low-carbon home retrofit. Section 6.1 provides the theoretical background to conceptualise fatigue development during the retrofit process. Section 6.2 develops the theoretical conceptualisation discussed in section 6.1 into a causal loop diagram. The diagram is formalised into a simulation model in section 6.3. Section 6.4 discusses model testing and validation. Section 6.5 presents simulation results for various behavioural tests and case studies. Section 6.6 explores different scenarios. Section 6.7 explains the results in light of the research question. The chapter concludes with a brief summary in section 6.8.

CHAPTER CONTENTS

6.1. CONCEPTUALISATION OF RETROFIT-RELATED PSYCHOLOGICAL FATIGUE

The results presented in *Chapter 5* highlight the implementation difficulties in the uptake of low-carbon home retrofit among UK homeowners. Insights were developed with the use of Rogers (2003) innovation diffusion theory and an understanding of a building as a socio-technical system. Nevertheless, this combination of theoretical lenses was not able to offer further insights into the dynamics of development of retrofit-associated psychological fatigue. Another theoretical lens is required to do so. This thesis uses a generic model of psychological fatigue to develop insights into the problem of retrofit-related psychological fatigue. This thesis argues that retrofit-related psychological fatigue has much in common with work-related psychological fatigue, and thus, the insights obtained from the study of the latter are applicable to the former. Thus, this thesis proceeds to understand work-related psychological fatigue in general and ways to neutralise it, and then applies the findings to retrofit-related psychological fatigue in particular.

6.1a. The outline of Hockey's motivation control theory of psychological fatigue

Fatigue has a widespread impact on human life as it affects many people's quality of life on an everyday basis. It is not a surprise that theoretical and practical research on the topic has a long tradition (Hockey, 2013). Despite the long history of research on understanding fatigue, the process of fatigue development is not fully understood. How is it possible for an individual to be tired, if he/ she does not seem to have done very much? How is it possible for an individual to quickly recover from fatigue under some conditions, but not others?

Several theoretical models on fatigue development exist in the literature. A comprehensive overview of these models can be found in Hockey's 2013 monograph, which is "the first dedicated to the scientific treatment of the topic of fatigue for more than 60 years, since Bartley and Chute's (1947) comprehensive review" (Hockey, 2013: p. 4). Hockey points out a confusion in the current literature between different types of fatigue: psychological, physical and sleepiness. He argues that physical and psychological types of fatigue have the same underlying mechanisms, while the development of sleepiness is underpinned by entirely different mechanisms. To avoid the confusion this thesis focuses solely on psychological fatigue.

Hockey makes a comprehensive evaluation of current models and proposes his own theoretical model, which he calls *motivation control theory of psychological fatigue*. He argues that his theory addresses the limitations, he identifies in current models of psychological fatigue. This thesis makes no attempt to re-evaluate existing theoretical models on psychological fatigue. The thesis uses Hockey's theory to understand the development of psychological fatigue in the process of low-carbon home retrofit. A brief overview of the theory is outlined in the rest of the section. The following paragraphs contrasts a widely accepted view on fatigue within psychology, which Hockey refers as the *work-fatigue hypothesis* (ibid.), with Hockey's own theory.

The work-fatigue hypothesis is a widely accepted view on fatigue within psychology, which explains its origin in terms of exhaustion of energy (ibid.). This hypothesis proposes that prolonged periods of work inevitably lead to energy resource depletion and a reduction in performance. This view has its origin in the work of Freud and Jung, among others, and has had a major influence on cultural thought in the first half of the twentieth century (ibid.). However, advances in research on human brain activity demonstrate that the brain consumes a stable amount of energy whether in rest or in stressful situation (ibid.). The variation of energy consumption is around 1% and there is never a sign of approaching a state of energy depletion. Thus, the explanation of fatigue development in terms of energy exhaustion is inconsistent with the modern understanding of the brain function.

The work-fatigue hypothesis suggests that prolonged periods of work lead inevitably to a reduction in performance. Nevertheless, increasing empirical evidence suggests that working for long hours or under stressful conditions does not necessarily lead to a performance breakdown. Similarly, it is now understood that a performance breakdown might not be the only behavioural outcome associated with fatigue. Instead, fatigue might result in a loss of interest in the current activity or a resistance to get involved in other effortful activity immediately after the current task is complete. Thus, the work-fatigue hypothesis is not a good basis to explain the variation in work management strategies.

The motivation control theory of fatigue proposed by Hockey offers an alternative to the understanding of fatigue development, which is in line with the modern understanding of the problem in psychology, as well as a modern understanding of the brain function in neuropsychology. The theory of psychological fatigue outlined by Hockey in his paper (1997) and in more detail in his book (2013), conceptualises fatigue development not in terms of energy depletion, but rather as a conflict in the "control of motivational choices — an unwillingness to continue with an activity that was unrewarding, rather than an inability to complete one that was too demanding" (Hockey, 2013: p. xiv). This conceptualisation does not contradict the modern understanding of the brain function. Moreover, it allows the capturing of different behavioural response patterns associated with the feeling of fatigue that depend on individual motivational priorities, and, thus, explain three different work management strategies: engaged, strain and disengaged.

Hockey's theory views psychological fatigue as an emotion, which may be felt as low mood, or an inability to focus, or an unpleasant bodily state such as headache (ibid.). In more extreme cases, fatigue can be felt as physical and emotional exhaustion, a profound lack of motivation or even depression. The feeling of fatigue is most commonly associated with tiredness, but it is more complex than that, and includes elements of boredom, frustration and anxiety, discomfort and even a loss of engagement with the goal (ibid.). From the evolutionary psychology perspective emotions are considered to operate as a mechanism, which set direction for human behavior in the context of one's goals and environmental situation (ibid.).

The feeling of fatigue serves to maintain the motivational equilibrium of an individual by interrupting the motivational fixation on current activities. Fatigue allows a reassessment of alternative choices for action, and ultimately directs behaviour towards the goals that bring greater rewards at lower costs to the individual (ibid.). The theory has its meta-theoretical origins in *control theory*, and conceptualises fatigue as a two-level control system: routine regulation of well-learned activities, which is not considered effortful (loop A); and effort-based regulation of performance, in which desired performance can be maintained at a cost of increased effort (loop B). Hockey uses a *block diagram* for pictorial representation of the theory (Figure 6.1). However, his diagram does not follow standard block diagram convention, established in control engineering, which makes it difficult to read and interpret the diagram. A summary of established block diagram conventions can be found in Box 6.1.

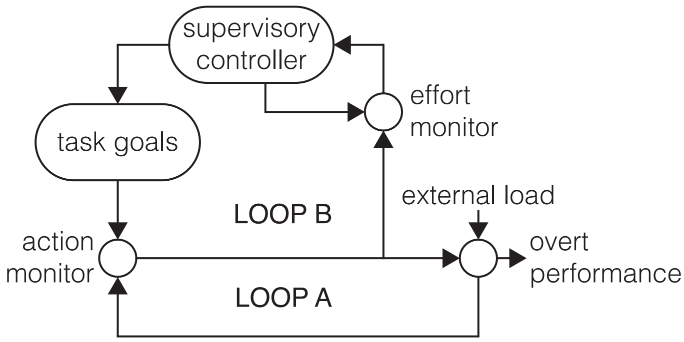

Figure 6.1. Compensatory control model of performance regulation (adapted from Hockey, 1997: p. 79)

Box 6.1. Block diagram conventions (based on Ogata, 2002)

A *block diagram* is a diagram of a system (Figure 6.2), in which principal functions are represented by blocks that are connected by arrows that show unilateral relationships between the blocks. An arrowhead pointing toward the block indicates the input, and an arrowhead leading away from the block represents the output. The block itself represents the mathematical operation of the input signal to the block that produces the output. Thus, the dimensions of the output signal equal the dimensions of the input signal multiplied by the dimensions of the transfer function in the block.

A *summing point* is represented by a circle with a cross. The plus and minus signs at each arrowhead indicates whether the signal is to be added or subtracted. A *branch point* is a point from which a signal goes concurrently to other blocks or summing points. Figure 6.2 gives an example of a block diagram of a temperature-control closed-loop system. The output *C(s)* signal, which has the dimension of temperature is converted to voltage with a transfer function *H(s)*. The corresponding output *B(s)* is then fed back to the summing point, where it is compared with the reference input *R(s)*. The resulting difference *E(s)* is used as an input to the block, in which a transfer function *G(s)* is used to obtain the output *C(s)* and complete the loop.

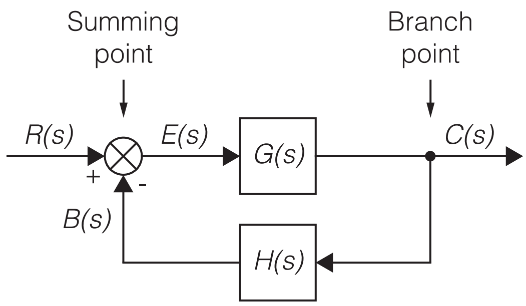

Figure 6.2. Block diagram of a closed-loop temperature-control system (adapted from Ogata, 2002: p. 59)

Following the work of Frankenhaeuser and her group (Frankenhaeuser, 1986; Frankenhaeuser, Lundberg and Forsman, 1980; Lundberg and Forsman, 1979; Lundberg and Frankenhaeuser, 1980, as referenced in Hockey, 2013: p. 127). Hockey distinguishes three work coping strategies or work management modes: (i) *strain*, which refers to the use of a high effort strategy in the absence of control; (ii) *disengaged*, which is characterised by a low effort strategy under low control; and (iii) *engaged*, which is characterised as an effortful strategy under high control (Table 6.1). A more traditional classification of work management modes distinguishes between proactive (active) and reactive (passive) coping strategies (Hockey, 2013). The proactive coping strategy corresponds to the engaged work mode and the reactive coping strategy to the disengaged one. The strain mode is best characterised as a combination of both coping strategies, that shift from initial proactive coping to reactive strategy as the requirements for effortful engagement with the goal increase.

A high level of performance is maintained in the engaged mode and in the beginning of the strain mode. The disengaged mode and the later stages of the strain mode are characterised by the acceptance of lower standards of activity related performance. Feelings of both anxiety and fatigue are typical under strain mode, whereas the disengaged mode is characterised primarily by feelings of anxiety and mild depression rather than fatigue. In contrast, both anxiety and fatigue are absent in the engaged mode, and individuals typically report feelings of alertness and increased energy.

Table 6.1. Modes of work management (adapted from Hockey, 2013: p. 128)

Mode	Coping strategy	Control	Effort	Performance	Subjective state
Strain	proactive → reactive	low	high	high	anxiety + fatigue
Disengaged	reactive	low	low	low	anxiety
Engaged	proactive	high	moderate	optimal	flow

6.1b. System dynamics for model formalisation

In his motivation control theory of psychological fatigue, Hockey conceptualises fatigue as one aspect of the complex set of control mechanisms that regulates performance in light of changing motivational priorities (Hockey, 1997; Hockey, 2013). In the presentation of his theory of psychological fatigue, Hockey points to the need for more empirical work in this area:

> The motivational control theory has been put forward in this monograph in the form of a broad perspective, rather than as a tightly argued set of postulates. This is partly because of a desire to set out a general position and theoretical framework, but also because the present state of knowledge is not sufficiently detailed to do much more than this. As a result, while the theory offers an alternative to the conception of fatigue as a general loss of energy or resources, the ideas remain somewhat speculative. (Hockey, 2013: p. 206)

Hockey calls for further research to explore the theory systematically, elaborate it and test its implications. Some theoretical constructs require clarification by empirical data. For instance, further clarification is needed of the factors that influence goal selection, and of the factors that determine whether externally imposed tasks will be protected by increased effort for extended period of time or executed at a lower level of performance (Hockey, 2013). One difficulty in testing some constructs is associated with conventional performance testing methods, which assume an unusual level of commitment to the activity from the performer (ibid.). How realistically do these tests capture commitment driven by intrinsic motivation?

Hockey's theory has its main focus on short-term cognitive control mechanisms. He then explains how chronic fatigue or burn-out can be developed as a result of a breakdown in normal mechanisms of motivational control. A challenge in testing the described mechanisms comes from the difficulty of carrying out empirical work to test the development of the dynamics of strain disengagement spiral and chronic fatigue syndrome (ibid.).

The present thesis addresses Hockey's call for systematic theory exploration. The theory serves as an ideal foundation for a systematic exploration, as the causal argument presented in the theory is detailed and explicit. Hockey's theory lends itself to system dynamics modelling and simulation as both originate in control theory. There is some system dynamics work related to fatigue development. Homer (1985) developed a system dynamics simulation model to explore work-related fatigue and the problem of burn-out. This model received attention in the system dynamics community. However, the model is based on the work-fatigue hypothesis and conceptualises fatigue in terms of depletion of energy resources — a view, which is no longer supported by the modern understanding of the problem in psychology. No attempts to improve on this with formal modelling of Hockey's theory are known. The current thesis sets to examine in detail the theory presented by Hockey, and formalise it to test computationally its internal coherence and consistency (Davis et al., 2007; Harrison et al., 2007).

A system dynamics model of the theory is developed to explore fatigue development in the process of low-carbon home retrofit. The model is first used to reproduce the theoretical modes of fatigue development proposed by Hockey (2013), and then it is applied to eight retrofit cases to investigate fatigue development, generate insights, and explore ways to keep fatigue levels low. The system dynamics model is developed in five steps:

(i) Hockey's rich textual description of psychological fatigue theory is used in the process of thematic coding to identify the theoretical constructs and their relations specified in the theory. The coding categories include four types of statements: (a) definitions of constructs; (b) explications of the relationships between other constructs that underpin the structure of the given construct; (c) description of behaviour over time for a particular construct, and (d) a conceptualisation of how each construct could be measured. The relationships between the constructs serve as the basis to develop the causal loop diagram (CLD) of the fatigue development process. This methodological step is described in section 6.2.

(ii) The developed endogenous causal explanation is formalised into a simulation model following established best practices for system dynamics modelling and simulation (Sterman, 2000). This step is implemented in section 6.3 with the model visualised via stock and flow diagrams (SFDs).

(iii) The validation of model's formulation and output is described in section 6.4. A variety of tests, specific to system dynamics is implemented to develop confidence in the model and validate it (Forrester and Senge, 1979; Sterman, 2000).

(iv) The model behaviour is explored through a series of simulation runs in section 6.5. The first set of simulation runs is used to reproduce a wide range of work management modes as proposed in Hockey's theory. The model is also tested for its generality and consistency with other relevant theories, such as Eisenberger's theory of *learned industriousness* (1992) or Seligman's theory of *learned helplessness* (1975), to explore the generality of the model in terms of the theoretical ground and phenomenon it covers. The second set of simulation runs is used to explore the model's ability to reproduce retrofit-related fatigue patterns, inferred from the empirical case studies carried out as part of this thesis.

(v) The third set of simulation runs explores scenarios aimed to reduce the development of the feeling of fatigue in the process of low-carbon home retrofit. These are discussed in section 6.6.

The data for model parametrisation was collected through in-depth interviews. Further clarification on the methodological steps can be found in *Chapter 3*.

6.2. CAUSAL STRUCTURE OF RETROFIT-ASSOCIATED FATIGUE

This section develops the causal loop diagram that provides the basis for the simulation model of fatigue development. Table 6.2 provides an example of the four types of statements in Hockey's theory that are used to formulate the model as discussed in *Chapter 3*: (i) *definition* of a construct, (ii) *structure* underpinning the construct, (iii) *behaviour over time* associated with the construct, and (iv) units used to describe the construct or potential ways designed in which the construct could be *measured* in reality.

Table 6.2. Example of textual coding categories

Coding category	Feeling of Fatigue (model variable)
Definition	"It may be felt as a low mood (tiredness, weariness, lethargy) or unfocused mental state (distraction, frustration, discomfort), or as an unpleasant bodily state, including headaches, tension, and vague pains in muscles and joints. It is also implicated in everyday disturbances of mood and quality of life, and, in more intense cases, can be felt as physical exhaustion, a total incapacity for any exertion, a profound lack of motivation, or depression". (Hockey, 2013: p. 1) "Subjective feelings of fatigue are more complex than tiredness alone, including elements of effort, anxiety, discomfort, frustration, boredom and loss of engagement with the goal". (Hockey, 2013: p. 135)
Structure	"More typically, fatigue occurs only under effortful, low control conditions, when demanding (normally externally imposed) tasks have to be performed well". (Hockey, 2013: pp. 132–133) "Fatigue may also be induced by stressors and high effort, and reduced by control opportunities". (Hockey, 2013: p. 20) "The feeling of fatigue only becomes strong when the signal for change is overridden by effort. Such effects are likely to be stronger in the presence of stressors because of the additional need to cope with the changed environmental conditions. The requirement to maintain work goals (or any other cognitive plan) under stress effectively means having to take on additional demands associated with the requirement to manage the stressor". (Hockey, 2013: p. 106)
Behaviour over time	"… it is clear that the patterning of fatigue may take three general forms: acceptance of interruption and its consequences; normal (manageable) resistance to interruption; and a state of strain, where extended resistance (and sustained effort) develops into an aversive state. Note that performance decrement and fatigue feelings are not considered to co-occur in the 'pure' states, though most responses to tasks involve a mixture of the two. Under strain, high effort may not be enough to sustain task fidelity and both effects may be observed". (Hockey, 2013: p. 14) "As has long been known, when activities are self-initiated (and sustained by personal goals) mental work is not generally perceived as tiring, and may even have the opposite effect: that of energizing the performer…" (Hockey, 2013: p. 9)

(continued)

Table 6.2. Example of textual coding categories *(continued)*

Coding category	Feeling of Fatigue (model variable)
Units & Potential ways to measure	"The most common way of assessing strain in such contexts is through the use of subjective reports of affective state (moods). In the cognitive energetical framework proposed here, two (functionally independent) dimensions of affective strain are distinguished. Based on the widely-supported analysis of mood states, such as the Watson & Tellegan (1985) dimensions of positive and negative affect (PA and NA), strain is defined as a combination of anxiety and fatigue. This is broadly equivalent to high NA and low PA, although the latter is more strongly identified with states such as depression, which have a stronger emotional content". (Hockey, 1997: p. 88)

The four statement categories are used to identify variables and their relations and transfer the textural description into a CLD that visually summarises Hockey's theory. The CLD illustrates how the dynamics of fatigue development can evolve during a low-carbon retrofit process and lead to the formation of a positive or negative impression about the process by the homeowners.

Hockey argues that the patterns of human performance cannot be fully understood without reference to the construct of resources. Energetic resources are conceptualised as a pool of general-purpose processing units, which could be allocated to achieve the desired performance of different activities. Hockey describes a two-level mechanism of resource allocation, which allows the differentiation between non-effortful, i.e. automatic, and effortful performance regulation. Hockey (1997) talks explicitly about two feedback loops, but a careful investigation of the theory reveals more causal loops that are used to theorise fatigue, which are not fully specified. These concern performance regulation, tensions between goals, stress development, recovery cycle, and a virtuous learned industriousness cycle, which can become a vicious learned helplessness cycle, if feedbacks are operating in the opposite direction. These concerns are discussed next.

The balancing loop **B1** in Figure 6.3 captures the process of routine-based *performance regulation*. The process begins with goal activation. The initial value for the *Expected Performance* is "determined by both long-term and short-term goals" (Hockey, 1997: p. 79). The *Actual Task Performance* is continuously adjusted to close the *Performance Gap* and match this goal-driven performance. An initial amount of *Energetic Resources Allocated to Current Activity* "is determined primarily by how much the performer assumes will be required" (Hockey, 2013: p. 145). Such an estimate can be quite accurate for well-established performance goals, for which the skills are already mastered. The performance regulation of such highly-skilled behaviour requires almost "automatic" cognitive skills and may be assumed to occur without further expenditure of energetic resources, i.e. without effort (Hockey, 1997: p. 80).

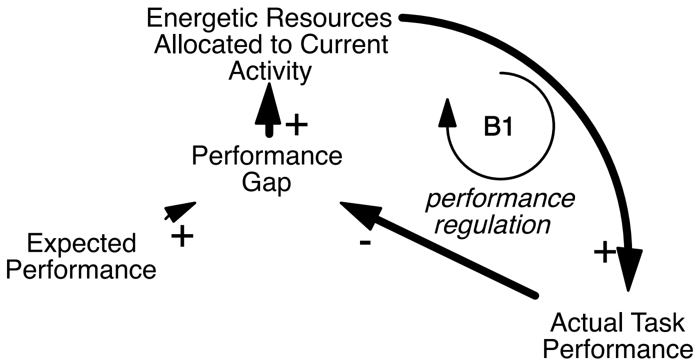

Figure 6.3. Causal diagram of Hockey's motivation control theory of fatigue: B1 performance regulation loop

If the individual has not mastered the skills required to perform an activity, performance regulation is not automatic. The balancing loop **B2** in Figure 6.4 captures *goals tension* in the process of effort-based performance regulation. *Actual Task Performance* "can then be maintained, but only at the expense of an increase in" *Energetic Resources Allocated to Current Activity*, which is felt via increased *Subjective Effort* (Hockey, 1997: p. 80). An increased *Subjective Effort* is assumed to involve the reassessment of the *Value of Pursuing Current Activity*. A commitment to a specific goal, such as a retrofit project, implies "a decrease in the relevance of other personal or biological goals, such as those concerned with leisure, rest or well-being" (Hockey, 1997: p. 78). The selection of goals is guided not only "by desire or need, but also by an evaluation of the goal as a worthwhile pursuit: what rewards it brings and how much effort it costs to achieve them" (Hockey, 2013: p. 134). Costs are interpreted as the expenditure of energetic resources required to maintain task performance. Most personal, self-initiated goals, such as a home retrofit project, have high value anticipated outcomes and, thus, normally attract continuous commitment to maintain them even with increased effort. However, the *Value of Pursuing Current Activity* "may become chronically diminished by the increasing costs required to attain them" (Hockey, 2013: p. 200). Priority may be given to pursue goals with greater rewards at lower costs, and thus, the *Expected Performance* of the current activity drops. "The resource construct also implies scarcity (the limited capacity assumption)" (Hockey, 1997: p. 76), as it is only possible to allocate a limited amount of resources to any particular activity. Different goals must compete for energetic resources and performance breakdown occurs when the overall resource capacity is exceeded.

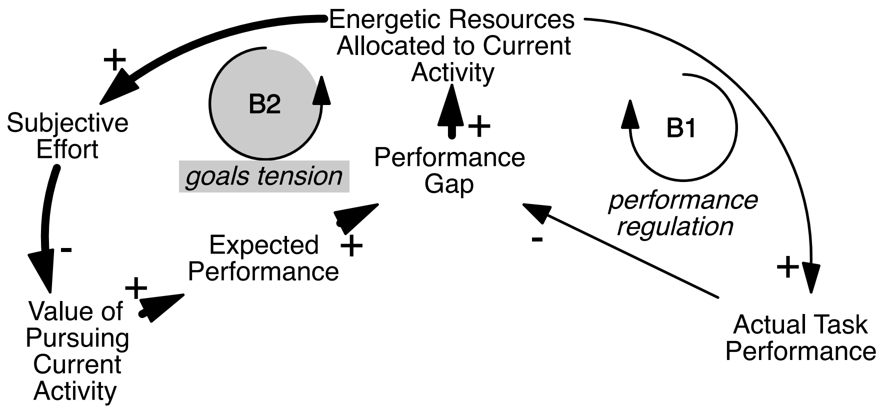

Figure 6.4. Causal diagram of Hockey's motivation control theory of fatigue: B2 goals tension loop

An activity sustained under high *Subjective Effort* provides the grounds for an experience of *Stress* that leads to development of the feeling of *Fatigue*. The reinforcing *strain spiral 1 (effort to stress)* loop **R1** in Figure 6.5 captures the accumulation of *Fatigue* from the sustained *Subjective Effort* necessary to maintain *Actual Task Performance* under conditions of *Stress*. More *Subjective Effort* in the form of *Energetic Resources Allocated to Current Activity* is required to maintain the same level of *Actual Task Performance* "under any emotional state, [such as a feeling of fatigue], at any level; as long as the goals of this state are incompatible with those of the task" (Hockey, 2013: p. 99). The unresolved *Stress* from the sustained strain response to an excessive *Subjective Effort* leads to *Fatigue*. This increases the need for effort in the form of *Energetic Resources Allocated to Current Activity* the following day, with a resultant further incremental effect on *Stress*, *Fatigue* and *Subjective Effort*. "Although highly motivated individuals (or workaholics) may be able to persevere with this strategy for a long period, … , work becomes progressively harder to maintain at the required level as the demand for effort increases" (Hockey, 2013: pp. 199–200). A continuously increasing demand for *Subjective Effort* will eventually move the system to a tipping point. "This is defined as the state where the utility of task goals (in terms of the costs and benefits of maintaining standards of performance) drops below an acceptable (or manageable) level. At this point a switch occurs, in which the default high effort mode is replaced" by that of disengagement (Hockey, 2013: p. 199).

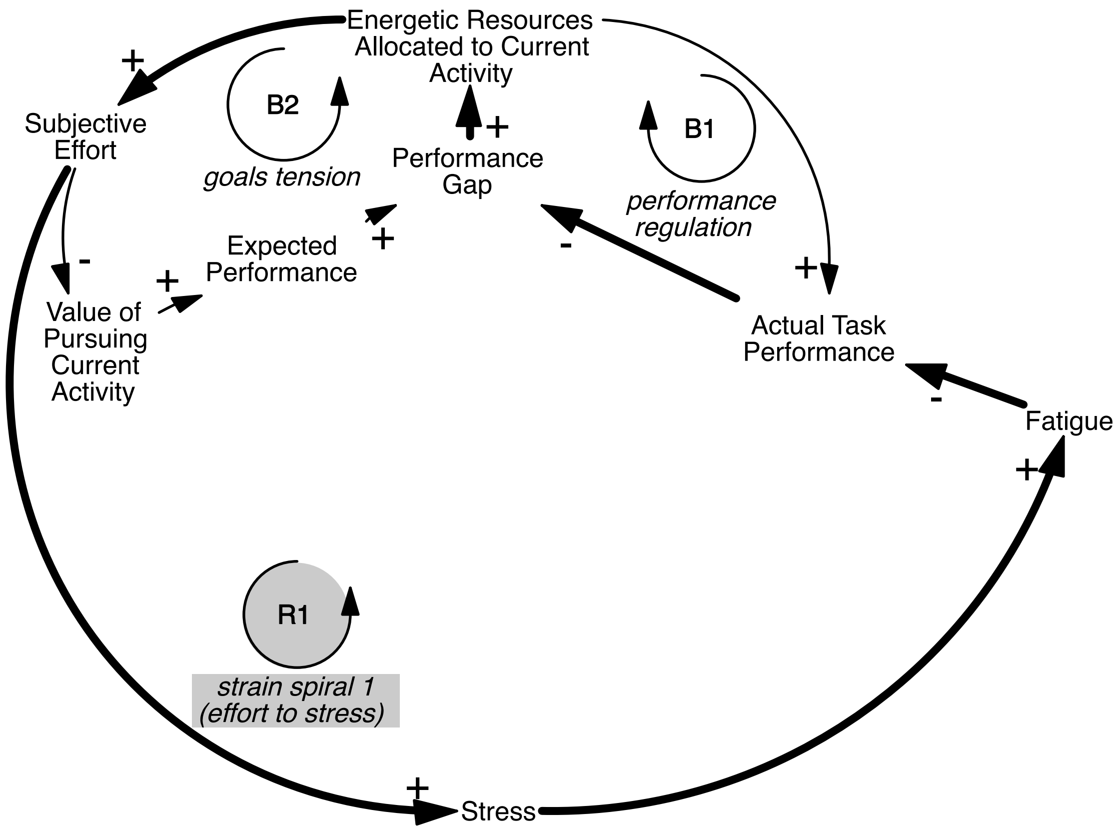

Figure 6.5. Causal diagram of Hockey's motivation control theory of fatigue: R1 strain spiral 1 (effort to stress)

The development of a state of *Stress* is not determined solely by the existence of a high *Subjective Effort*, but rather "occurs only under effortful, low control conditions, when demanding (normally externally imposed) tasks have to be performed well" (Hockey, 2013: pp. 132–133). The reinforcing *strain spiral 2 (control to stress)* loop **R2** in Figure 6.6 captures the accumulation of *Fatigue* from sustained *Subjective Effort* under conditions of low *Perceived Control*, which underpins a state of *Stress*. Control is understood as "a sense of self-determination or autonomy in how, when and what work is carried out" (Hockey, 2013: p. 35). The concept is closely linked to the notions of "intrinsic motivation and satisfaction from work well done" (ibid: p. 41). This implies that the level of control, an individual has over the activity, is not entirely up to an individual. An individual acquires gradually a sense of *Perceived Control* he or she has over the activity by actually doing the task. It should be noted that an effortful activity, where control is available, appears to have a very moderate impact on fatigue development or even "no relationship between the level of overtime and reported fatigue" (Hockey, 2013: p. 192).

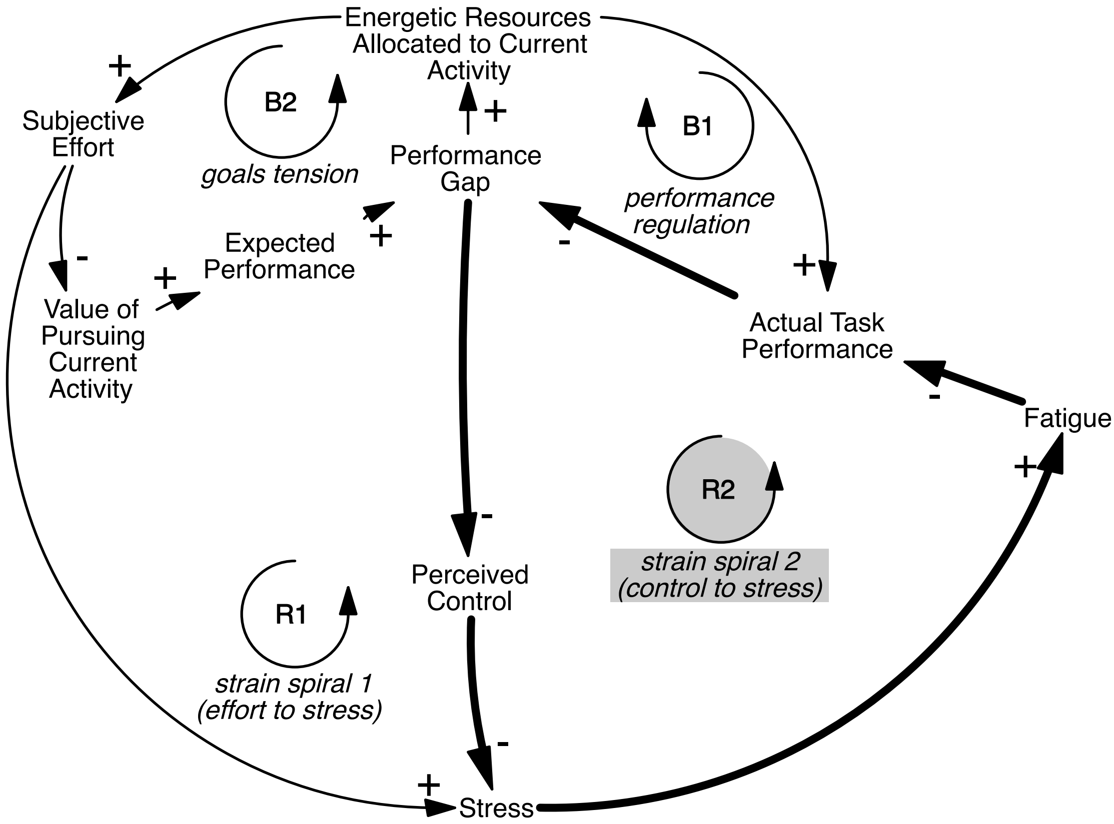

Figure 6.6. Causal diagram of Hockey's motivation control theory of fatigue: R2 strain spiral 2 (control to stress)

The reinforcing loop **R3** in Figure 6.7 captures the *recovery cycle*. Work-associated *Fatigue* may be countered, if an individual manages to "switch off from work" (Sonnentag, 2011: p. 253) during non-work hours and engage in leisure activities, hobbies and socialising, which allow to recover and be more effective with managing *Actual Task Performance* on the next day. The effectiveness of such activities on reducing *Fatigue* levels depends on the effectiveness of an individual's *Psychological Detachment* abilities, which is in effect a "trained strategy or a skill" (Sonnentag, 2011: p. 268). There also should be enough time to allow for recovery to happen. Hockey notes that long working hours are unlikely to be a direct cause for persistent fatigue. "More likely, they act as indirect causes, by reducing the opportunity for sleep and recovery from work stress, as well as limiting the buffering effects of family and social activities" (Hockey, 2013: p. 192–193).

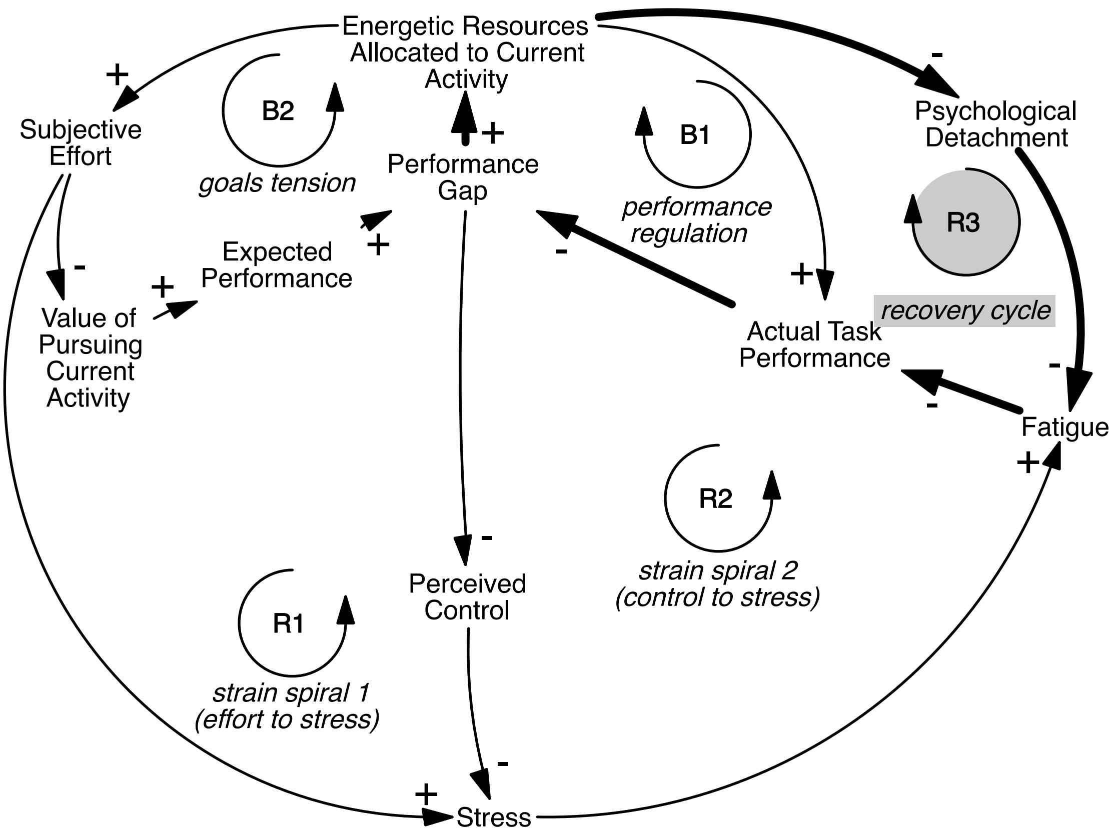

Figure 6.7. Causal diagram of Hockey's motivation control theory of fatigue: R3 recovery cycle

The reinforcing loop **R4** in Figure 6.8 is comprised of two balancing loops and captures the process of *learned helplessness OR learned industriousness*. Individuals may acquire a habit to employ high effort strategies, and the ability to tolerate high levels of effort, if they learn to associate such strategies with high levels of rewards, which describes the mechanism of learned industriousness (Eisenberger, 1992). The rewards include intrinsic rewards and a satisfaction from the work well done as an individual successfully rises up to a challenge. These rewards contribute to shaping one's perception of the *Value of Pursuing Current Activity*. Industriousness may be learned, but also unlearned through the repeated experience of performance failure, and the resulting sustained *Performance Gap*, as a result of increasingly uncontrollable events. The cycle becomes a vicious cycle of helplessness and is in the heart of the development of reduced expectations of future *Perceived Control* (Seligman, 1975).

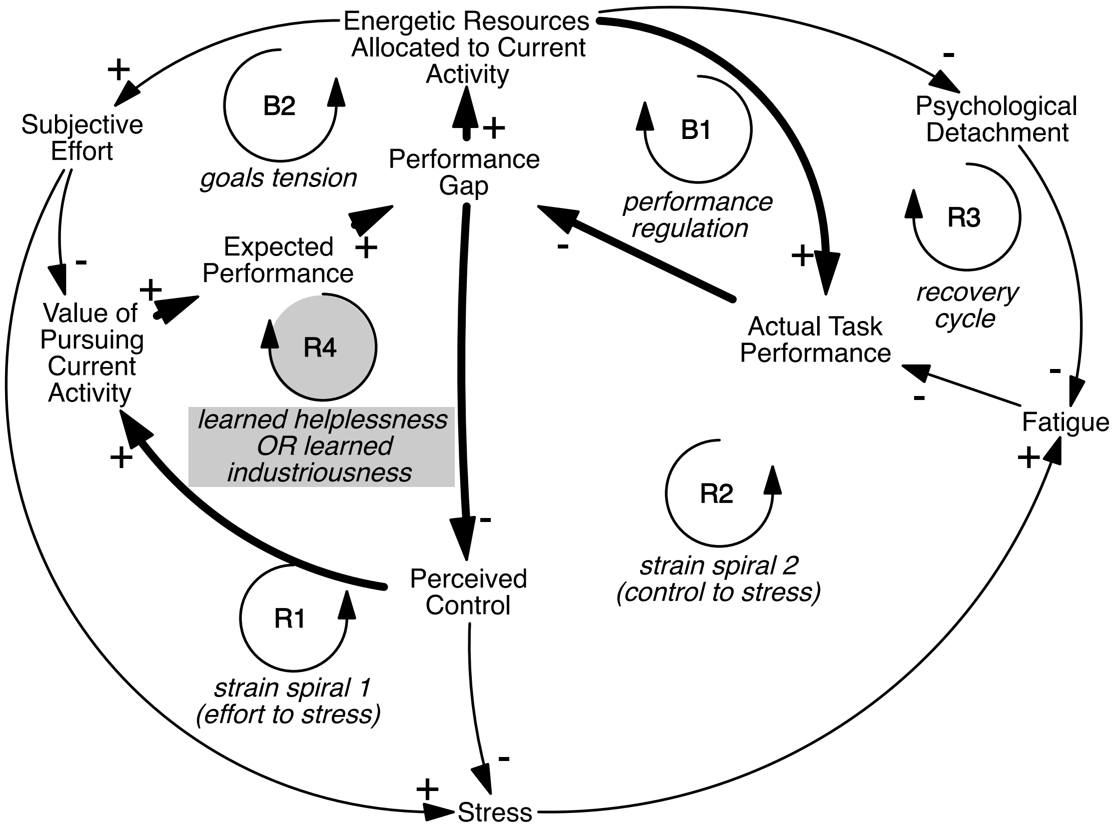

Figure 6.8. Causal diagram of Hockey's motivation control theory of fatigue: R4 learned helplessness OR learned industriousness cycle

The described combination of positive and negative feedback loops in Figures 6.3–6.8 depicts the fundamental tension between the "complex set of control systems that manage goal activity in the service of motivational requirements" described by Hockey (2013: p. 11). Fatigue serves as one element of this system. The complete CLD that captures this tension is shown in Figure 6.9. While the CLD is useful to illustrate how the interrelations between different components evolve over time, a formal model is essential to explore their dynamic implications (Sterman, 2000). Computer simulation ensures that the dynamics resulting from the simultaneous interactions of different elements are correctly inferred (ibid.). The formal model is developed in the next section.

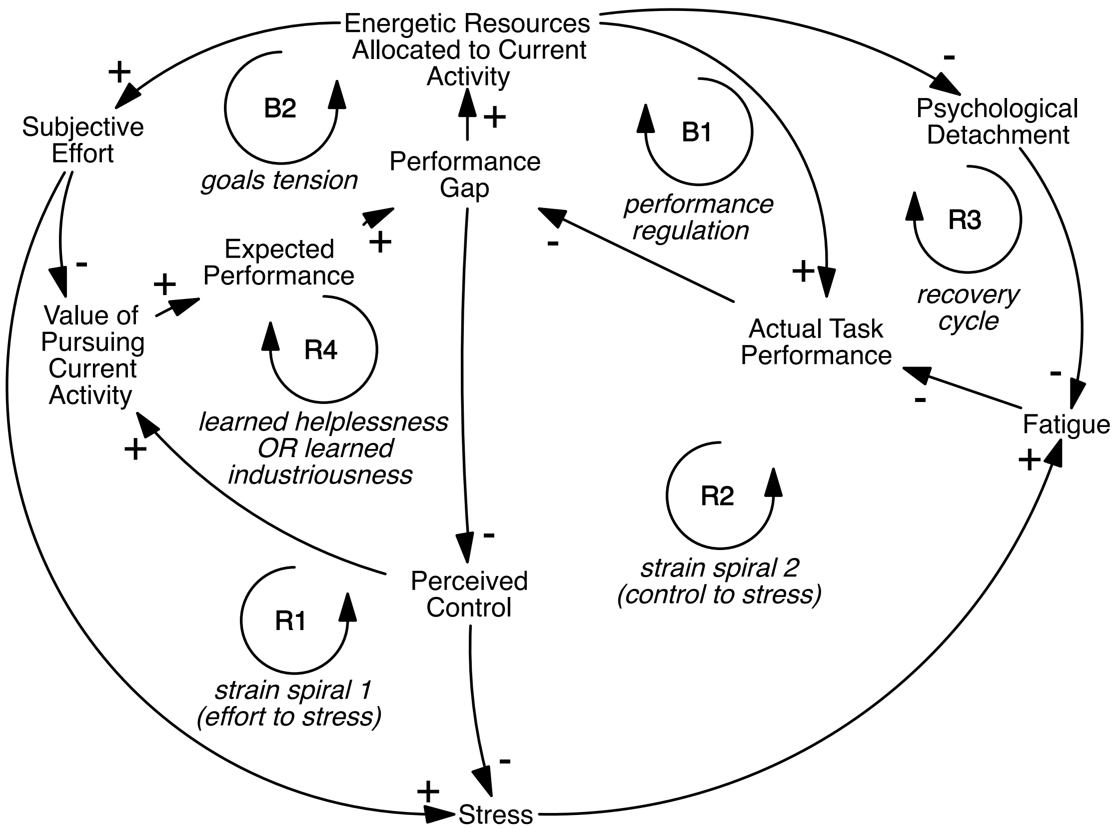

Figure 6.9. Causal loop diagram of Hockey's motivation control theory of fatigue

6.3. SYSTEM DYNAMICS MODEL FORMALISATION

This section discusses the state variables of the model, and then develops the equations that describe its dynamics. The variable names used in the formal model might differ from the ones used in the CLD, as the CLD is developed to provide an overall picture, while the model is a more detailed rendition of Hockey's theory. The variables in the formal model were named as similar as possible to the way Hockey names these variables in his theory. Table 6.3 captures the corresponding names between the CLD shown in Figure 6.9 and the formal model.

Table 6.3. Corresponding variable names between the CLD and the formal model

CLD	Formal model
Actual Task Performance	Perceived Performance per Day
Energetic Resources Allocated to Current Activity	Hours worked per Day on Current Activity
Expected Performance	Desired Task Performance per Day
Fatigue	Feeling of Fatigue
Perceived Control	Perceived Control
Performance Gap	Gap between Current and Required Performance
Psychological Detachment	Psychological Detachment
Stress	State of Stress
Subjective Effort	Normalised Perceived Effort
Value of Pursuing Current Activity	Relative Value of Daily Activity

6.3a. Overview of the state variables

The model formalisation started with the five state variables summarized in Table 6.4: *Perceived Control*, *Desired Task performance per Day*, *Perceived Performance per Day*, *Hours Worked per Day on Current Activity* and *Feeling of Fatigue*. The motivation control theory of fatigue contains many variables that are essential to the model such as intrinsic and extrinsic motivation, but they do not represent state variables. State variables cannot be instantaneously changed, but rather represent all cumulative past changes. For instance, *Perceived Control* equals the original perception of control before embarking on the task plus all the changes to this perception since as the individual started the activity. Similarly, the *Desired Task Performance per Day* is cumulative. The *Perceived Performance per Day* is modelled as a state variable, because it is a combination of past and current perceptions of performance. Actual performance is continuously determined anew.

Hours Worked per Day on Current Activity serves as proxy to the concept of energetic resources and effort, described by Hockey. It is not possible for an individual to directly manipulate the level of energetic resources, but it is feasible to affect the rate with which resources are allocated to or are withdrawn from a particular activity. Similarly, an individual cannot directly affect the level of the *Feeling of Fatigue*, which builds up under conditions of high effort and low control. Nevertheless, it is possible for an individual to reduce the level of fatigue through appropriate strategies of psychological detachment.

Some variables are directly linked to the state variables. For instance, the *Feeling of Fatigue* is a function of a *State of Stress*. To specify both stress and fatigue as state variables would be redundant. Four types of statements are shown for the state variable (Table 6.4):

(i) constructs names (in grey), (ii) explications of the relationships between other constructs that underpin the *structure* of a given construct, (iii) description of *behaviour over time* specific for a particular construct, and (iv) *potential measure*s for each construct.

Table 6.4. State variables in the motivation control theory of fatigue

Structure	Behaviour over time	Potential Measures
Perceived Control		
Described by a match between desired and actual outcomes of actions: "… the way I have discussed control (in the sense of… satisfaction from work well done)". (H, 2013: p. 41)	Low performance decreases a sense of control: "… tasks themselves may be considered to act as stressors…; for example, high levels of workload may generate anxiety associated with threat to task outcomes or fear of failure from ineffective coping". (H, 2013: p. 86)	Identify various control characteristics on Likert scale: e.g., a match between one's abilities and opportunities.
Desired Task performance per Day		
Determined by motivation, and value of perusing alternative actions: "… overt performance is assumed to be driven by… long-term and short-term goals… [and] to be subject to modification in the light of changes in the perceived costs and benefits of alternative states and actions". (H, 1997: pp. 78–79)	A reduction in expectations, if the task is too demanding: "An alternative response to excessive demands is to adopt a passive coping mode, involving downwards adjustment of performance targets…" (H, 1997: p. 82)	Individual's assessment of overall performance: e.g., accomplishments per week.
Perceived Performance per Day *is one's perception of actual Performance per Day*		
A mismatch between desired and actual performance leads to behavior change: "… performance output values are continually adjusted to match these (goal-driven) target states". (H, 1997: p. 79)	Worse performance if a feeling of fatigue is present: "More effort will be required to maintain task goals under any emotional state, at any level…" (H, 2013: p. 99)	Individual's assessment of overall performance: e.g., accomplishments per week.
Hours Worked per Day on Current Activity *used as a proxy for the construct of Energetic Resources*		
Constrained by a limited capacity: "… the resource construct also implies scarcity (the limited capacity assumption)" (H, 1997: p. 76)	Allocated to the most valuable activity: "… simultaneous mental operations making demands on the same pool of resources must compete for processing units". (H, 1997: p. 76)	Hours worked per week

(continued)

Table 6.4. State variables in the motivation control theory of fatigue *(continued)*

Structure	Behaviour over time	Potential Measures
Feeling of Fatigue		
Driven by stress, which occurs under conditions of high effort and low control: "… fatigue occurs only under effortful, low control conditions, when demanding (normally externally imposed) tasks have to be performed well". (H, 2013: pp. 132–133)	Diminishes the value of current activity: "[Fatigue] responds to falling utility (benefits to costs ratio) of current behaviour by interrupting the flow of control, thus allowing a reassessment of the cost and benefits of alternative actions". (H, 2013: pp. 136–137)	Measure positive affect (PA) on a scale from low to high. Feeling of fatigue is associated with low PA (H, 2013: p. 17)

* H, 1997 refers to Hockey (1997); H, 2013 refers to Hockey (2013)

The model is divided in five sectors corresponding to the five state variables: — *motivation and control; goal value and performance targets; resources allocation and effort; stress, fatigue and recovery* and *activity performance*. Each sector includes equations that govern the behavior of the state variables. The main equations are described in the following subsections. Each subsection starts with a corresponding stock and flow diagram for clarity. The detailed list of all equations can be found in *Appendix DA. Model documentation*.

Some functions predefined in Vensim software have been used. A description of some functions used are given in Table 6.5. A full list of functions can be found in Vensim documentation (Ventana Systems, 2019).

Table 6.5. List of some predefined functions used in the model

INTEG (R,N)	Performs numerical integration of R starting at N (defines a Stock)
MAX (A,B)	The larger of A and B
MIN (A,B)	The smaller of A and B
SQRT (X)	Returns the square root of X
ZIDZ (A,B)	Zero (0.0) if dividing by zero (B=0) otherwise returns A divided by B

6.3b. Motivation and control

Goal-directed behaviour, such as retrofit activity, cannot be fully understood without the concept of motivation. Motivation is understood not just as an energising force, but rather as an "integral part of the information processing system that initiates, [maintains and] guides goal-directed behaviour" (Hockey, 2013: p. 134). Goals can be distinguished based on the motivational origins of different kinds of activities. Task goals are driven by extrinsic motivation such as pay or tangible short-term rewards. Personal goals, on the other hand, are driven by intrinsic motivation, "concerned with the pursuit of meaningful, desired activities, and integrated into the developed motivational structure of the individual" (ibid: p. 110).

In the model the *Normalised Perceived Benefits of an Active Goal* are a function of both *EXTRINSIC MOTIVATION* and *Intrinsic Motivation* (Figure 6.10). The intrinsic and extrinsic motivation variables are dimensionless and vary on a scale from zero to one. At the limit where only one kind of motivation is present, the *Normalised Perceived Benefits of an Active Goal* equate to a full range of this motivation. However, the combined effect of two kinds of motivation cannot be above one, even if each variable equals one. Thus, a lenient combination of soft variables is used to formulate perceived benefits of an active goal (Hayward et al., 2014: p. 9):

Normalised Perceived Benefits of an Active Goal [Dmnl] =
(EXTRINSIC MOTIVATION [Dmnl] + *Intrinsic Motivation* [Dmnl]*)* – (1)
*EXTRINSIC MOTIVATION * Intrinsic Motivation*

Under most circumstances, an increase in the *Relevance of an Active Goal* implies a decrease in relevance of other goals (Hockey, 1997). For instance, an increased commitment to a retrofit activity implies a decreased relevance of other personal goals, such as the ones concerned with leisure or rest. However, it is possible that *Normalised Perceived Benefits of an Active Goal* are equal to *PERCEIVED BENEFITS OF OTHER ACTIVITIES*. In this case these different goals attract the same level of commitment, and, thus, the same amount of effort is allocated to each activity (Figure 6.10):

Relevance of an Active Goal = ZIDZ (Normalised Perceived Benefits of an Active Goal, (Normalised Perceived Benefits of an Active Goal + (2)
PERCEIVED BENEFITS OF OTHER ACTIVITIES))

The notion of *Intrinsic Motivation* is closely related to a sense of satisfaction from the work well done and a feeling of *Perceived Control* over the process. Control is understood as "a sense of self-determination or autonomy in how, when and what work is carried out" (Hockey, 2013: p. 35). Personal goals, driven by *Intrinsic Motivation*, tend to have high levels of control, including the possibility to abandon the activity altogether. Thus, when self-initiated goals lose their earlier reward value and become a burden, they can be quickly abandoned and the performance drops to zero. In the model *Intrinsic Motivation* is a function of *INITIAL INTRINSIC INTEREST* and *Effect of Control on Intrinsic Motivation* (Figure 6.10). The function uses harmonic average (Hayward, 2014: p. 8). Thus, if there is full *Normalised Perceived Control* and a strong *INITIAL INTRINSIC INTEREST* to pursue the activity, *Intrinsic Motivation* equals one. However, if one of the variables equals zero, for instance, if there is no *INITIAL INTRINSIC INTEREST* to engage with an activity to begin with, *Intrinsic Motivation* is zero, regardless of the level of *Normalised Perceived Control* over the activity:

Intrinsic Motivation [Dmnl] = *SQRT (Effect of Control on Intrinsic Motivation * INITIAL INTRINSIC INTEREST* [Dmnl]*)* (3)

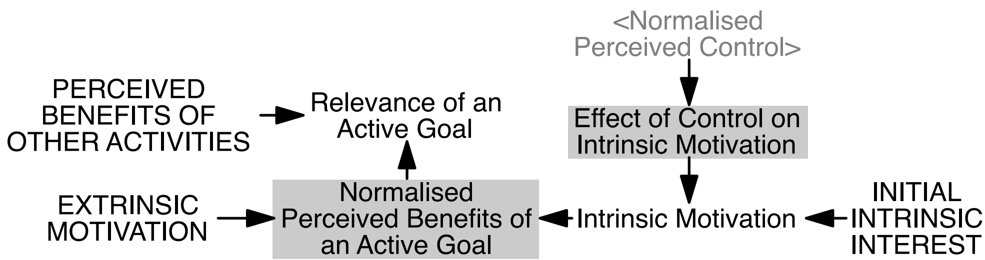

Figure 6.10. SFD for goals and motivation variables

The feeling of *Perceived Control* should be understood in relation to performance, stress and fatigue. “The development of a stress state often precedes fatigue” (Hockey, 2013: p. 94). In motivation control theory of fatigue, “stress is considered primarily from the perspective of task performance” (Hockey, 1997: p. 76) and is identified with the occurrence of a mismatch between the required and prevailing task performance. The mismatch underpins a sense of losing control over an activity, which can itself act as a stressor: “… for example, high levels of workload may generate anxiety associated with threat to task outcomes or fear of failure from ineffective coping” (Hockey, 2013: p. 86).

In the model, *Perceived Control* is a stock that represents the degree to which an individual perceives the chosen coping strategy as successful (Figure 6.11). *Perceived Control* is externally determined by *ACTUAL CONTROL*, and represents the degree of control an individual actually has over autonomy in how, when and what work is carried out. The feeling of *Perceived Control* variable is dimensionless and varies on scale from zero to one, with zero representing no perceived autonomy and one representing absolute perceived autonomy over the choice of performed activity:

Perceived Control [Dmnl] = *INTEG (increase in control* [1/Day] – *decrease in control* [1/Day], *ACTUAL CONTROL* [Dmnl]*)* (4)

The *Perceived Control* stock is determined as a function of the *Gap between Current and Required Performance*. The gap is normalised against *Maximum Possible Performance per Day*. It is assumed that the perception of control varies linearly with the gap. As long as an individual performs as well as required, or better, the sense of control increases. The increase is assumed to be determined by a summative effect from the gap and the constant *PERFORMANCE INCREASE BIAS*. *PERFORMANCE INCREASE BIAS* variable allows an increase in *Perceived Control* to be captured, when an individual performance as good as required, and thus there is no *Gap between Current and Required Performance*. If an individual performs worse than required, the sense of *Perceived Control* diminishes gradually over time. A decrease is assumed to be determined by the *Gap between Current and Required Performance*.

Regardless of how much control an individual actually has over a choice of how, when and what work is carried out, the possibility of *MAXIMUM POSSIBLE CONTROL* is assumed, which an individual is aware of. The variable of *Perceived Control* is normalised against that *MAXIMUM POSSIBLE CONTROL* and the value is used to calculate the effect of *Perceived Control* on other variables in the model.

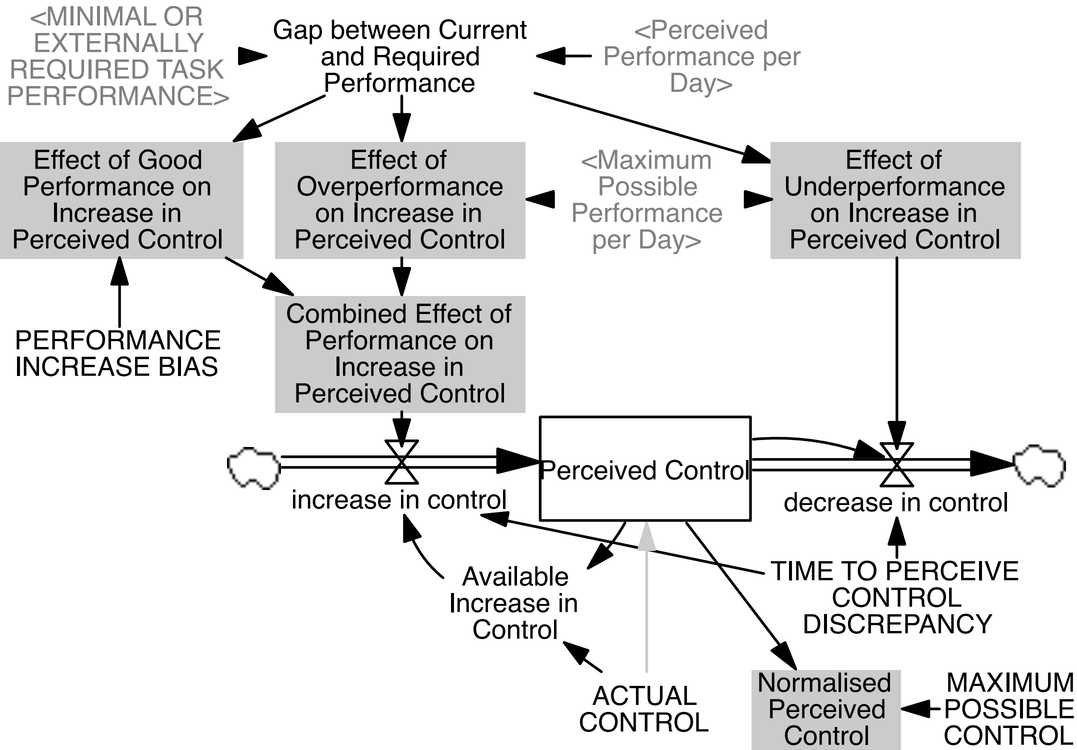

Figure 6.11. SFD for Perceived Control stock

6.3c. Goal value and performance targets

The term 'human performance' has a narrow set of meanings within experimental psychology and normally describes "the effectiveness of specific skills in meeting (typically externally-imposed) cognitive goals, the underlying mental operations associated with such behaviour" (Hockey, 1997: p. 77). The motivation control theory of fatigue highlights the role of effortful strategies in the management of human performance under stressful conditions by outlining the dynamics behind "the use of effort to control motivational priorities" (Hockey, 2013: pp. 194–195).

The initial level of *Desired Task Performance per Day* is "determined by both long-term and short-term goals, which determine output criteria for behaviour (how fast to work, how much monitoring of accuracy is required, the order in which actions are executed, and so on)" (Hockey, 1997: p. 79). The selection of *Indicated Desired Task Performance* targets "is guided not only by desire or need, but also by an evaluation of the goal as a worthwhile pursuit: what rewards it brings and how much effort it costs to achieve them" (Hockey, 2013: p. 134). This evaluation is "assumed to be subject to modification in the light of changes in the perceived costs and benefits of [current and] alternative states and actions" (Hockey, 1997: p. 79). In the model, the evaluation of the goal as a worthwhile pursuit is determined by the variable *Relative Value of Daily Performance*, which depends on *Normalised Perceived Benefits of an Active Goal* and *Normalised Perceived Effort* (Figure 6.12). In line with Hockey's definition of the concept as a "ratio of benefits to costs" (Hockey, 2013: p. 102), the variable is defined as following:

Relative Value of Daily Activity [Dmnl] = *ZIDZ (Normalised Perceived Benefits of an Active Goal* [Dmnl], *(Normalised Perceived Benefits of an Active Goal + Normalised Perceived Effort* [Dmnl]*))* (5)

This formulation puts the value on a scale from zero to one. When the value is below 0.5, the activity is considered more effortful than rewarding to pursue and desired performance targets are reduced. When the value is above 0.5, the activity is more rewarding than effortful and desired performance targets are increased. The variables *Effect of Relative Value on Increase in Desired Performance* and *Effect of Relative Value on Decrease in Desired Performance* put the corresponding effects on the scale from zero to one. A linear effect is assumed between the benefits to effort ratio and the change in desired performance.

The *Desired Task Performance per Day* is a stock that represents the change over time of *Indicated Desired Task Performance* targets (Figure 6.12). The rate of change in performance targets is the rate of *increase in desired performance* less the *decrease in desired performance*:

Desired Task Performance per Day [Accomplishments/Day] = *INTEG (increase in desired performance* [Accomplishments/(Day*Day) – *decrease in desired performance* [Accomplishments/(Day*Day), *MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE* [Accomplishments/Day]*)* (6)

An *increase in desired performance* targets depends not only on the *Relative Value of Daily Activity*, but also on the sense of *Perceived Control* over the activity. A lost sense of *Perceived Control* leads to an unwillingness to get involved in an effortful activity regardless of the *Relative Value of Daily Activity* or *ACTUAL CONTROL* options. This mechanism is similar to the one of learned helplessness, since the experience of uncontrollable events leads to the developments of reduced expectation of future control and a reduced willingness to engage in any effortful activity (Seligman, 1975). It is assumed that *Effect of*

Control on Desire to Engage in an Effortful Activity is linear. The rate of *increase in desired performance* targets is formulated as:

increase in desired performance [Accomplishments/(Day*Day)] =
(Indicated Desired Task Performance [Accomplishments/Day] –
Desired Task Performance per Day) [Accomplishments/Day] / (7)
TIME TO CHANGE EXPECTATIONS [Day] * *Effect of Control on Desire to Engage in an Effortful Activity* [Dmnl]

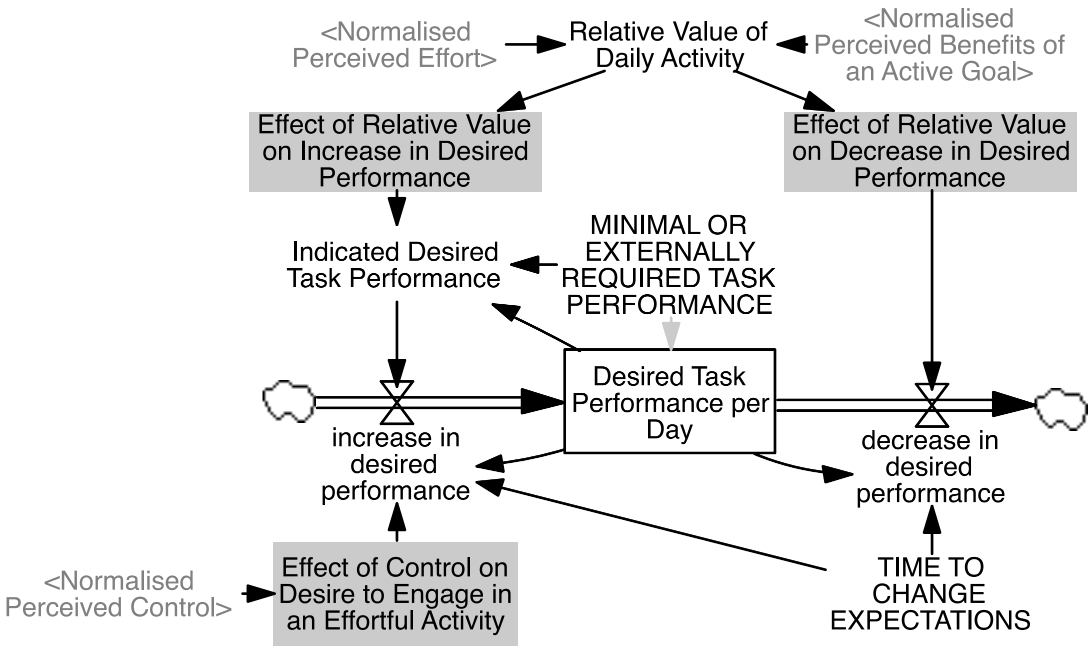

Figure 6.12. SFD for Desired Task Performance per Day stock

6.3d. Resources allocation and effort

The construct of resources is central to the development of motivation control theory of fatigue. "[Resources] are conceptualised as the availability of one or more pools of general-purpose processing units, capable of performing elementary operations across a range of tasks, and drawing upon common 'energy' sources". (Hockey, 1997: p. 75). The resource construct also implies an assumption of limited capacity, so that "simultaneous mental operations making demands on the same pool of resources must compete for processing units" (ibid.: p. 76). The notion of resource capacity is important to understand performance and breakdown in performance, as it is not possible to allocate further resources beyond its capacity. Thus, a performance breakdown occurs when the capacity is exceeded.

In the current model *Hours Worked per Day on Current Activity* are used as a proxy for the construct of resources (Figure 6.13). *Hours Worked per Day on Current Activity* are modelled as a stock that captures a change in the allocation of energetic resources to a particular task. The use of working hours as a proxy for the construct of resources is a reasonable approximation, as the concept of time is consistent with the definitive characteristics of the concept of resources: (i) the allocation of time (resources) to a particular goal inevitably excludes allocation of these resources (time) to other goals; (ii) there is a limited number of hours per day (limited capacity assumption) and the breakdown in performance occurs, when the demand for working hours exceeds the hours available in a day:

Hours Worked per Day on Current Activity [Hours/Day] = *INTEG (increase in number of hours worked per day* [Hours/(Day*Day)] – *decrease in number of hours worked per day* [Hours/(Day*Day)], *INITIAL HOURS WORKED* [Hours/Day]*)* (8)

A change in the number of *Hours Worked per Day on Current Activity* is associated with a perceived *Gap in Task Performance*, which captures a discrepancy between current and desired performance. The current output is compared to the one specified by the goal and "performance output values are continually adjusted to match these (goal-driven) target states" (Hockey, 1997: p. 79). If an individual performs worse than desired, the number of *Hours Worked per Day on Current Activity* is increased until *Maximum Hours Available for Current Activity* are allocated. If an individual performs better than required, the number of *Hours Worked per Day on Current Activity* is gradually decreased. The *Gap in Task Performance* is determined by a simple subtraction. The values for overperformance and underperformance are defined by a normalised value between *Gap in Task Performance* and *Maximum Possible Performance per Day*. It is assumed that the *Gap in Task Performance* has a linear effect on a change in *Hours Worked per Day on Current Activity*.

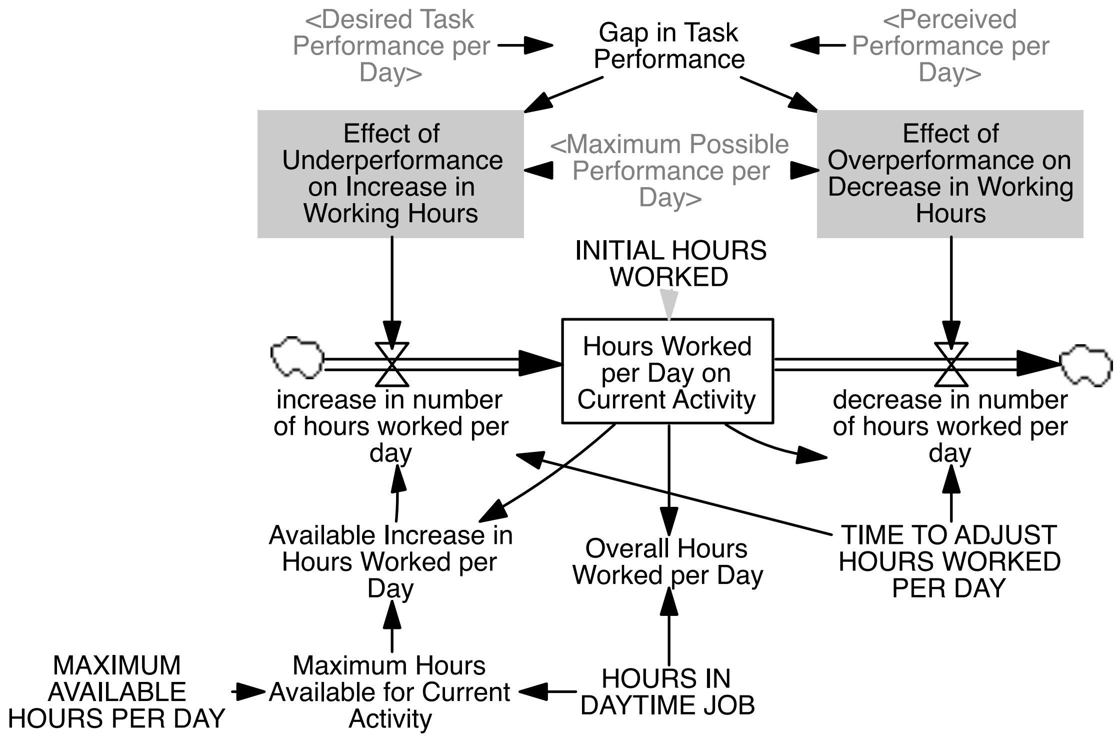

Figure 6.13. SFD for Hours Worked per Day on Current Activity stock

The concept of energetic resources is closely related to the concept of effort. Effort is an ambiguous construct and different aspects of the concept are highlighted in different literatures. In the motivation control theory of fatigue effort is interpreted as “the subjective awareness of resource deployment” (Hockey, 1997: p. 80). Thus, as soon as energetic resources are allocated to an activity, an individual can assess the costs of this activity in terms of expenditure of energetic resources (Figure 6.14). In the current model the construct of time is used as a proxy for the constructs of energetic resources and effort. The model distinguishes four set points associated with effort and resources: *WORKING EFFORT BUDGET*, *Operational Maximum for Effort Expenditure*, *LIMIT TO EFFORT TOLERANCE* and *MAXIMUM AVAILABLE HOURS PER DAY* (Table 6.6).

Table 6.6. Set points associated with the constructs of resources and effort

Variable name	Hours/Day (default values)	Description
WORKING EFFORT BUDGET	8	The variable represents the amount of resources an individual is ready to spend altogether on effortful activities per day. Time spent on activities within working effort budget is not considered strenuous.
Operational Maximum for Effort Expenditure	Min 8.5, Max 11	Represents an upper effort set-point. The set point is motivational in origin and varies between working effort budget and an individual's limit to effort tolerance.
LIMIT TO EFFORT TOLERANCE	11	"The high effort (strain) response to work can be sustained only up to the individual's upper limit for effort tolerance". (Hockey, 2013: p. 199–200). A limit of 11 hours per day is assumed.
MAXIMUM AVAILABLE HOURS PER DAY	16	Mental fatigue and sleepiness have different origins in brain processes (Hockey, 2013: p. 175–176). The model only deals with mental fatigue. Thus, the maximum hours worked per day are limited to 16 hours, allowing 8 hours for sleep.

The changes in perceived costs and benefits of current and alternative activities determine the change in *Desired Task Performance per Day*. In the model the costs of action are determined by the *Normalised Perceived Effort* required to maintain them, which is calculated using a normalised value of *Overall Hours Worked per Day* against *Operational Maximum for Effort Expenditure* (Figure 6.14):

Normalised Perceived Effort [Dmnl] = *Overall Hours Worked per Day* [Hours/Day] / *Operational Maximum for Effort Expenditure* [Hours/Day] (9)

The *Operational Maximum for Effort Expenditure* is one of the effort set-points theorised in Hockey's theory. Hockey differentiates between lower and upper effort set points, which he refers to as *WORKING EFFORT BUDGET* and *Operational Maximum for Effort Expenditure* respectfully (Hockey, 1997). Hockey highlights two characteristics of *WORKING EFFORT BUDGET*. First, this budget is determined for a particular task based on anticipated resource needs, level of skills and so on. The anticipated resource needs may be estimated quite accurately through experience with the task at hand or similar tasks. Second, the *WORKING EFFORT BUDGET* "is likely to be quite stable for a given individual" (Hockey, 1997: p. 80). The energetic resource expenditure below *WORKING EFFORT BUDGET* is not considered strenuous. In the model *WORKING EFFORT BUDGET* represents a set point of expenditure of energetic resources across different tasks throughout the day, below which an engagement in effortful activities is not considered strenuous. Thus, the *WORKING EFFORT BUDGET* is determined in the model for all effortful activities together rather than for each individual activity in particular. Working for eight hours per day is assumed not to be strenuous.

The *Operational Maximum for Effort Expenditure* variable is more motivational in its origin. Hockey conceptualises it as a function of individual goals and motivation, the individual capacity for sustained work, and the tolerance to high levels strain. He highlights that it is "likely to change more under the influence of short-term factors such as fatigue and prevailing affective states" (Hockey, 1997: p. 80). In the model *Operational Maximum for Effort Expenditure* is a value between *WORKING EFFORT BUDGET* and *LIMIT TO EFFORT TOLERANCE*. It is affected by the perceived *Relevance of an Active Goal* and the *Feeling of Fatigue*. The effects are assumed to be linear:

Operational Maximum for Effort Expenditure [Hours/Day] = *MAX (WORKING EFFORT BUDGET* [Hours/Day] + *0.5, LIMIT TO EFFORT TOLERANCE* [Hours/Day] * *Combined Effect of Fatigue and Motivation on Operational Maximum for Effort Expenditure)* (10)

An addition of half an hour per day represents an assumption that an individual is only prepared to work half an hour more than initially planned on a demanding task, if fatigued. It is assumed that *Operational Maximum for Effort Expenditure* cannot go beyond the upper *LIMIT TO EFFORT TOLERANCE*, which is assumed to be 11 hours per day in the model. The model is set to allow an individual to work up to 16 hours per day, however, such activity is perceived as strenuous. Hockey conceptualised different types of fatigue: psychological, physical and sleepiness (Hockey, 2013). Though not conclusive, there is evidence that psychological fatigue and sleepiness originate in different brain processes (ibid.: p. 175–176). As the current model deals only with psychological fatigue, thus, the *MAXIMUM AVAILABLE HOURS PER DAY* are limited to 16 hours per day, allowing 8 hours for sleep.

The difference between *WORKING EFFORT BUDGET* and *Operational Maximum for Effort Expenditure* provides "a reserve effort budget for meeting additional demands, unpredictable changes in the demands-resources balance, or the additional burden associated with stressful environments" (Hockey, 1997: p. 80). In the model this difference is normalised and this *Normalised Effort within Reserve Effort Budget* is used to determine the effect of the effort above working effort budget on generating stress:

Normalised Effort within Reserve Effort Budget [Dmnl] = *MIN (1, MAX (0, (Overall Hours Worked per Day* [Hours/Day] – *WORKING EFFORT BUDGET* [Hours/Day]*) / (Operational Maximum for Effort Expenditure* [Hours/Day] – *WORKING EFFORT BUDGET* [Hours/Day]*)))* (10)

MAX and MIN functions ensure that the output is between zero and one.

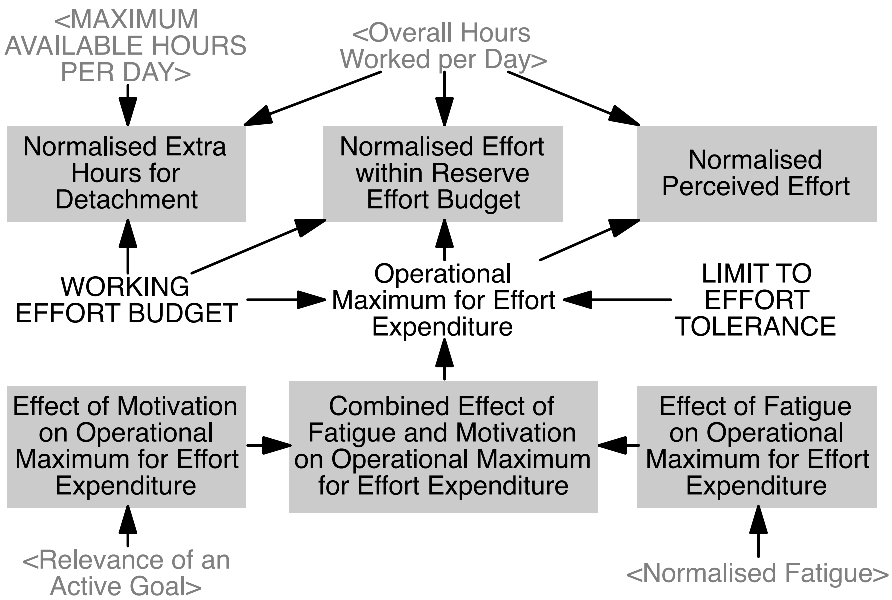

Figure 6.14. SFD for effort variables

6.3e. Stress, fatigue and recovery

Hockey conceptualises fatigue as an emotion. The *Feeling of Fatigue* is modelled as a stock to capture the cumulative change in emotional response of perusing an effortful activity under conditions of low *Perceived Control* (Figure 6.15). The level of the *Feeling of Fatigue* varies on a scale from zero to one, with zero representing no *Feeling of Fatigue* and one representing a full state of fatigue. The low-carbon home retrofits in the case studies are self-initiated activities and it is assumed that individuals embark on the journey fully rested, thus, the *INITIAL LEVEL OF FATIGUE* is assumed to be zero:

Feeling of Fatigue [Dmnl] = *INTEG (increasing fatigue* [1/Day] – *depleting fatigue* [1/Day]*, INITIAL LEVEL OF FATIGUE* [Dmnl]*)* (11)

The development of a *Feeling of Fatigue* should be understood in relation to the *State of Stress*. Hockey makes no strict distinction between the two constructs and considers them to "be different facets of the same adaptive process" (Hockey, 2013: p. 4). The *Feeling of Fatigue* increases in a stressful situation and decreases when the stressors are no longer present, allowing for *Psychological Detachment* and recovery. It is assumed that the *State of Stress* has a linear effect on an increase in the *Feeling of Fatigue*. The *State of Stress* is defined as a "state in which homeostasis is threatened" (ibid.: p. 87). Within the focus of motivation control theory of fatigue endogenous dynamics of stressful situations are determined in relation to task performance and control options. A *State of Stress* that leads to the *Feeling of Fatigue* "occurs only under effortful, low control conditions, when demanding (normally externally imposed) tasks have to be performed well" (ibid. 2013: p. 132–133). However, the overall *State of Stress* can be determined not only in relation to task performance, but as a combination of job-related stress and non-job-related *EXTRA STRESS*:

State of Stress [Dmnl] = *(Effect of Effort on Stress* [Dmnl] *
Effect of Control on Stress [Dmnl] + *EXTRA STRESS* [Dmnl]) –
Effect of Effort on Stress [Dmnl] * *Effect of Control on Stress* [Dmnl] *
EXTRA STRESS [Dmnl]) (12)

The combination of *Effect of Effort on Stress* and *Effect of Control on Stress* is determined by a multiplication. If the effect of one variable is switched off, then other variable has no effect (Hayward, 2014: p. 8). For instance, if there is full *Perceived Control* over the activity, then a situation is not considered stressful regardless of the amount of effort put in. If one variable is set to the maximum value of one, then combined effect follows the full range of the second variable. Thus, if an individual works on the limit of *Operational Maximum for Effort Expenditure*, then the *State of Stress* will be determined by the *Perceived Control* options available. Lenient combination or Logical OR (formula: $x + y – x * y$) has been used to model how job-related and non-job-related *EXTRA STRESS* combine to form the overall *State of Stress* (Hayward et al., 2014: p. 9).

The concept of *Psychological Detachment*, or an experience of 'switching off' from work, is used to conceptualise the process of recovery from the *Feeling of Fatigue* and "not being busy with job-related tasks during nonwork time and, most important, refraining from job-related task thoughts" (Sonnentag, 2011: p. 253). Two aspects are characteristic of the process of *Psychological Detachment*. First, *Psychological Detachment* is a skill that people have. For some people it is easier to detach from work-related stress, while others may continue to dwell on the work-related problems. In the model the *EFFECTIVENESS OF PSYCHOLOGICAL DETACHMENT* is assumed to range from zero to one, with zero representing an absence of such ability and one representing a full ability to switch off from work and detach.

Second, there should be enough time to detach and recover, which is represented by *Normalised Extra Hours for Detachment* in the model. Long working hours do not necessarily cause a development of the *Feeling of Fatigue*, but they are likely to “act as indirect causes, by reducing the opportunity for sleep and recovery from work stress, as well as limiting the buffering effects of family and social activities” (Hockey, 2013: pp. 192–193). The model formulation ensures a possibility of complete recovery, if performance is below *WORKING EFFORT BUDGET*. As an individual starts working above *WORKING EFFORT BUDGET*, the possibility for recovery is reduced:

Normalised Extra Hours for Detachment [Dmnl] *= MAX (0, (Overall Hours Worked per Day* [Hours/Day] – *WORKING EFFORT BUDGET* [Hours/Day]) */ (MAXIMUM AVAILABLE HOURS PER DAY* [Hours/Day] – *WORKING EFFORT BUDGET))* (13)

The MAX function ensures that the output is never below zero. It is assumed to take a month to fully develop a *Feeling of Fatigue* as well as to fully recovery from it. In the model the *Feeling of Fatigue* is normalised against *MAXIMUM FATIGUE* and the normalised value is used for the effect of fatigue on other variables in the model.

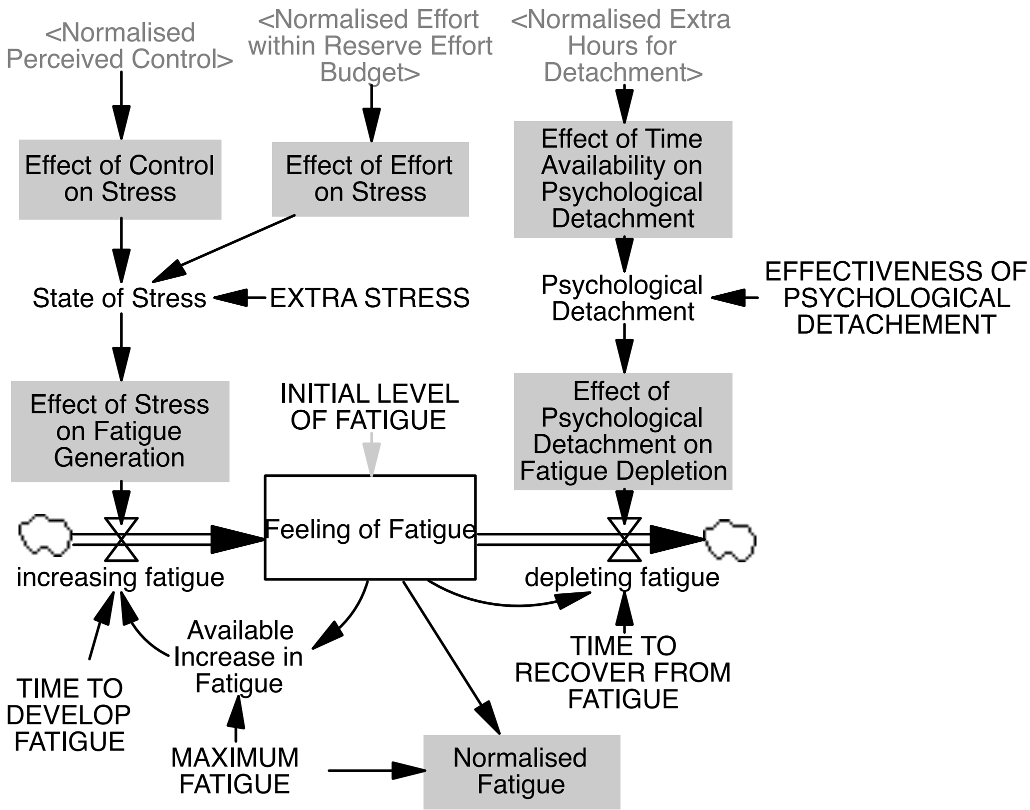

Figure 6.15. SFD for Feeling of Fatigue stock

6.3f. Activity performance

It is not possible to assess performance instantly, so decision makers are modelled as reacting to *Perceived Performance per Day*, rather than to actual *Performance per Day* (Figure 6.16). *Perceived Performance per Day* is modelled as a stock that is adjusted to the values of actual *Performance per Day* over time:

Perceived Performance per Day [Accomplishments/Day] = *INTEG*
(change in perceived performance [Accomplishments/(Day*Day)]*,* (14)
Performance per Day [Accomplishments/Day]*)*

It is assumed that individuals take about a week to perceive performance discrepancies. The *Maximum Possible Performance per Day* variable corresponds to the ideal possible performance value, when an individual works with *MAXIMUM PERFORMANCE PER HOUR* during the *Maximum Hours Available for Current Activity*:

Maximum Possible Performance per Day [Accomplishments/Day] =
Maximum Hours Available for Current Activity [Hours/Day] * *MAXIMUM PERFORMANCE PER HOUR* [Accomplishments/Hour] (15)

For the sake of simplicity *MAXIMUM PERFORMANCE PER HOUR* is assumed to be one accomplishment per hour. Actual *Performance per Day* is determined by multiplication of *Performance per Hour* and the number of *Hours Worked per Day on Current Activity*.

The *Feeling of Fatigue* decreases the actual *Performance per Hour*. As Hockey notes "[m]ore effort will be required to maintain task goals under any emotional state, at any level; as long as the goals of this state are incompatible with those of the task a compensatory (high effort) strategy will be required to override them" (Hockey, 2013: p. 99). The feeling of fatigue is incompatible with the goal of finishing the retrofit. In the model a linear effect of the *Feeling of Fatigue* on *Performance per Hour* is assumed.

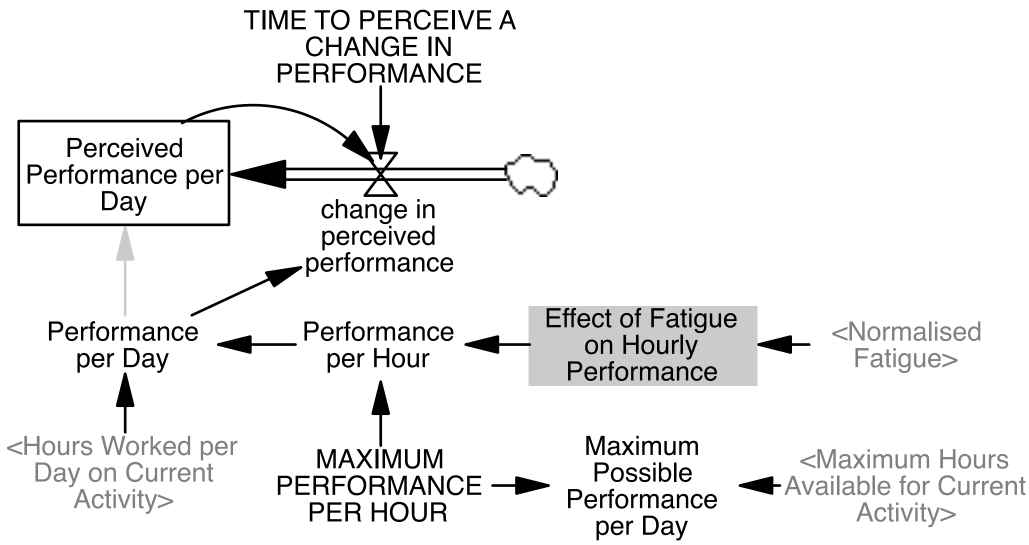

Figure 6.16. SFD for Perceived Performance per Day stock

This completes the description of the formal model of Hockey's motivation control theory of fatigue. The description of model testing and validation is presented in the next section.

6.4. MODEL TESTING AND VALIDATION

A range of tests, specific to system dynamics, has been developed to build in confidence in system dynamics models and validate them (Sterman, 2000: p. 859–861; Forrester and Senge, 1980). To ensure that the model corresponds to the structure described by Hockey, a rigorous process of structure elicitation has been followed, which included thematic coding. The model has been thoroughly documented and the logic for each equation has been specified with quotes from Hockey's theory, where appropriate. After the model was complete and documented with discussion of results, Professor Robert Hockey was contacted to further test the model, and was sent *Chapter 6*, *Appendices D. System dynamics modelling process* as well as the information from the methodology chapter, relevant to the system dynamics model. He reviewed the work and confirmed that the research is an accurate depiction of his theory:

> I have now worked my way through your various documents and thought I would send you a few comments. I was very impressed with what you have done — at least in relation to the role of fatigue in the behaviour you are looking at… First of all, you appear to have captured the details of what I have proposed very clearly and fully. I have impression that you really understand the theory and the reasons why a motivational control approach works better than the traditional one based on energy depletion. (Hockey, 2019)

As all models are inevitably a simplification of reality, it is important to recognise which phenomena lie outside of the model boundary. Boundary definition and adequacy tests have been part of the development process of the model, and the case studies that were part of this research served as a reference to determine the model boundary. Hockey's theory of fatigue is generic and can be used to look into various aspects of relations between effort, fatigue and performance. However, not all of the aspects of these relations were identified in the empirical cases on retrofit-related fatigue development. For instance, Hockey describes a mechanism for the development of a chronic fatigue syndrome, caused by a breakdown in the normal mechanisms that underlie the dynamics of motivation, effort and goal orientation (Hockey, 2013). However, the development of chronic fatigue syndrome was not observed in empirical cases. Thus, a decision was made to exclude the mechanisms responsible for such dynamics from the model boundary. Boundary adequacy test included time horizon tests for theoretical exploration results. The initial time horizon of the model, aimed to investigate theoretical results, was set to two years. The model was tested under a wide range of parameters over the time span of four years to see if unexpected behaviour is generated outside the chosen time horizon.

A dimensional analysis of the model equations confirmed dimensional consistency throughout the model. The constructs of *Perceived Control*, the *Feeling of Fatigue*, the *State of Stress* and motivation (*Intrinsic Motivation* and *EXTRINSIC MOTIVATION*) were measured on a dimensionless scale from zero to one, with zero corresponding to minimum value of the construct and one corresponding to a maximum value. In real life this corresponds to identifying one's experience of motivation, control, stress and fatigue as ranging from low to high. In psychological tradition, however, there might be alternative methods to give dimensions to such constructs. For instance, one of the models, which is used to give dimensions to various feelings, introduces dimensions of *positive affect* (PA) and *negative affect* (NA), that range from low to high. High PA describes the feelings such as elated, energetic and enthusiastic; low PA corresponds to the feeling of fatigue and depression. High NA describes the state of distress, such as feelings of anxiety or anger; low NA describes a person that is calm and content (Hockey, 2013: p. 17–18). Nevertheless, a dimensionless scale of the mentioned constructs was chosen for simplicity.

A model test for numerical sensitivity to simulation time step was also carried out. Rates and constants are set in units per day. The integration time step was progressively reduced in half until there was no significant difference in numerical results for a time step of ¼ day. The integration method was set to Euler because the aim of the model is a qualitative exploration of the patterns of behaviour, therefore numerical integration precision is not overly crucial.

The model was tested under extreme conditions, for which high and low values were assigned to the state variables and initialisation parameters in the model. Behaviour exploration tests were carried out. The model was tested under a wide range of parameters with variation in initial values for the constructs of *ACTUAL CONTROL, INITIAL INTRINSIC MOTIVATION, EXTRINSIC MOTIVATION* and *MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE*. The model exhibited various patterns of behaviour, consistent with the logic of the model formulation and underpinning theory, which strengthens the internal validity of Hockey's theory (Davis et al., 2007). For instance, the level of fatigue does not go beyond 0.7 under any conditions. The model structure allows for fatigue to build up to one, but model dynamics prevents that from happening, as individuals in the model start working less to allow for recovery, when fatigue increases. Such dynamics are consistent with Hockey's formulation of fatigue as a mechanism to prevent motivational fixation on a task, which leads to a reduction in work effort long before the actual ability of work has suffered any significant changes (Hockey, 2013: p. 5). The range for the input parameters as well as the patterns of behaviour for the state variables can be found in *Appendix DB. Model testing and validation.* Hockey's theory is already externally valid, as it is largely based on empirical evidence (Davis et al., 2007). The external validity of the applicability of the generic theory to the retrofit-associated fatigue is further strengthened via the application of the model to empirical cases (ibid.).

This completes the description of the model testing and validation. The next section discusses the results of behaviour exploration tests, including reproduction of fatigue-related behavior as discussed by Hockey.

6.5. MODEL SIMULATION

The model was explored in three ways. First, the model was tested to see whether it is possible to reproduce the three work management modes described by Hockey. Behavioural anomaly tests were carried out to see if the model is capable to produce behavior not originally described by Hockey. The model was also tested for behavioural reproduction of other related theories. The second way to explore the model was to parameterise it for the behavioural reproduction of empirical cases. The results of these two sets of simulations runs are presented in this section. Input parameters for theoretical simulation runs are presented in this section. *Appendix DC. Empirical cases simulation* provides tables of parameter values and initial conditions used in each simulation run for empirical cases.

The third set of simulation runs was set to explore the interventions to moderate the work pace and reduce or alleviate the presence of fatigue. Two scenarios were developed and applied to the model to see whether the level of fatigue, if generated, can be reduced. The results of this set of simulation runs are discussed in section 6.6.

6.5a. Work management modes

The compensatory control model of fatigue is a new theoretical explanation of the phenomenon of fatigue by Hockey, who calls for further research to explore the theory systematically. The theory describes three general coping strategies or work management modes: engaged, disengaged and strain (see section 6.1). Hockey suggests that the existence of more work management modes is possible and suggests that a full test of the theoretical model "will need to be able to identify a range of alternative coping modes" (Hockey, 1997: p. 90). The current subsection explores, whether the three working modes described by Hockey can be deduced from the model developed from his theory, and whether alternative coping strategies can be identified through simulation. The subsection describes five sets of simulation results. The input parameters for the graphs presented in this subsection, which differ from the default values, can be found in Table 6.7.

Table 6.7. Input parameters for the work management modes

Variable name Figure №	Engaged 6.17, 6.22	Disengaged 6.18, 6.22	Strain I 6.19, 6.22	Strain II 6.20, 6.22	Strain III 6.21, 6.22
ACTUAL CONTROL	1	0.3	0.6	0.9	0.4
EXTRINSIC MOTIVATION	1	0.3	1	1	1
INITIAL INTRINSIC MOTIVATION	1	0.3	1	1	1
MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE	8	7	10	8	2
INITIAL HOURS WORKED	8	8	6	8	2

The first set of simulation results examines the behavioural reproduction of the *engaged* work mode (Figure 6.17). The model is initiated to conditions of high intrinsic and extrinsic motivation, full control and a situation when individual's performance expectations match external demands. As expectations and demands are matched, an individual is able to meet the goals easily, so strain spirals **R1** and **R2** are not active. The reinforcing loop **R4** works in a virtuous cycle, as the perceived success of meeting external demands reinforces the feeling of control and satisfaction from the job well done. As the activity is seen as highly rewarding, an individual eventually increases the working hours up to 11 per day, reaping even higher rewards. No feeling of fatigue is developed.

This behaviour is consistent with Hockey's conceptualisation of the engaged work management mode, who argues that a performance breakdown is not an inevitable consequence of working for long hours (Hockey, 2013: p. 132). The activities that are self-selected, as well as the externally driven tasks under conditions of high control, are not perceived as "tiring, and may even have the opposite effect: that of energizing the performer" (ibid.: p. 9). Hockey draws a link from this description of re-energising activity to the experience of 'flow' described by Csikszentmihalyi (1977; 2000), who describes the flow experience as "a sense of elation, a feeling of creative achievement, which… can be provided in any structured activity, including work" (Csikszentmihalyi, 2000: p. 46). In the model, the 'self-selected want to' activities, described by Hockey, are interpreted as activities with high intrinsic motivation and high level of control. The same behaviour (Figure 6.17) is produced by the model when both intrinsic and extrinsic motivation are set to their maximum values, and when only one is set to the maximum and another one to the minimum.

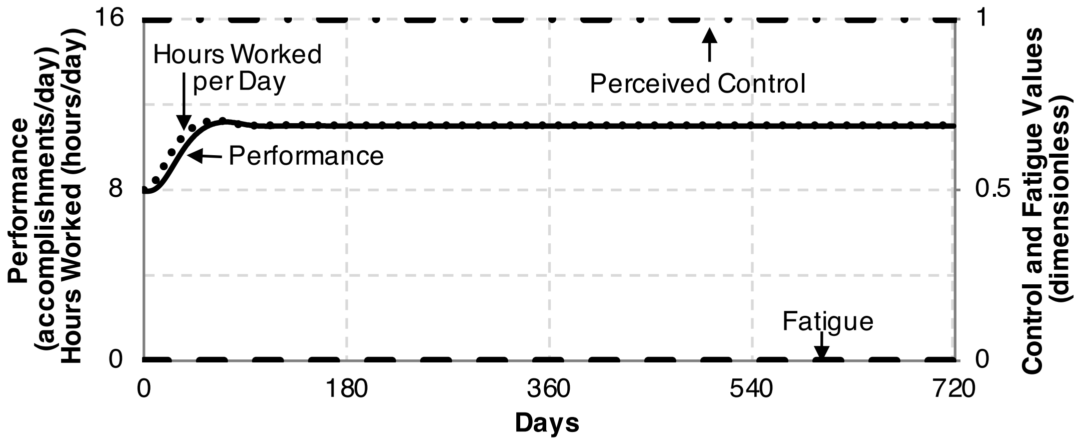

Figure 6.17. Engaged work management mode. Input parameters can be found in Table 6.7.

The second set of simulation results reproduced the *disengaged* work management mode (Figure 6.18). The model is initiated to conditions of low intrinsic and extrinsic motivation, low control and a situation, when individual's performance expectations are slightly greater than external demands. An individual is able to meet performance demands, but as the activity is not extrinsically or extrinsically rewarding, the balancing loop **B2** becomes active and alternative activities become more attractive. Subsequently, less effort is allocated to the current activity and performance decreases. Nevertheless, the activity is not very demanding in terms of energy resources, thus, no feeling of fatigue is developed.

The model behavior is in line with Hockey's description of the disengaged working mode, which is described as a passive coping mode involving "downwards adjustment of performance targets" (Hockey, 1997: p. 82). Nevertheless, Hockey mostly talks about passive coping strategy as a later stage of a strain work management mode. Such dynamics are explored in the next set of simulations.

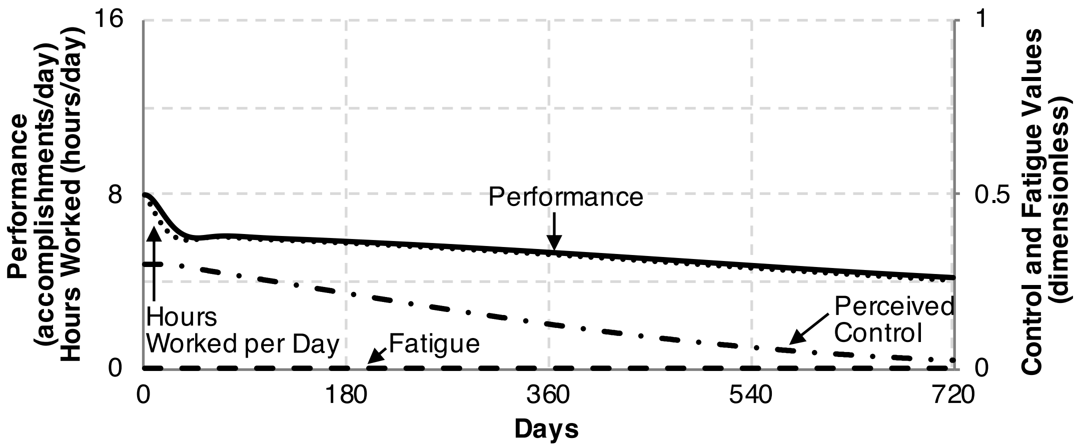

Figure 6.18. Disengaged work management mode. Input parameters can be found in Table 6.7.

The third set of simulation results reproduces the strain work management mode (Figure 6.19). The model is initiated to conditions of high intrinsic and extrinsic motivation, average control, and external performance demands that are slightly higher than individual expectations. Performance demands are initially slightly higher than individual expectations, thus, an individual puts more effort to meet the demands as described by balancing loop **B1**. The activity is highly rewarding extrinsically and intrinsically, thus, the reinforcing loop **R4** works first in a virtuous cycle, as the individual sees more value in pursuing current activity and increases performance expectations. Nevertheless, the actual level of control over the activity is limited, leading to stress and fatigue. Vicious strain spirals **R1** and **R2** become active, and performance drops, despite the effort put in to maintaininig it. Previously in virtuous mode, **R4** loop turns into a vicious one, as the individual loses a sense of control over the activity. A downward adjustment of performance expectations occurs, and the system stabilises at low levels of performance with no fatigue.

The observed pattern is consistent with Hockey's description of the strain work management mode. He argues that, when an individual is highly motivated, the performance is protected by the use of effortful strategies (Hockey, 2013). The model shows this behaviour in the first month of the simulation. The state of stress, which develops as an individual continues with the strain mode, gives rise to a growing feeling of fatigue, that further escalates the need for sustained high effort:

> At some point the system is assumed to reach a tipping point. This is defined as the state where the utility of task goals (in terms of the costs and benefits of maintaining standards of performance) drops below an acceptable (or manageable) level. At this point a switch occurs, in which the default high effort mode is replaced by a strategy of low engagement; the attempt at sustained effort is abandoned and replaced by what is, in essence, a passive strategy. (Hockey, 2013: p. 199).

Only in very extreme cases does a switch to a passive strategy mean that the goal is abandoned altogether. A more typical response is a reduction of performance criteria, for instance, cutting corners or reducing the pace of work (ibid.: p. 200). In the model, the tipping point occurs after the first month of simulation. It then takes about a year for the performance targets to adjust downwards and reach an equilibrium.

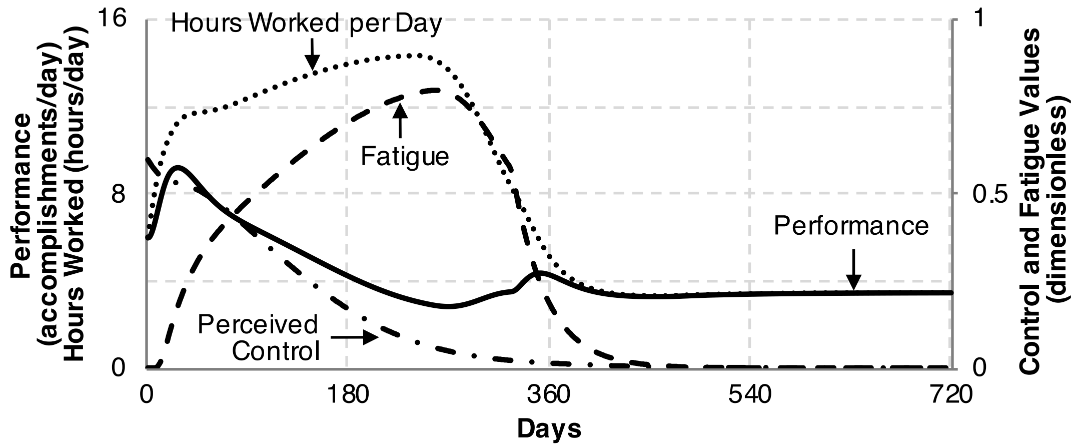

Figure 6.19. Strain work management mode I (proactive to reactive coping). Input parameters can be found in Table 6.7.

The model simulation under a wide range of parameters revealed two more work management modes, which the author here refers to as strain II (sustained proactive coping) and strain III (oscillations between proactive and reactive coping), as opposed to already described strain I mode (proactive to reactive coping).

The model set up for the strain II (sustained proactive coping) work management mode is identical to the set up for the engaged work management mode (high intrinsic and intrinsic motivation, a match between individual performance expectations and extrinsic demands) except for the initial actual control conditions, which are set to a high, but not the maximum value. Initially, an individual performs in an engaged manner, as performance and hours worked are increased by the reinforcing loop **R4** (Figure 6.20). With time, the lack of control underpins a state of stress that leads to the development of the feeling of fatigue by the reinforcing loop **R1**. Performance goals are adjusted downwards and performance stabilises. Interestingly, the level of fatigue also stabilises. Thus, the individual continues working with less efficiency and with a constant background level of fatigue.

Even though Hockey does not distinguish this coping strategy explicitly, the description of it can be traced in his conceptualisation of the strain I work management work mode. The dynamics of the strain II work management mode represent the behaviour before the switch to a disengagement mode, described by Hockey for the strain I work management mode. Performance goals "remain in place but with a higher level of effort" (Hockey, 2013: p. 145). Interestingly, the model shows no performance decrements as compared to external demands. Nevertheless, the feeling of fatigue is present. This reinforces Hockey's statement, that the observation of performance impairment cannot be regarded as a defining feature of the presence of fatigue (Hockey, 2013: p. 51).

Performance protection strategies are employed when the goals are considered important. The behaviour in Figure 6.20 is produced also by the model when both intrinsic and extrinsic motivation are set to their maximum value, and when only extrinsic motivation is set to the maximum and intrinsic one to the minimum. When the conditions are reversed with maximum intrinsic and no extrinsic motivation, the same level of performance is achieved with less effort, while a smaller level of fatigue is developed during the process.

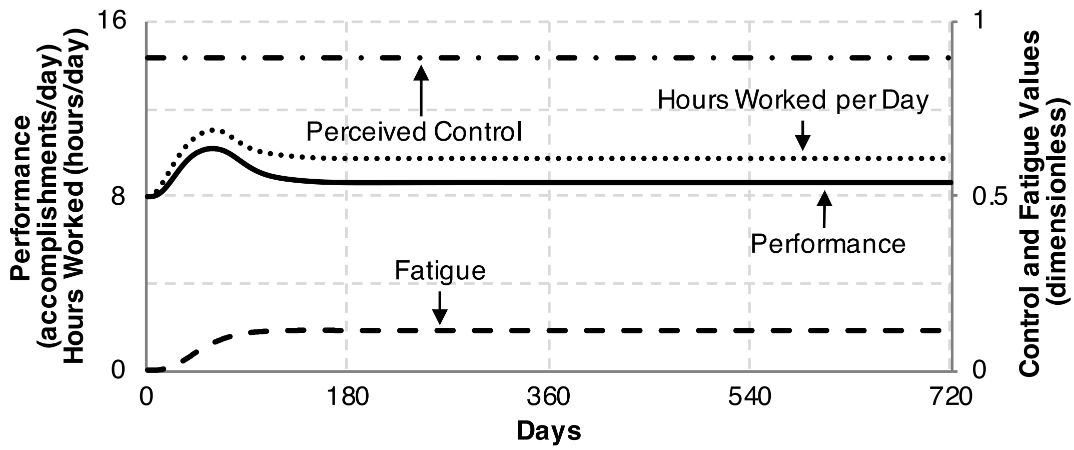

Figure 6.20. Strain work management mode II (sustained proactive coping strategy). Input parameters can be found in Table 6.7.

Another additional work management mode revealed through simulation is a strain mode III, characterised by continuous oscillations between proactive and reactive coping strategies (Figure 6.21). For this set up the model is initiated with high extrinsic motivation, no intrinsic motivation, and slightly lower than average control and minimal external initial requirements. Initially, as the individual starts reaping the external rewards associated with the activity, its perceived value increases via the reinforcing loop **R4**, similar to the behaviour observed in the engaged work management mode (Figure 6.17). However, as the level of control over the activity is average, the individual becomes stressed, develops fatigue, the virtuous cycle **R4** turns into a vicious one, and the work management mode switches to a disengaged one. As the level of perceived control never drops to zero, with time, the vicious cycle **R4** turns again to a virtuous one, and the oscillatory behaviour persists.

Hockey does not talk about oscillatory behaviour. Nevertheless, he emphasises several times that the development of fatigue is more readily associated with task goals (extrinsic motivation) rather than self-initiated (intrinsic motivation) activities (Hockey, 2013). Indeed, the behaviour in the Figure 6.21 is only observed when extrinsic motivation is set to its maximum value. When extrinsic motivation is given a zero value and intrinsic motivation is set to the maximum value, the model exhibits the engaged work management mode, even under conditions of low control.

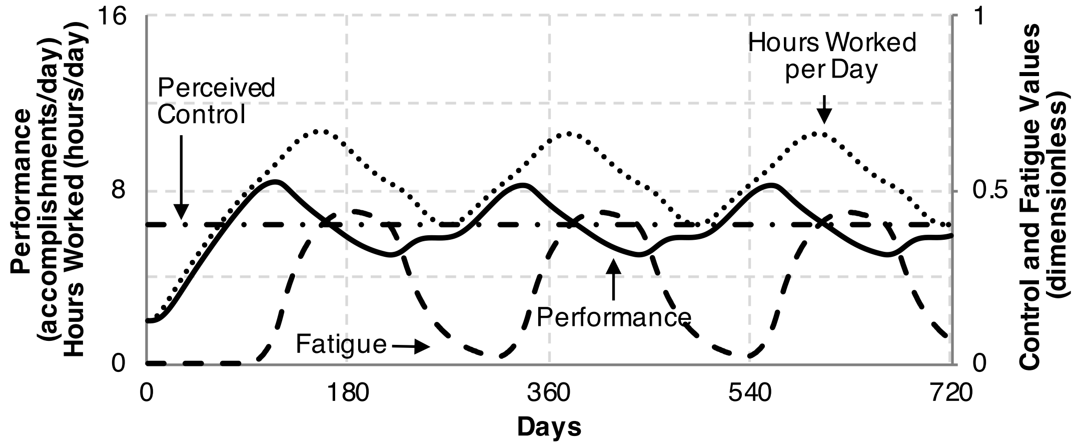

Figure 6.21. Strain work management mode III (oscillations between coping strategies). Input parameters can be found in Table 6.7.

In summary, the model is able to reproduce the three work management modes, described by Hockey. Moreover, simulation results reveal two additional work management modes that show different dynamic patterns between fatigue, effort and performance. A comparison of the *Feeling of Fatigue* development between five identified work management modes is shown in Figure 6.22. Note that the lines for the engaged and the disengaged modes are coincident in the graph, as no feeling of fatigue is present in neither of the cases. The comparison of different dynamics patterns for the variables of *Hours Worked per Day, Perceived Performance per Day* and *Perceived Control* can be found in *Appendix DB. Model testing and validation*. The figure for the dynamics of the *Feeling of Fatigue* is reproduced in the appendix, which also lists the setup for the input variables for the comparison graphs.

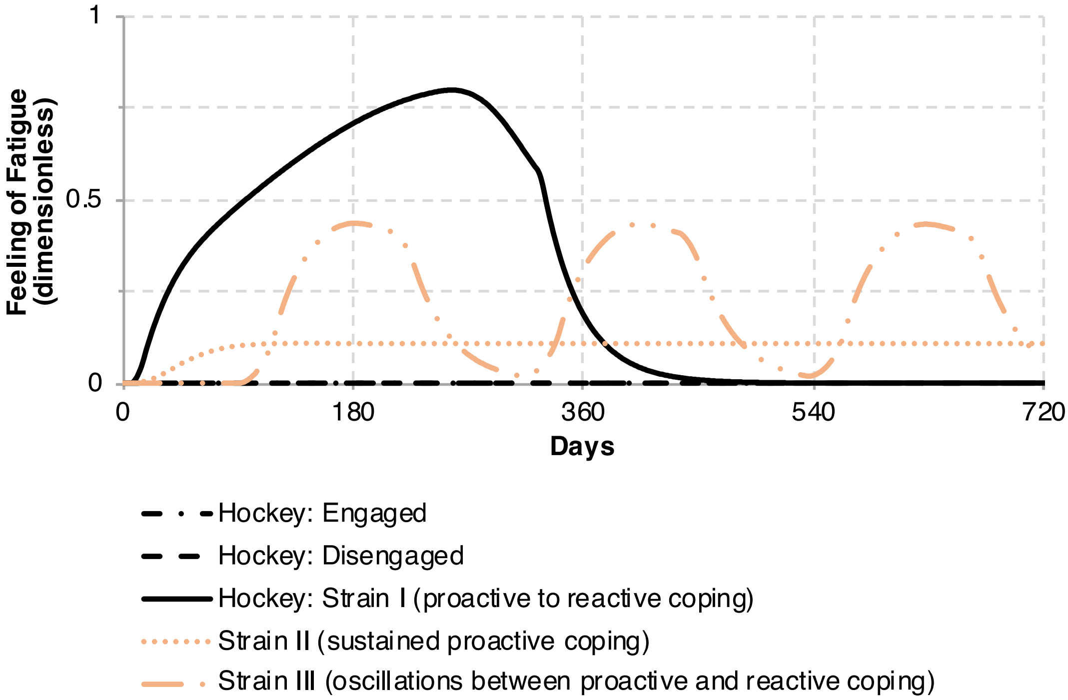

Figure 6.22. Dynamics of the Feeling of Fatigue for five work management modes. Input parameters can be found in Table 6.7.

6.5b. Learned helplessness

Hockey describes the development of work management modes when the control over one's environment is unchanging. However, in real life, the work environment is never stable and the level of control may rise or decline due to changes in the environment. To reflect this, the model was tested for a change in the level of *ACTUAL CONTROL* over the activity with some interesting results. The results of two simulation runs are displayed here. In both cases the model is initialised with high initial intrinsic and extrinsic motivation. The *ACTUAL*

CONTROL is increased from a slightly above average value to the maximum possible value at one and a half years into the simulation. The results of two simulation runs are displayed in Figures 6.23 and 6.24. The input parameters for the graphs presented in this subsection, which differ from the default values, can be found in Table 6.8.

Table 6.8. Input parameters for the learned helplessness modes

Variable name	Learned helplessness Fig. 6.23	No learned helplessness Fig 6.24
ACTUAL CONTROL	0.6, then 1	0.6, then 1
EXTRINSIC MOTIVATION	1	1
INITIAL INTRINSIC MOTIVATION	1	1
MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE	10	2
INITIAL HOURS WORKED	10	2

In the first run the external performance demands are set slightly higher than initial individual's expectations (Figure 6.23). The model exhibits the strain I work management mode, shifting from proactive to reactive coping strategy and stabilising at a lower level of performance. No change in the model behavior is observed after a change in *ACTUAL CONTROL*.

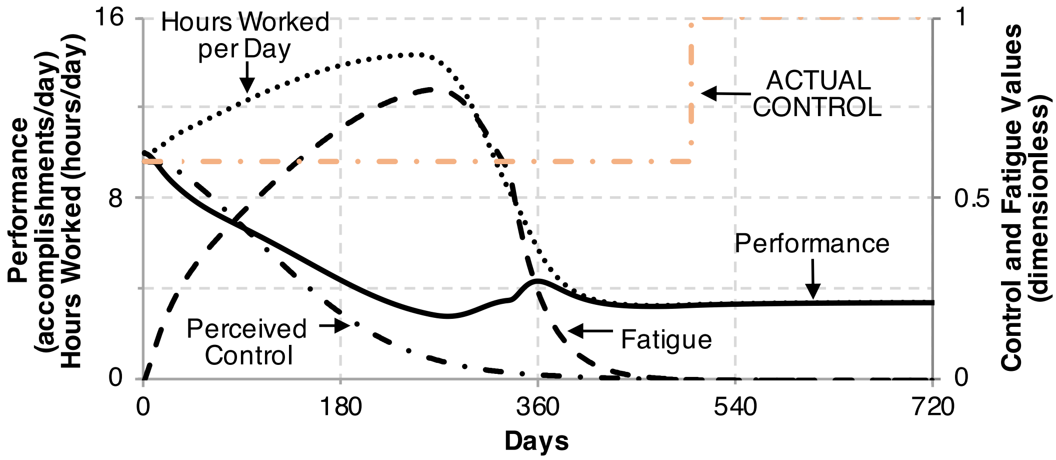

Figure 6.23. Learned helplessness. Input parameters can be found in Table 6.8.

In the second run, the external performance demands are set relatively low and match those of expectations (Figure 6.24). The model exhibits oscillations between a proactive and a reactive coping strategy. When the level of *ACTUAL CONTROL* is increased to its maximum value, the dynamics change and the model stabilises in engaged work management mode.

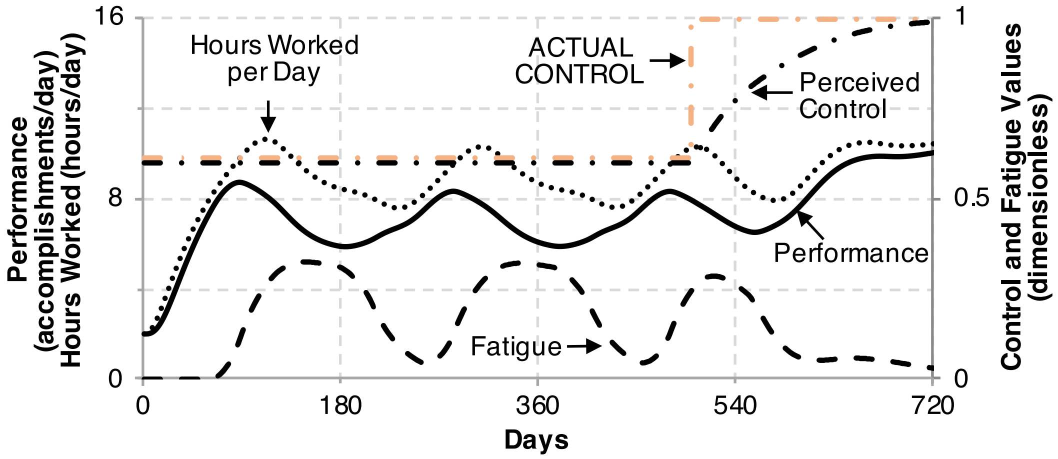

Figure 6.24. No learned helplessness. Input parameters can be found in Table 6.8.

The behaviour is consistent with the mechanism of learned helplessness, which describes the experience of dealing with uncontrollable events (Seligman, 1975). The theory proposes that an individual learns that the outcome of the actions is independent of the responses, when exposed to uncontrollable events. "A major consequence of experience with uncontrollable events is motivational: uncontrollable events undermine the motivation to initiate voluntary responses…" (Seligman, 1975: p. 37). In Figure 6.23 the experience of uncontrollable events leads to a drop of perceived control to zero. An individual learns that responses to motivational stimuli are futile. As a result, when the level of actual control changes, the individual does not try to change the performance. On the contrary, the level of perceived control in Figure 6.24 never drops to zero. Thus, the individual never develops a feeling of helplessness. As a result, when the level of actual control changes, the individual is still motivated to try to change the performance.

6.5c. Psychological detachment

The level of stress in one's life can be associated not only with work related activities, but could arise from other dimensions of one's life, such as family commitments or worries about one's health. The model has been tested for a context that represents the condition of *EXTRA STRESS* not related to work activities. The model was initialised to produce the engaged work mode as shown in Figure 6.17. An additional variable *EXTRA STRESS* is added to the model, which produces maximum stress levels after the first half a year of simulation. The variable takes the maximum value of one for the duration of three weeks in Figure 6.25, and for the duration of two months in Figure 6.26. The input parameters for the graphs presented in this subsection, which differ from the default values, can be found in Table 6.9.

Table 6.9. Input parameters for the psychological detachment modes

Variable name	3 weeks of additional stress Fig. 6.25	2 months of additional stress Fig 6.26
ACTUAL CONTROL	1	1
EXTRINSIC MOTIVATION	1	1
INITIAL INTRINSIC MOTIVATION	0	0
MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE	8	8
INITIAL HOURS WORKED	8	8
EXTRA SRESS	0, then 1 (for 3 weeks), then 0	0, then 1 (for 2 months), then 0

In both figures the model produces initially the same behaviour as in the engaged work management mode, as the individual starts putting more and more effort in the activity to reap further benefits. However, as extra stress is introduced in the model, the level of fatigue builds up and affects the performance. In Figure 6.25, the additional level of stress is removed before the individual burns out. With time, the level of fatigue drops and performance is restored to the original values.

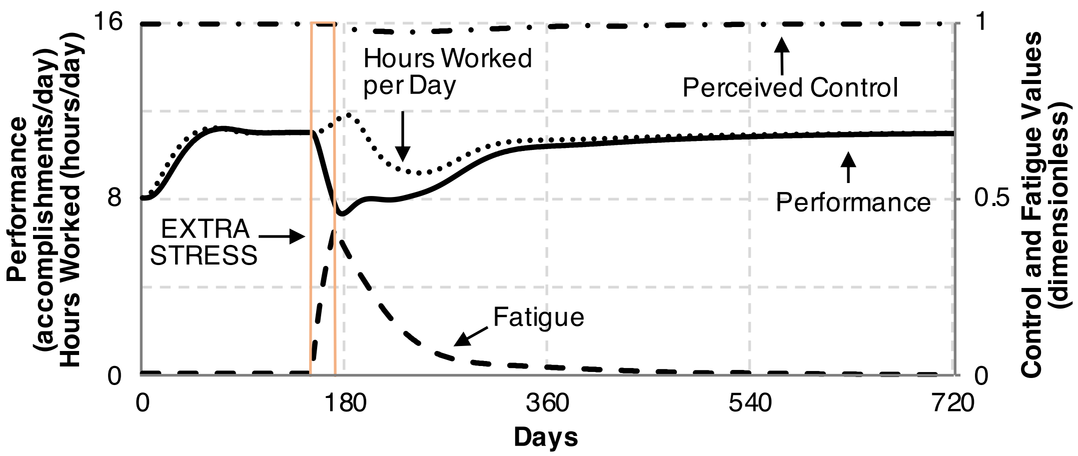

Figure 6.25. Effect of three weeks of additional stress. Input parameters can be found in Table 6.9.

However, in Figure 6.26, the exposure to the additional level of stress is long enough for the individual to start losing the sense of control. The tipping point is reached, and even after the additional level of stress is removed, performance does not restore to its initial level, the individual switches to a disengaged mode and accepts lower levels of performance.

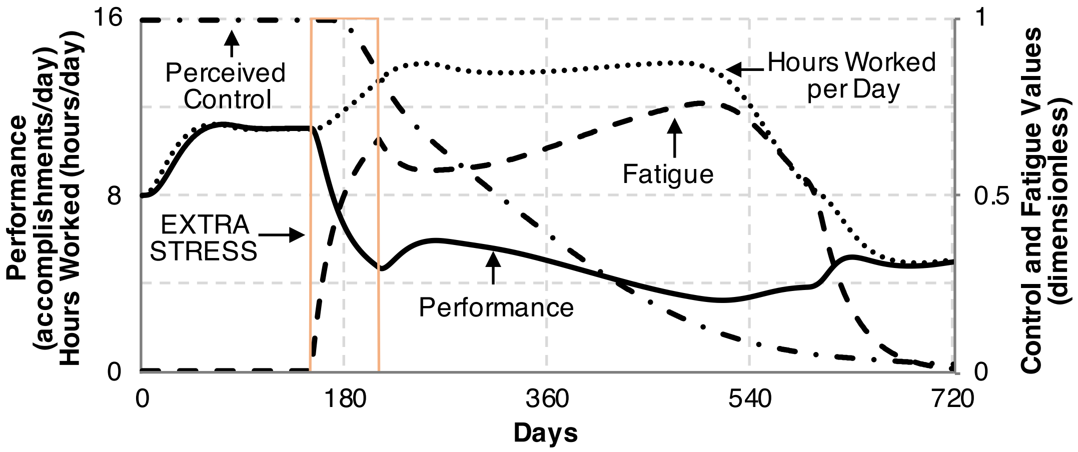

Figure 6.26. Effect of two months of additional stress. Input parameters can be found in Table 6.9.

The behaviour of the model can be explained with Sonnentag's theory of psychological detachment (2011) and Eisenberger's theory of learned industriousness (1992). The concept of learned industriousness describes an acquired habit to employ high effort strategies, because of the learned association of such strategies with high levels of reward. The model produces such behaviour in the first half year of the simulation. However, working for long hours reduces the opportunity for psychological detachment. "[T]his suggests that the most industrious individuals may be the most at risk" (Hockey, 2013: p. 201). In the run described in Figure 6.26 the experience of non-job-related stress for two months leads to the individual's burn out and disengagement, precisely because the individual does not have the extra capacity to deal with additional levels of stress.

6.5d. Model application to fatigue development in the seven retrofit case studies

This subsection discusses the simulation results of the generic model that has been parameterised to reproduce the behavioural patterns inferred in the seven empirical cases carried out for this research. The input parameter values for the runs described here can be found in *Appendix DC. Empirical cases simulations.* The appendix also contains the participants' answers to the 7-point Likert scale questions, which, together with the answers to open-ended questions, were used to parametrise the generic model for each case. This section is used solely to validate the applicability of the model for empirical cases in the thesis. Thus, the section is used solely to show that the model can reproduce behaviour observed in the cases.

Behaviour-very-time graphs for the feeling of fatigue variable were drawn by the interviewed homeowners during the second set of interviews. The owners, who did not report any feeling of fatigue (cases A, E and H), opted not to draw anything for the behaviour-over-time graphs. The next section explores the generic scenarios, and it is argued that insights obtained from the generic scenario exploration is applicable to empirical cases observed in the thesis.

The owner in case A is a professional architect, who owns her own architectural studio. Even though she did not have previous experience with low-carbon construction, she had an extensive knowledge of construction process. She approached the project as a usual project of her studio, redistributing the workforce to different tasks as needed. The work has been carried out within normal working hours. The house was unoccupied during construction. The owner recalls the experience as highly enjoyable and had not reported a feeling of fatigue during the process (Figure 6.27).

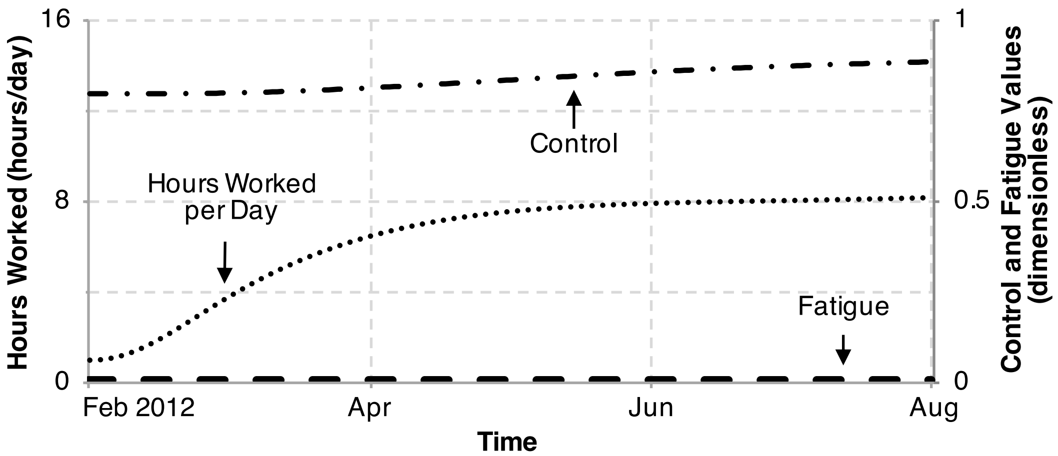

Figure 6.27. Simulation run for case A

One of the owners in case B is a professional builder, who had extensive experience with low-carbon construction in mainland Europe. He carried out the works DIY, which he was very comfortable with. Both owners were in full-time employment during the project, so the retrofit works had to be carried out in the evenings and weekends. The family lived in the house during construction, so construction works had to be coordinated to allow for comfortable living conditions. As the works were carried out by the owners themselves after a full-time job, it was tiring. The effortful retrofit strategy after a full-time job led to the development of fatigue (Figure 6.28). To counterbalance it, the owners carried out the project incrementally, and allowed for breaks to restore. As a result, the owner recalled being only a bit tired:

> At most, I was a bit tired and a bit overwhelmed. That happened on a few occasions, when I was really just absolutely knackered. Not overwhelmed in a sense that it was not in any way unbearable, just needed a bit of a break. (case B, interview 2)

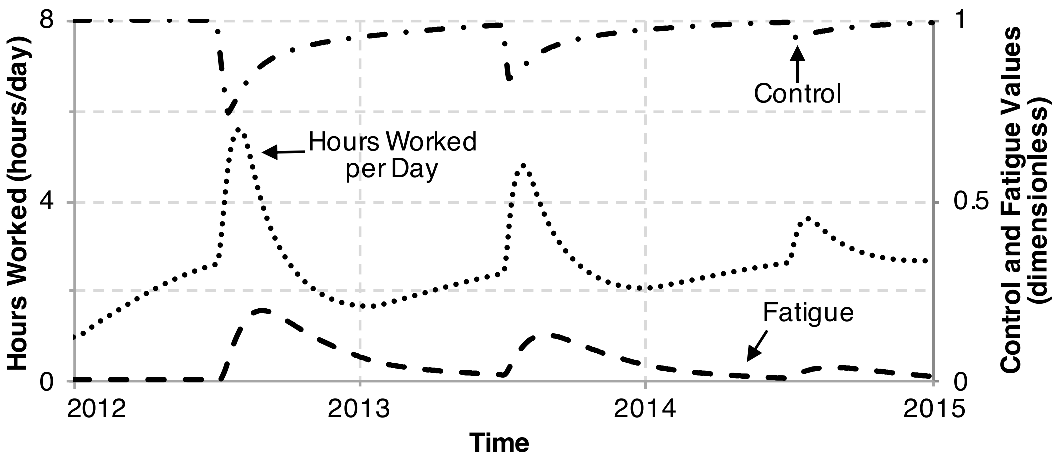

Figure 6.28. Simulation run for case B

Figure 6.29 shows a comparison of the graphs for fatigue development in case B between the model output and the graph, drawn by the homeowner during the interview. The owner drew an oscillatory pattern for fatigue development, which the model reproduced. The phase shift is an unsystematic error, as the owner tried to capture the mode with his drawing rather than particular phases.

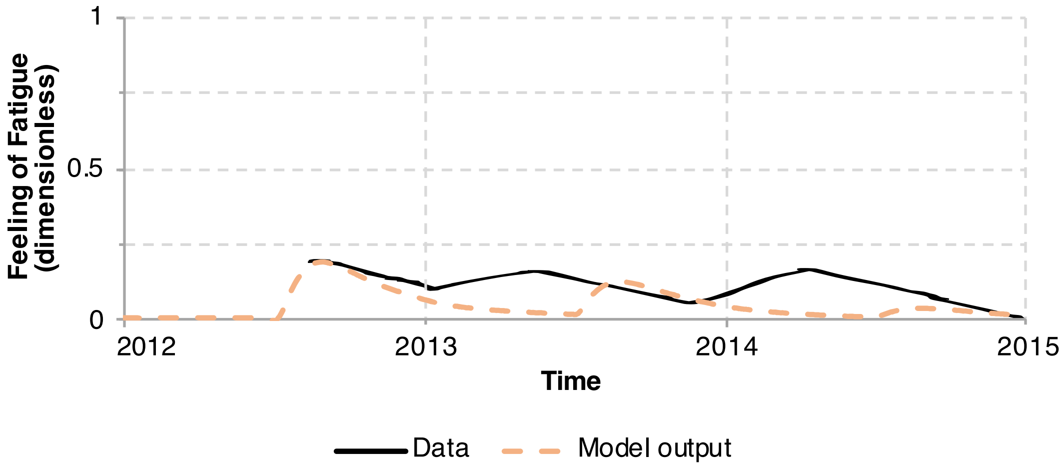

Figure 6.29. Fatigue development: simulation run and behaviour over time graph, drawn by the participant. Case B

One of the owners in case C works in sustainability construction consultancy and had expert theoretical knowledge of sustainable construction and building physics before starting the retrofit project. The family decided to do the works DIY, which they had no previous experience of. They underestimated the amount of time and effort that had to be put in educating themselves about practical aspects of sustainable construction. The owners were in full time employment during the project, and they had to carry out the retrofit works after working hours. They lived in the house during retrofit. The house was in a state of disrepair; thus, the owners were pushing hard to bring the house to pleasant habitable conditions. As the owners carried out the works DIY, they had the flexibility to phase out the works to allow time to rest and restore. The interviewed owner reports only being a bit tired overall (Figures 6.30 and 6.31). Nevertheless, some works were carried out by contractors. The owner remembers working extra hours beforehand, making sure that everything is set for the contractors to do their job:

> There were some times, when we were working till two or three in the morning. Frantically trying to get sorted before a contractor arrives the next day. (case C, interview 2)

An increase in hours worked per day in the model output represents such an occasion, when the owners worked extra hours in an expectation for the contractors to arrive.

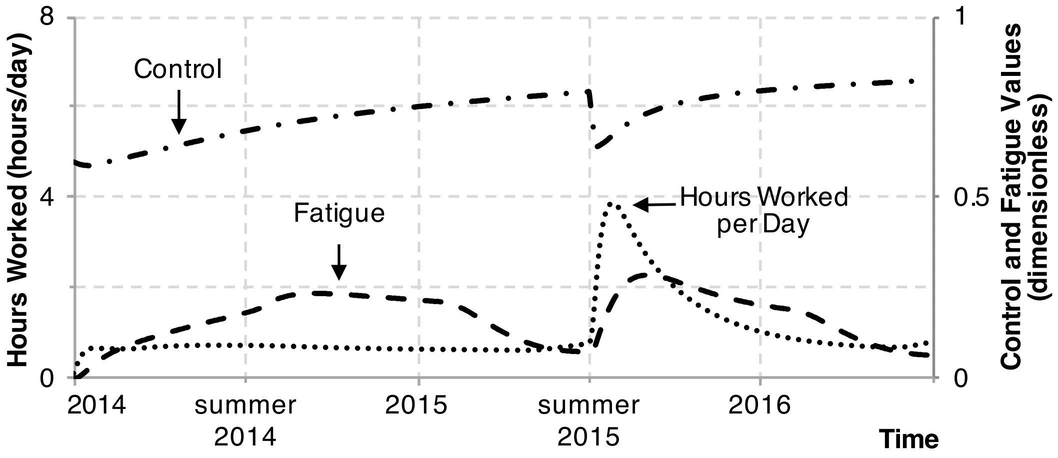

Figure 6.30. Simulation run for case C

Figure 6.31 compares fatigue development in case C between the model output and the graph, drawn by the homeowner during the interview.

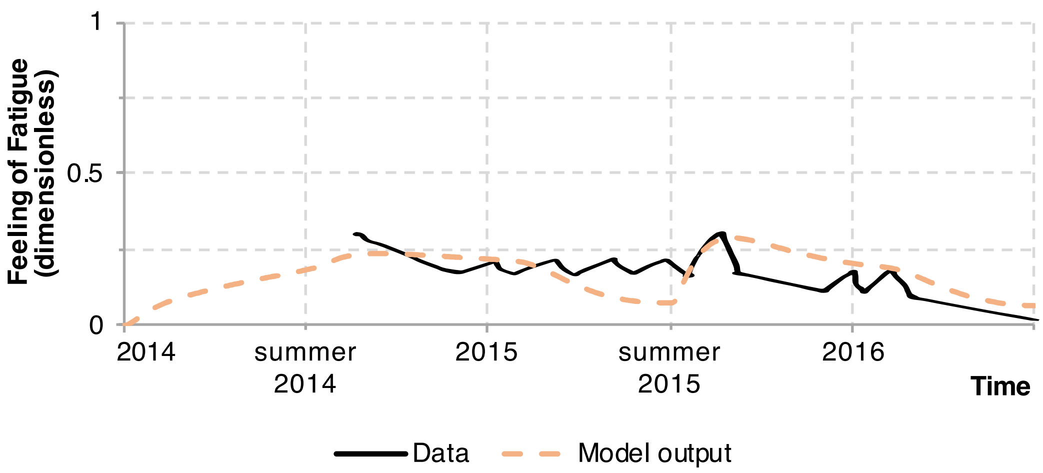

Figure 6.31. Fatigue development: simulation run and behaviour over time graph, drawn by the participant. Case C

The owner in case D worked in sustainability construction consultancy and had expert theoretical knowledge regarding sustainability construction before the project. The owner hired different experts and tradespeople to carry out the retrofit. She had enough theoretical knowledge to supervise the works and control the quality. The owner was in full time employment during the project, thus, the works had to be carried out after working hours. The family lived in the property during retrofit. Even though the house was not decorated to owner's liking, it was in comfortable living conditions. Thus, the owner did not have to rush the construction process and carried it out at a comfortable pace. She reports being tired only a bit with one of the most overwhelming experiences being an internal wall insulation (Figures 6.32, 6.33):

> It's just that the internal wall insulation was more disruptive than I thought it would be. … Because there were different trades people here. All at the same time. And it was a little bit chaotic. Because you had plumbers and electricians and carpenters. They did not necessarily know each other and it wasn't particularly well coordinated by the company involved. (case D, interview 2)

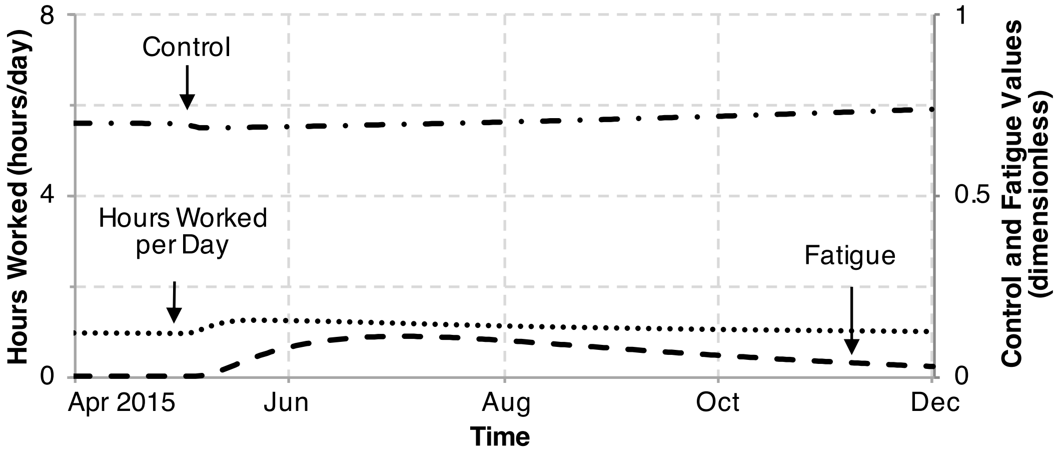

Figure 6.32. Simulation run for case D

Figure 6.33 compares fatigue development in case D between the model output and the graph, drawn by the homeowner during the interview.

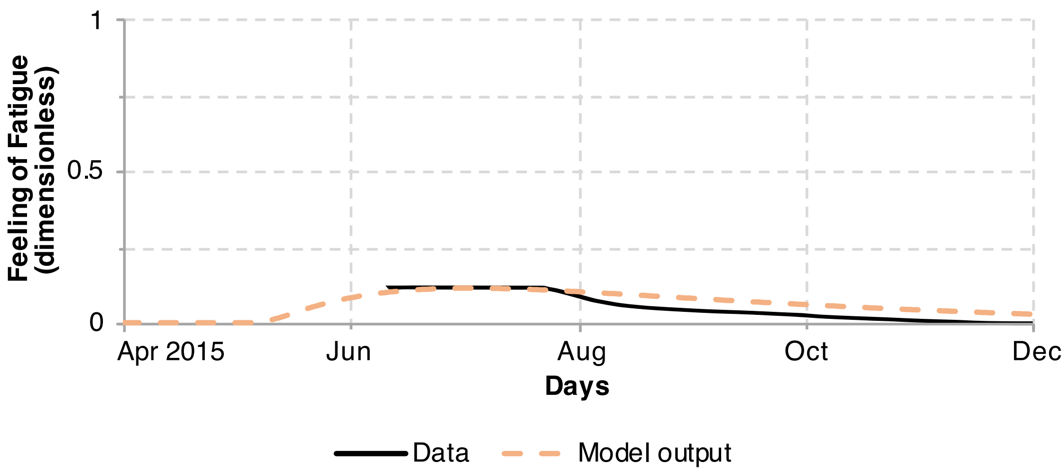

Figure 6.33. Fatigue development: simulation run and behaviour over time graph, drawn by the participant. Case D

The owner in case F used to work in sustainability construction consultancy, thus she had good theoretical knowledge of low-carbon retrofit. The family did not live in the property during construction works. The family hired a professional builder to carry out the works. They also hired a sustainability construction consultant, who transferred relevant knowledge on low-carbon construction to the builder on site. One of the owners quit her job to supervise the construction, allowing for a comfortable work pace. Overall, no feeling of fatigue was reported (Figure 6.34).

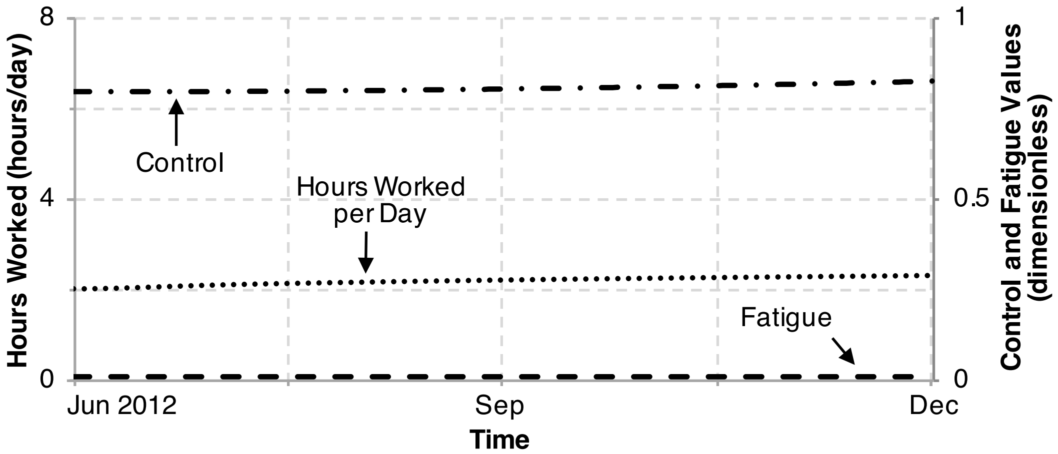

Figure 6.34. Simulation run for case E

The owner in case G did not have any construction-related experience before starting the project. Both owners have an IT background. They believed that having a technical background allowed them to grasp quickly the principles of building physics, necessary to make informed decisions regarding retrofit. The owners decided to retrofit to Passivhaus standard, despite not having an expert on Passivhaus construction on the team. One of the owners became a Passivhaus certifier during the retrofit, in an attempt to get necessary theoretical and practical knowledge. The owners employed professional builders to carry out the works. Thus, they were interested to finish the works as soon as possible to stop paying the fees to the builders. The owners began the works before they had a clear picture of what should be done. The owners managed the project themselves, giving tasks to the builder and educating themselves regarding Passivhaus construction at the same time. It was a daunting task to stay ahead of the game and make sure the builders have work to do:

> We had to just race with the time and the builders to be ahead of them. And that was a difficult thing to do. (case G, interview 2)

The owners moved to the house before the retrofit works were finished, and this limited their ability to detach and restore from the daily stress. Overall, the retrofit project was a very tiring experience, even almost unbearable at times (Figures 6.35, 6.36):

> Going this way [implementation difficulties], I think it [retrofit project] probably would break a few marriages. (case G, interview 2)

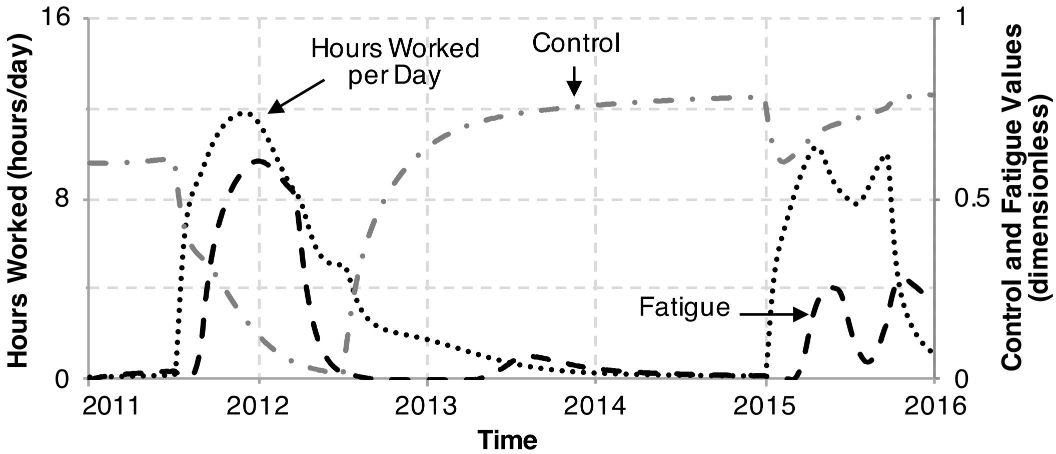

Figure 6.35. Simulation run for case G

Figure 6.36 compares fatigue development in case G between the model output and the graph, drawn by the homeowner during the interview.

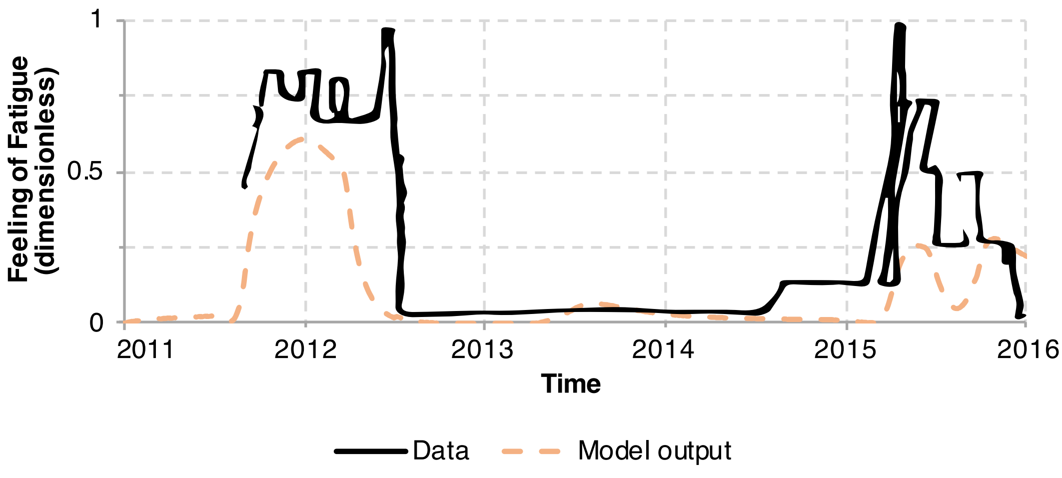

Figure 6.36. Fatigue development: simulation run and behaviour over time graph, drawn by the participant. Case G

The owners in case H have no construction-related or technical background. One of the owners is a guitar teacher, and another one does acupuncture, medical research and recently started painting. The owners lived in the house during the retrofit works, thus, limiting the opportunity for daily recovery from stress. Even though, the conditions present the perfect context for the development of the feeling of fatigue, it was not reported by the owners (Figure 6.37). An explanation for the phenomenon can be found in the length of different decision-making stages. The owners did retrofit measure-by-measure. They were not in a rush and did not have an overarching vision from the outset. The outcomes of every measure or technology installation showed them what else should be done. The owners took their time to research and find an option they are comfortable with. The works themselves took only from a few days to a few weeks to complete for each installation. The works were carried out by tradespeople rather than homeowners themselves. Thus, the owners spread the burden of acquiring the necessary knowledge to carry out the works over significant periods of time, which meant that the feeling of fatigue never built up.

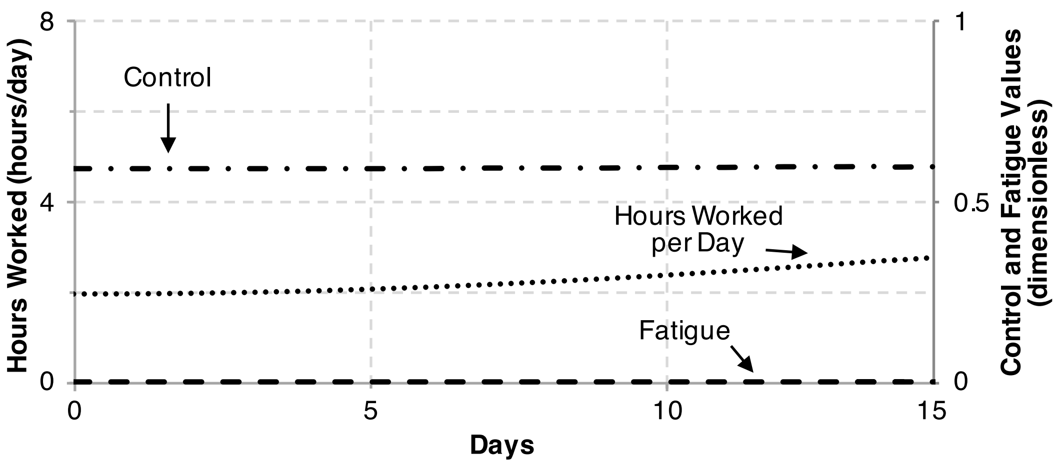

Figure 6.37. Simulation run for case H

This section presented the results for the model exploration simulation runs. The first set of simulation runs were concerned with theoretical model exploration. Work management modes, described by Hockey, were reproduced, and two addition strain work management modes were revealed through simulation. The behaviour exhibited by the model was also found to be consistent with Eisenberger's theory of learned industriousness (1992), Seligman's theory of learned helplessness (1975) and Sonnentag's theory of psychological detachment (2011). This provides a measure of the model generality of the model in terms of the theoretical ground and phenomena it covers. The second set of simulation runs reproduced the fatigue patterns associated with low-carbon home retrofit, inferred from the interviews, carried out for this thesis. The next section explores the intervention scenarios that aim to reduce the level of fatigue, if present.

6.6. SCENARIO EXPLORATION

The insights from the qualitative analysis of interviews, carried in *Chapter 5* suggested that a step-by-step retrofit approach might appeal to a wide range of owner-occupiers, as it is more likely to be a less tiresome experience than an in-depth whole house retrofit in one go. Model simulation identified three strain work management modes that are described in section 6.5a:

(i) Strain work management mode I (proactive to reactive coping).
(ii) Strain work management mode II (sustained proactive coping).
(iii) Strain work management mode III (oscillations between proactive and reactive coping).

This section examines how the introduction of a stop-and-go pattern of work changes the corresponding behaviour of the three strain work management modes. This section applies the following scenarios of stop-and-go pattern to the three work management modes:

(i) Work with regular small breaks.
(ii) Work with regular small and occasional big breaks.

The first scenario corresponds to a work pattern similar to the one of a full-time job with breaks for weekends. The second scenario corresponds to a work pattern similar to the one of a full-time job with weekends breaks as well as holiday breaks. The input parameter values for the graphs presented in this subsection, which differ from the default values, can be found in Table 6.10. This subsection contains seven runs. The *Appendix DD. Scenario exploration* reproduces these runs as well as features another five runs, which amounts to 12 scenarios.

Table 6.10. Input parameters for the stop-and-go patterns of three strain work management modes

Variable name	Work management modes		
	Hockey: Strain I Figures 6.42, 6.43, 6.44	**Strain II Figures 6.38 and 6.39**	**Strain III Figures 6.40 and 6.41**
ACTUAL CONTROL	0.9	0.9	0.6
EXTRINSIC MOTIVATION	1	1	1
INITIAL INTRINSIC MOTIVATION	1	1	1
MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE	10	1	1
INITIAL HOURS WORKED	0	0	0
SCENARIO EXPLORATION			
Work with regular small breaks (weekends)	**Figure 6.43 only**	**Figure 6.39 only**	**Figure 6.41 only**
	For the period of a break EXTRINSIC MOTIVATION, INITIAL INTRINSIC MOTIVATION and MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE drop to zero. PERCEIVED BENEFITS OF OTHER ACTIVITIES rise to 1. Breaks are determined by PULSE TRAIN (0 ,6 ,7, 720)		
Work with regular small and occasional big breaks (weekends and holidays)	**Figure 6.44**	**n/a**	**n/a**
	For the period of a break EXTRINSIC MOTIVATION, INITIAL INTRINSIC MOTIVATION and MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE drop to zero. PERCEIVED BENEFITS OF OTHER ACTIVITIES rise to 1. Breaks are determined by a multiplication of PULSE TRAIN (0, 6, 7, 720) and PULSE TRAIN (0, 170, 185, 720)		

The model exhibited a similar response to the introduction of stop-and-go patterns for the strain II and the strain III work management modes. In both modes, the introduction of regular small breaks, equivalent to weekends breaks, was sufficient to stabilise performance and reduce the feeling of fatigue to zero. The behaviour in both of these scenarios can be explained as follows. The job an individual is engaged in is highly rewarding both intrinsically and extrinsically, and, thus, the individual puts a lot of effort in the activity. There are almost no external requirements of how much work needs to be done. Nevertheless, the individual is not in full control of when and how to carry out the work, which might form a fruitful ground to develop a feeling of fatigue. However, the individual maintains a healthy work-life balance, allowing to restore from any work-related stress during weekends, thus, no feeling of fatigue is developed. The strain II work management mode is characterised by a sustained proactive coping strategy. Continuous work mode without breaks for the strain II work management mode is shown in

Figure 6.38. The difference the introduction of regular small breaks makes to the strain II work management mode is shown in Figure 6.39.

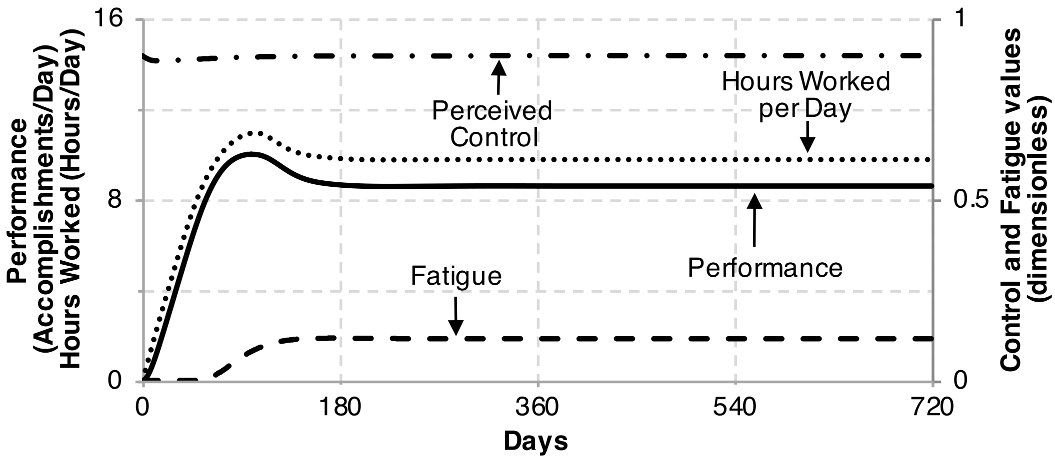

Figure 6.38. Strain work management mode II (sustained proactive coping). Continuous work without breaks. Input parameters can be found in Table 6.10.

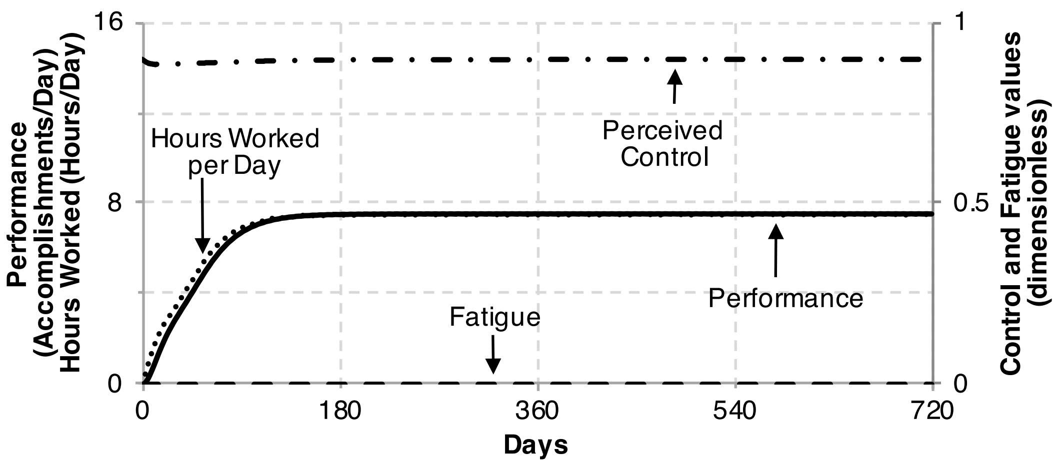

Figure 6.39. Strain work management mode II (sustained proactive coping). Work with regular small breaks (weekends). Input parameters can be found in Table 6.10.

The strain III work management mode is characterised by oscillations between proactive and reactive coping. Continuous work mode without breaks for the strain III work management mode is shown in Figures 6.40. The difference the introduction of regular small breaks makes to the strain III work management mode is shown in Figure 6.41.

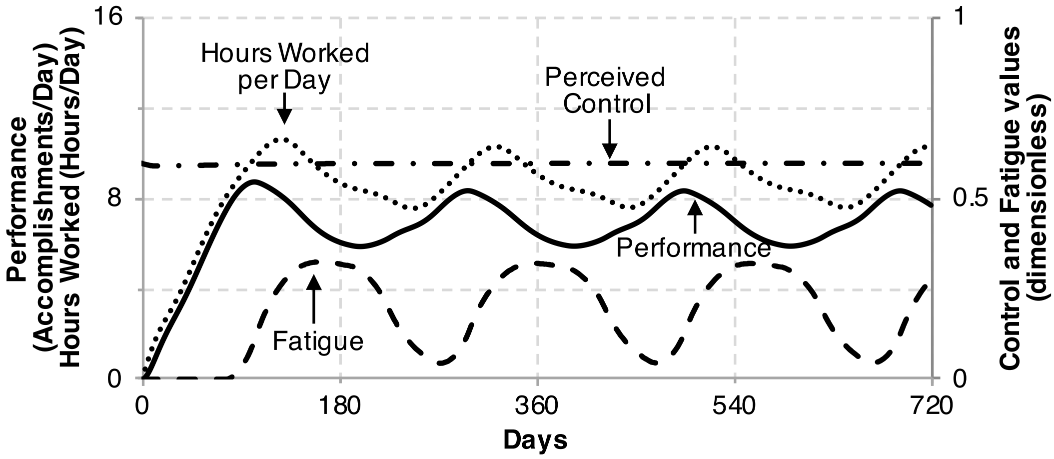

Figure 6.40. Strain work management mode III (oscillations between proactive and reactive coping). Continuous work without breaks. Input parameters can be found in Table 6.10.

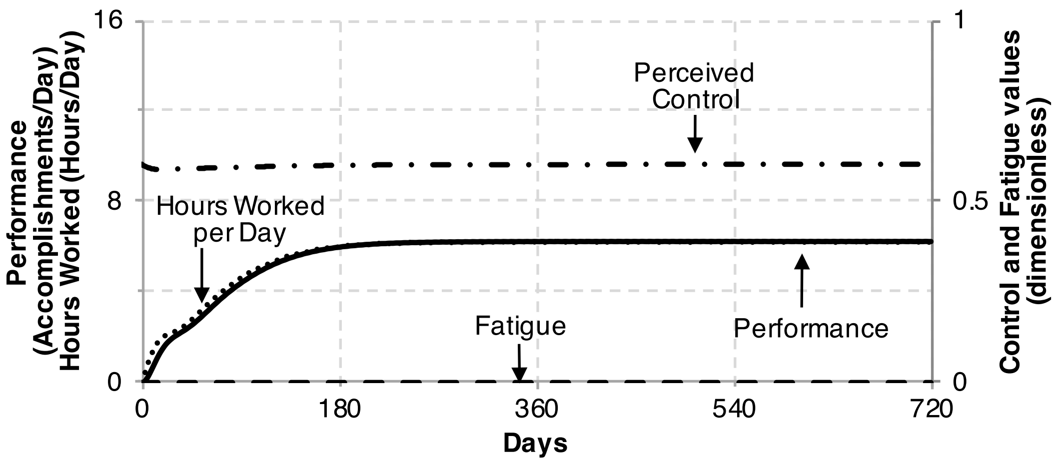

Figure 6.41. Strain work management mode III (oscillations between proactive and reactive coping). Work with regular small breaks (weekends). Input parameters can be found in Table 6.10.

The model exhibited a different pattern of behaviour for the scenarios for the strain I work management mode. The strain I work management mode describes a behaviour, when an effortful strategy leads to a burn out, eventually giving way to the disengaged work management mode (Figure 6.42). The introduction of regular small breaks, equivalent to weekends breaks, ensured that burn out does not happen. However, the feeling of fatigue is never completely reduced, the model stabilises with a constant background level of fatigue. The behaviour in this scenario can be explained as following. The job an individual is engaged in is highly rewarding both intrinsically and extrinsically, and the individual has a very ambitious plan of how much work needs to be accomplished on a daily basis. Thus, the individual puts a lot of effort in the activity. Overly ambitious performance expectations together with imperfect control of the situation result in a steady development of the feeling of fatigue. The work situation is so stressful that the weekend breaks are not enough to completely restore the retrofitters' energy resources. As tiredness builds up, the individual reduces performance expectations, until they are manageable, and at this point the system stabilises. The stabilisation happens with a constant high level of fatigue, as the weekend breaks are not enough to completely neutralise it. The difference the introduction of regular small breaks makes to the strain I work management mode is shown in Figure 6.43.

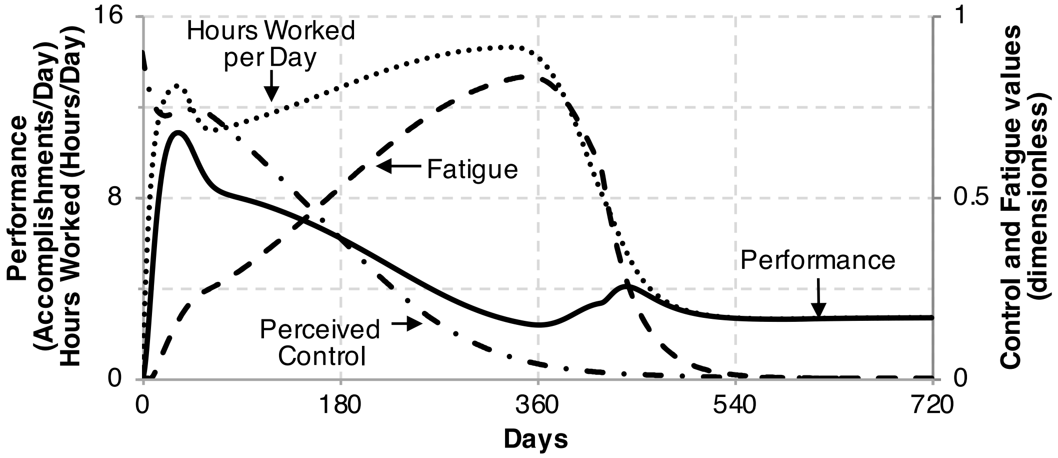

Figure 6.42. Strain work management mode I (proactive to reactive coping). Continuous work without breaks. Input parameters can be found in Table 6.10.

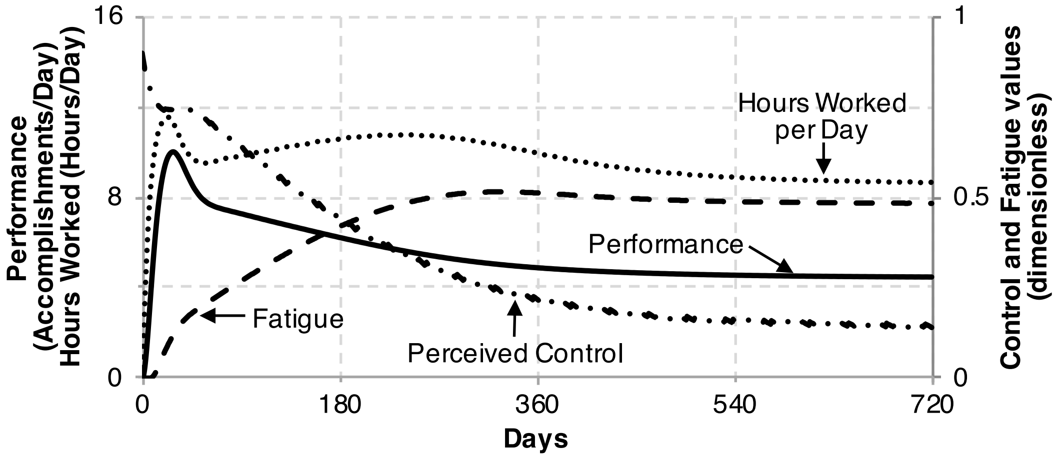

Figure 6.43. Strain work management mode I (proactive to reactive coping). Work with regular small breaks (weekends). Input parameters can be found in Table 6.10.

The introduction of smaller breaks together with bigger breaks, equivalent to weekend breaks and holiday breaks, allowed to reduce the feeling of fatigue to zero (Figure 6.44), a marked difference to the introduction of small breaks only (Figure 6.43). The behaviour in the scenario with both small and big breaks can be interpreted as follows. When an individual starts a highly rewarding new job, he or she puts a lot of effort initially, trying to reach high performance targets. However, the performance targets are high and unrealistic. Thus, the individual quickly develops the feeling of fatigue, which cannot be neutralised with the weekend breaks. Subsequently, the individual starts reducing performance expectations, until they become manageable. Holiday breaks allow the individual to completely switch off and restore, and come refresh to the work after the holidays. Eventually, the individual settles into a new work pace with a stabilisation at a lower than initial level of performance with no feeling of fatigue.

It should be noted that this scenario is not equivalent to the ones observed in Figures 6.39 and 6.41, which showed how the introduction of small weekend breaks lead to neutralisation of fatigue for strain I and strain II work management modes. In all three scenarios (Figures 6.39, 6.41 and 6.44) fatigue is neutralised and performance is comparable. However, in Figures 6.39 and 6.41 the level of *Perceived Control* remains equivalent to the one of *ACTUAL CONTROL*. On the contrary, in Figure 6.44 the level of *Perceived Control* gradually diminishes, even though the level of *ACTUAL CONTROL* does not change. This is due to inability to match unrealistic external goals, which eventually leads to the loss of intrinsic satisfaction from the job.

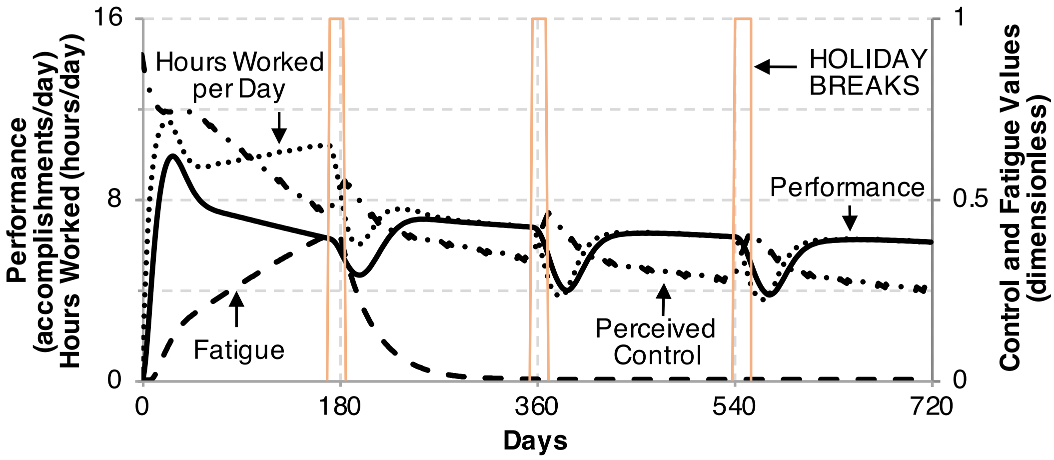

Figure 6.44. Strain work management mode I (proactive to reactive coping). Work with regular small breaks (weekends) as well as occasional big breaks (holidays). Input parameters can be found in Table 6.10.

In summary, scenario exploration revealed that it is possible to neutralise fatigue development for all three strain work management modes. However, the results highlight the trade-off in the heart of the dynamics between effort, performance and fatigue. On the one hand, a constant pace of work, if manageable, ensures a higher productivity, and thus, a quicker pace of goal accomplishment. Nevertheless, a constant pace of work is more likely to be associated with the development of stress and a subsequent feeling of fatigue. On the other hand, a combination of regular small and occasional big breaks ensures that the feeling of fatigue is neutralised. However, it comes at a price of a reduced productivity. The results also highlight the paramount importance for an individual to have a feeling of control over the activity to have intrinsic rewards from it. The next section explains the findings in light of the research question.

6.7. EXPLANATION OF THE FINDINGS FROM SYSTEM DYNAMICS MODEL OF PSYCHOLOGICAL FATIGUE IN LIGHT OF THE RESEARCH QUESTION

The results presented in *Chapter 5* highlight retrofit-associated fatigue as one of the implementation difficulties in the uptake of the low-carbon home retrofit among UK homeowners. Thus, the third objective of the thesis focuses on the development of a generic simulation model of retrofit-associated fatigue and an exploration via the simulation of how fatigue development can be neutralised to ensure an overall positive experience of low-carbon retrofit by the homeowners. Retrofit-related psychological fatigue has much in common with work-related psychological fatigue, and thus, the insights obtained from the study of the latter are applicable to the former. Indeed, the reproduction tests of the empirical cases presented in subsection 6.5d validate the appropriateness to use insights generated from a generic model to the specific cases in the thesis.

The results presented in this chapter lead to the conclusion that it is possible to neutralise fatigue development through the combination of small and big breaks in the pace of work. In the context of low-carbon home retrofit it might imply the adoption of a step-by-step retrofit approach to secure a pleasant retrofit experience by the homeowners, and thus, result in an overall satisfaction with the retrofit results, and a subsequent positive word of mouth regarding retrofit process, which is needed to persuade other to retrofit to low-carbon standards. The results confirm the results obtained via qualitative analysis of the interviews using Rogers' diffusion theory, which are presented in *Chapter 5*.

The use of Hockey's generic theory of psychological fatigue as an additional theoretical lens brings new insights into the phenomenon. The theory, model development and scenario exploration highlight the importance of intrinsic motivation and the feeling of control over the activity to minimise the development of retrofit-related psychological fatigue. In the context of low-carbon home retrofit it might imply the adoption of a do-it-yourself retrofit approach to secure the feeling of control over the retrofit experience by the homeowners. Implications from the findings presented in the chapter, including the trade-off between work pace, performance and fatigue, and the importance of intrinsic motivation and the feeling of control over activity are discussed in *Chapter 7*.

6.8. SUMMARY OF THE FINDINGS FROM THE SYSTEM DYNAMICS MODEL OF PSYCHOLOGICAL FATIGUE

Tiredness related to the retrofit process was revealed as one of the reasons for the formation of a negative impression regarding low-carbon home retrofit in *Chapter 5*. Hockey's theory of psychological fatigue (Hockey, 1997; 2013) was used to develop an endogenous causal explanation of the development of retrofit-associated fatigue, formalise the explanation into a system dynamics model and explore the theory through model simulation.

The system dynamics model of psychological fatigue was explored through a series of simulation runs. The first set of simulation runs reproduced the wide range of work management patterns from workaholism to disengagement and burn-out as proposed in Hockey's theory. Hockey theorises three work management modes in his compensatory control theory of fatigue: engaged, disengaged and strain (Hockey 1997, Hockey 2013). The formalisation of the theory and the simulation of the model revealed two additional, distinct strain work management modes not previously conceptualised by Hockey (Figure 6.22). Strain II work management mode is distinguished by the sustained proactive (active) coping strategy and the stabilisation of fatigue at a constant level. Strain III work management mode is distinguished by the oscillations between a proactive (active) and a reactive (passive) coping strategy.

Further confidence in model behaviour is gained by its consistency with Eisenberger's theory of learned industriousness (1992). The runs indicate that, when an individual performs well in an activity, satisfaction from the job well done leads to an increase in intrinsic rewards. As a result, an individual learns to associate high rewards with the employment of an effortful strategy, and, consequently, puts even more effort in an anticipation of further rewards.

The model behaviour is also consistent with Seligman's theory of learned helplessness (1975). The runs that explored this behavior indicate that, when exposed to uncontrollable events, an individual cannot perform as desired, regardless of the amount of effort put in the activity. The learning outcome is the one of helplessness, where the individual believes that the outcome is unrelated to the action. Even when the situation changes and the level of actual control is sufficient to allow maximum performance, the individual does not even try to change his or her performance as he or she already believes that any effort is futile. In contrast, if the sense of control is not lost, the individual continues to try to change the performance. When the circumstances change and the level of actual control is sufficient to allow maximum performance, the individual makes the most of the circumstances and performs to the maximum.

The model behavior is also consistent with Sonnentag's theory of psychological detachment (2011). The runs that explore this behavior indicate that the most industrious individuals are the most prone to burn out. Such individuals have no time or resources left for psychological detachment and coping with additional stress. If they are exposed to additional levels of stress, such as worries about personal relations, it is likely that they experience burn out, even if they are in full control over the work activities.

The range of results obtained from the first set of runs provide a measure of the generality of the model in terms of the theoretical ground and phenomena it covers. The second set of simulation runs was designed to explore the relevance of the model for the behavioural patterns observed in the case studies. The model was able to reproduce behavioural patterns observed in the cases, when parameterised to each case, which validates the appropriateness to use insights generated from a generic model to the specific cases in the thesis.

Scenario exploration revealed that fatigue development in the cases can be suppressed, if an individual takes regular breaks, either regular small breaks, equivalent to weekend breaks, or a combination of small breaks and large breaks, equivalent to weekend breaks and annual leave respectively. In all scenarios, the reduction in fatigue development came at the price of a reduced overall performance. Thus, the results highlighted an important trade-off between work pace, performance and fatigue. A constant pace of manageable work ensures a higher performance and, thus, a quicker pace of goal accomplishment. Nevertheless, a constant pace of work is more likely to lead to stress and a subsequent feeling of fatigue. In contrast, a combination of regular small and occasional big breaks ensures that the feeling of fatigue is neutralised. However, it comes at a price of a reduced daily productivity and a slower work pace. The results presented in this chapter allow to conclude that, in the context of low-carbon home retrofit, the adoption of a step-by-step retrofit approach might secure a pleasant retrofit experience by the homeowners, that is necessary to persuade other homeowners to retrofit to low-carbon standards. The use of Hockey's generic theory of psychological fatigue as an additional theoretical lens highlights the importance for an individual to have a feeling of control over the activity to be able to have intrinsic rewards from it. In the context of low-carbon home retrofit it might imply the adoption of a do-it-yourself retrofit approach to ensure the feeling of control over the retrofit experience by the homeowners, that is necessary for a pleasant retrofit experience.

Chapter 7

Discussion

This discussion chapter brings together findings from the result *Chapters 5* and *6*, and considers their joint implications. Section 7.1 provides policy suggestions on the promotion of low-carbon home retrofit among UK homeowners, which are based on: (i) understanding of low-carbon retrofit as a contextually embedded process, developed in *Chapter 5*; (ii) understanding of the dynamic interactions between retrofit work pace, performance, and satisfaction from the retrofit journey, explored by simulation modelling and presented in *Chapter 6*. Section 7.2 discusses the contribution of the thesis to the literature of home-meanings, innovation diffusion, and psychological fatigue. Section 7.3 evaluates critically the methodological strategy followed in the research. First, the socio-technical systems approach is discussed, followed by the discussion of the process research design choice to understand retrofit decisions. The section then discusses the methodological implications of the approach used to develop a generic simulation model that can be applied to specific cases. Section 7.4 acknowledges the limitations, shortcomings and uncertainties of the study and outlines the room for potential improvements in future research. The chapter concludes with a summary in section 7.5.

CHAPTER CONTENTS

7.1. POLICY SUGGESTIONS TO ENCOURAGE LOW-CARBON HOME RETROFIT

This section discusses how the following three research objectives of the thesis have been met:

Objective 1. Understand retrofit decisions as processes, shaped in the context of home-meanings.

Objective 2. Capture the dynamics of such individual context-rich retrofit-decision processes that result in low-carbon operational energy use, and explore the implications for the transition to a low-carbon housing stock.

Objective 3. Identify patterns and regularities in retrofit implementation difficulties, captured when addressing objective 2. Develop a simulation model based on these and explore ways to minimise them via different simulation scenarios. Consider the implications for the transition to a low-carbon housing stock.

The following main insights were generated when meeting the objectives of the thesis (Figure 7.1):

(i) The context of a low-carbon home is associated with: enhanced feelings of comfort, safety, security and control, as well as an identity of a broader social responsibility.

(ii) Low-carbon home retrofit as an innovation should be understood as comprised of three imbedded aspects: a product, a design option and a socio-technical system.

(iii) Homeowners collect information that is relevant to these aspects during the retrofit stages, through different communication channels. Such channels cannot be substituted by one another.

(iv) The experience of retrofitting a home to low-carbon standards can affect the homeowner's satisfaction with results and the associated positive word of mouth that is needed to persuade others to retrofit their homes. Implementation difficulties can be reduced via the choice of appropriate work pace. Such difficulties are also subject to influence by the dynamics between homeowner intrinsic motivation and control over the retrofit process.

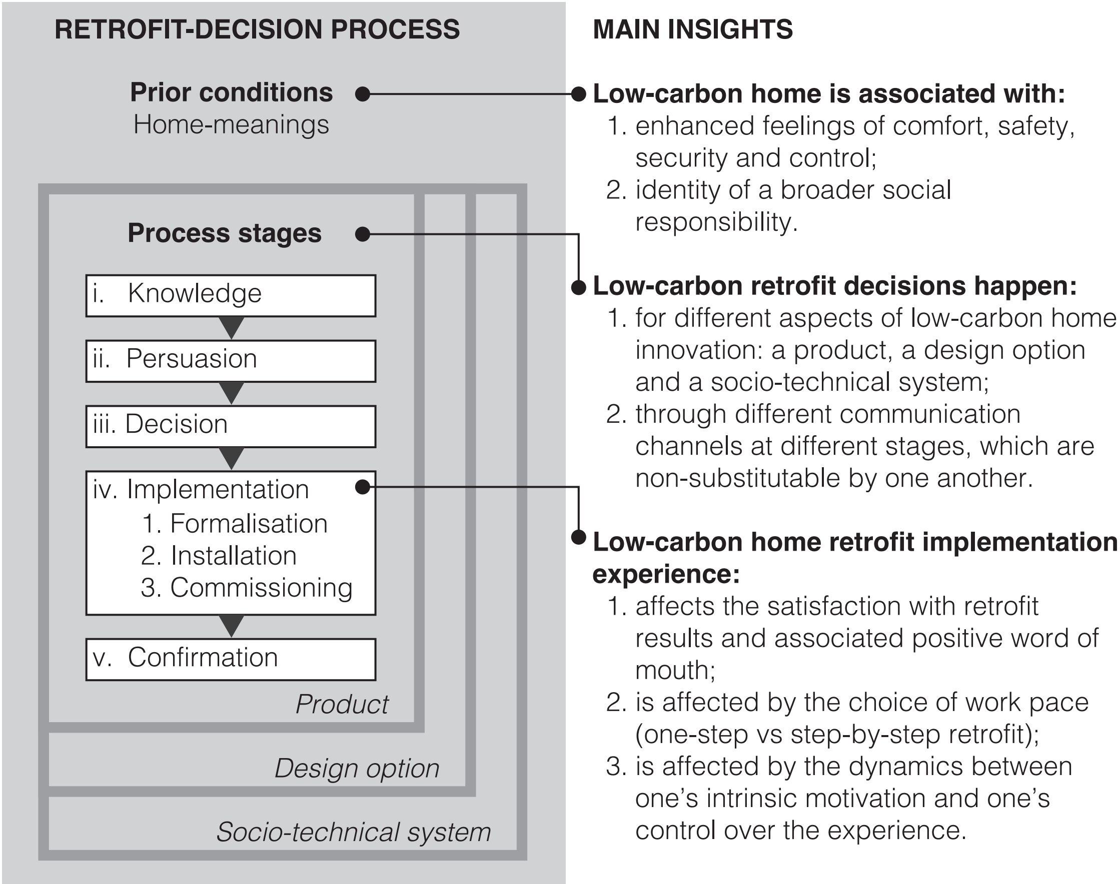

Figure 7.1. Main insights from the analysis mapped onto the conceptualisation of home retrofit

In order to reduce the carbon emissions associated with operational energy use in dwellings, a carefully managed combination of governmental interventions and market support is required (Mallaburn and Eyre, 2014). However, the reduction of operational energy use in buildings is not easy, nor can it be achieved at low cost (Oreszczyn and Lowe, 2010: p. 110). The market will simply not deliver without governmental support, and this partially explains the failure of the Green Deal, a policy that took deliberately a market-led view (Mallaburn and Eyre, 2014). The analysis, carried out to meet the objectives of the thesis, opens the way for recommendations on energy policy. Some of these recommendations have been already implemented in UK policy, and in such cases the thesis findings serve as an affirmation of the policy direction. Nevertheless, some novel recommendations were also afforded by the thesis findings. The discussion on how research objectives have been met, as well as policy recommendations are presented in the rest of the section.

7.1a. Home as a context to promote low-carbon retrofit

Policies that promote low-carbon retrofit and energy conservation are shaped by governmental views on energy that vary with historical period (Lutzenhiser, 2002). Energy efficiency policy in the UK, as in many parts of the world, was focused on energy dependence and national security after the energy shortages in the 1970s (Mallaburn and Eyre, 2014). After the crisis, policies focused on the financial self-interest of consumers, such as energy bill reduction. During the 1990s the focus shifted towards an environmental movement and appeals to reduce greenhouse emissions. Recently, low-carbon construction policies shifted towards occupant health and well-being (International Energy Agency, 2014). Governmental views and intentions shape the understanding of homeowner objectives for low-carbon retrofit, such as objectives to reduce energy use and carbon emissions reduction, and improvement of thermal comfort and indoor air quality.

However, the roots for homeowners' intentions towards their homes differ from government intentions towards energy preservation. The low-carbon retrofit goals of homeowners should be understood under the broader scope of home-related dimensions, rather than the scope of energy preservation intentions. Home is a place of a great significance and meaning for individuals and current policies do not account for this in promoting low-carbon retrofit. Previous research has suggested that such dimensions can be captured by the meanings people attach to their homes (Wilson et al., 2015).

The first objective of the thesis is to understand how home-meanings can be used to promote low-carbon home retrofit. To address this objective, this thesis developed a framework of meanings people attach to their homes in *Chapter 2* and used it to evaluate homeowner retrofit goals, intentions, associations and post-retrofit living experience related to low-carbon dwellings in *Chapter 5*. The results of the analysis indicate that low-carbon dwellings are associated with enhanced feelings of comfort, safety, security and control, as well as with an extra-domestic identity of broader social responsibility. Given the small sample size of the study, it does not attempt to provide a comprehensive overview of all possible insights that can be obtained using a framework of home meanings. Further research is needed to identify further insights, convert them into messages to promote low-carbon retrofit, and understand how these messages can be distributed for greater impact. The rest of the subsection uses the insights generated in this thesis to make policy suggestions on the promotion of low-carbon retrofit among homeowners.

Enhance feelings of comfort, safety, security and control through pictures of everyday activities

The first suggestion concerns the use of enhanced feelings of comfort, safety, security and control associated with a low-carbon dwelling to promote low-carbon retrofit. Domestic practices, routinised activities and formative experiences were found to enhance the feelings of both actual and perceived control (Taylor and Brower, 1985, as stated in Després, 1991: p. 99), safety and security (Somerville, 1997) and comfort (Manzo, 2003). It is said that some dimensions of being-at-home can only be experienced through taken-for-granted routines (Westman, 1995). It follows that messages of enhanced feelings of comfort, safety, security and control, that are afforded by low-carbon settings, are better communicated via an image of everyday activities and how a low-carbon dwelling provides a better setting for them.

The processes that establish psychological and social attributes and feelings, such as the feelings of comfort and control, can be both conscious and unconscious (Manzo, 2003). It follows that visual images together with textual messages can be more effective, than textual messages only, in the formation of a conscious and unconscious perception of a low-carbon home as a setting that affords enhanced feelings of comfort, safety, security and control. For instance, a visual image could include a picture of children playing in front of a big triple-glazed window, while there is heavy rain and wind outside. Yet, the weather does not distract the children from their game, as there is no sense of cold air flow in the proximity of the window. The supporting textual messages could include a scientific explanation of the relations between the room temperature, air flows and the surface temperature, and their combined effect on the perceived thermal comfort and, consequently, a comfort of carrying everyday domestic activities.

Such messages can be combined with other categorisations, already present in the literature, to target different population segments for a successful promotion campaign. For instance, the categorises of household lifecycle stages in Munro and Leather (2000) can be used to create visual messages of comfort, safety, security and control for: (i) a young household, (ii) a household with young children, (iii) a household with teenage children and (iv) an empty-nester household. The categories are linked to domestic renovation activity, thus, each category represents a potential target for a low-carbon home retrofit campaign. However, undoubtedly, people at different lifestyle stages understand differently the notions of comfort, safety, security and control. Thus, different visual images might appeal to them.

Considerations for occupants' comfort, health and safety have been acknowledged and implemented in current UK policies that focus on low-carbon domestic retrofit (British Standards Institution, 2019a). The findings from this thesis contribute to the current discourse by suggesting that for greater success the messages regarding comfort, health and safety should be communicated via a combination of visual images and textual messages about everyday activities, and how a low-carbon dwelling provides a better setting for such activities, compared to a non-low-carbon one.

Shape the identity of a broader social responsibility

The second suggestion concerns the use of an identity of a broader social responsibility to promote low-carbon retrofit. The thematic analysis of interviewees' associative experiments revealed that a low-carbon home is associated with an extra-domestic identity of a broader social responsibility. The literature on home-meanings highlights several processes that contribute to the establishment of one's identity with the re-occurring character of producing and re-producing one's identity that solidifies it (Blunt and Dowling, 2006). The establishment of one's identity has an inter-personal component: one's identity is shaped when it is recognised and, hopefully, accepted (Molony, 2010; Després, 1991).

It follows that the encouragement of low-carbon living is more readily achieved, when the reproduction of a low-carbon household's identity is visible and, thus, constantly acknowledged by others. This can occur only on a group level where peer-acknowledged good behaviour can lead to individual behaviour change (Lewin, 1948). The peer group can be on a community level. An example of a message, which encourages low-carbon living via the establishment of an extra domestic identity of a broader social responsibility, can include the promotion of a solar photovoltaic installation that is linked to a peer-to-peer trading local system, rather than to the national grid. In this setting, an identity of a broader social responsibility, which is associated with a low-carbon home, is visible to the peers in the grid, and is constantly re-produced through electricity trading. The peers, who are living a low-carbon life already, are more likely to continue doing so, while the peers, who were not, are more likely to follow the example of the group. Such identity can be linked to a national identity and what it means to be a British citizen and be proud of being so.

The recognition of an identity of a broader social responsibility does not need to occur on a community level, it can occur among the household members themselves. As some interviewees have noticed, the maintenance of a low-carbon house, especially building systems, can be a noticeable part of household chores. Nevertheless, as the interviewees noted, engaging in such chores, e.g. the regular cleaning of a biomass boiler, together with their children might create a good formative experience for the children, during which they learn to take care of a house, environment and the Earth. The re-occurring nature of everyday life activities, such as household chores related to low-carbon living, can also create a bonding experience between generations, as some interviewees noted.

A fruitful direction for generating more messages that promote a recognition of an extra-domestic identity of a broader social responsibility by others, is to develop such messages specific to different population groups. Categories of pro-environmental behavior by DEFRA (GB. DEFRA, 2008) might be a good starting point to consider, which elements of an identity of a broader social responsibility might appeal to different groups. Further research is needed to bring more insights to this topic.

UK policies that focus on low-carbon domestic retrofit do not consider the use of the identity of a broader social responsibility to promote low-carbon living (British Standards Institution, 2019a; British Standards Institution, 2019b). The findings from this thesis suggest that for greater success, the circumstances in which such an identity is recognised by others should be delineated. For example, identity formation can be encouraged on a communal level through peer-to-peer electricity trading, or on a household level between household members themselves through the promotion of low-carbon living as a good formative experience for one's children.

7.1b. Different communication channels at different stages for different aspects of low-carbon home innovation

The second objective of the thesis is to capture the dynamics of individual retrofit-decision journeys that result in low-carbon operational energy use, and explore the implications for the transition to a low-carbon housing stock. To address this objective, the thesis conceptualised operational energy use as a result of an interaction of a socio-technical system of a low-carbon dwelling in *Chapter 5*. This conceptualisation, together with Rogers' innovation diffusion theory, was subsequently used to develop insights in the process of home retrofit that result in low-carbon operational energy use. The results of the analysis presented in *Chapter 5* indicate that the low-carbon home as an innovation should be understood as comprised of three imbedded aspects: individual products, design options and as a socio-technical system (Figure 7.2). The review of the literature in *Chapter 2* and results presented in *Chapter 5* highlighted a need to create an overarching socio-technical vision for a given retrofit project. A creation of such overarching vision requires technical competence, which homeowners do not always have. Some researchers claim that it is "clearly a role of government" to support unbiased information provision and advice to people on which technologies to choose and why (Mallaburn and Eyre, 2014: p. 36).

The case study analysis also revealed that homeowners gather information for different innovation aspects at different retrofit stages through different communication channels (Figure 7.2). Such channels cannot be substituted by one another. Based on this insight, it is recommended to use different information channels at different retrofit stages to deliver information to homeowners. In particular, it is suggested to encourage information exchange among homeowners through non-professional networks. The interview data analysis suggests that homeowners in the case studies use two kinds of interpersonal networks to acquire information about retrofit options: construction experts, and other homeowners who already did similar works. The two kinds of information are not substitutes for one another but they are complementary. The findings are in line with the research that repeatedly identifies the positive impact of 'open home' on homeowner retrofit decisions (Berry et al., 2014; Gupta et al., 2014; McMichael and Shipworth, 2013).

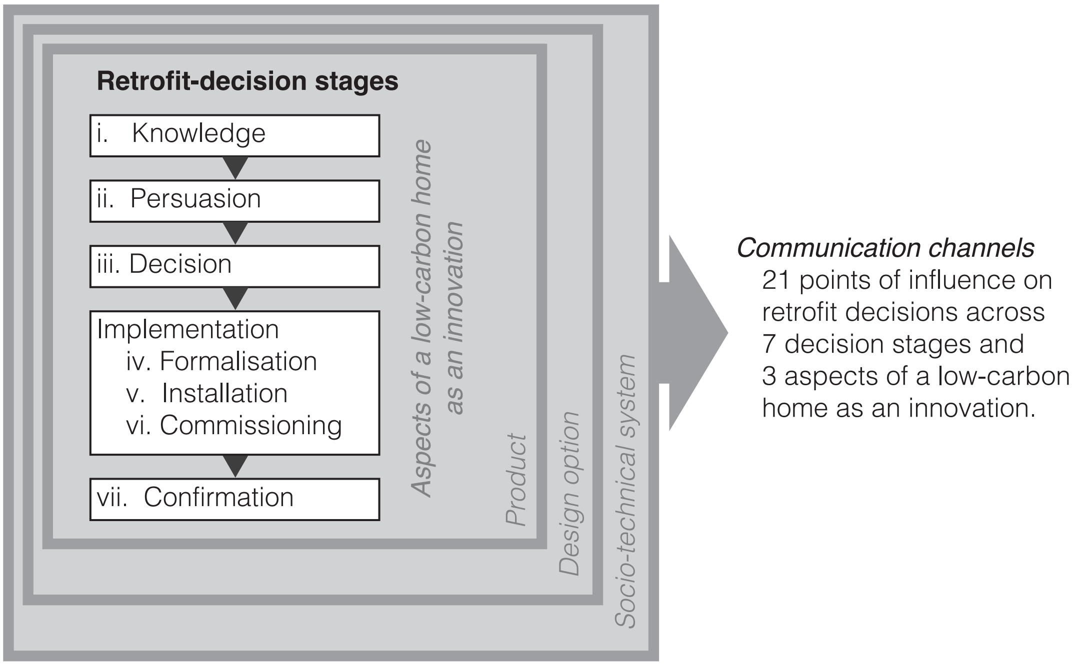

Figure 7.2. A multi-layer stage model of the home retrofit-decision process

Current UK policies that focus on low-carbon domestic retrofit conceptualise a dwelling as a socio-technical system, that is comprised of the building envelope, the building services (such as ventilation, heating, hot water, lights and appliances), renewable energy systems and the occupants (British Standards Institution, 2019a). The PAS 2035 document (ibid.) removes the burden to create an overarching socio-technical vision for low-carbon retrofit from the homeowners, and puts it on the retrofit team. The team is comprised of Retrofit Advisors, Retrofit Assessors, Retrofit Coordinators, Retrofit Designers and Retrofit Evaluators, who all are required to have working knowledge of building physics and acquire appropriate qualifications (ibid.). The document requires to propose a medium-term (20–30 years) improvement plan to improve energy efficiency and reduce carbon emissions to all retrofit projects, even if only small improvements are carried out in the short term (ibid.).

Current UK policies that focus on low-carbon domestic retrofit also understand the need for information provision at different stages of the retrofit process through different communication channels (British Standards Institution, 2019a). The PAS 2035 document (ibid.) outlines the stages of the domestic retrofit process, the types of different information required at different retrofit stages (e.g. improvement options for the dwellings, user friendly information on the use and maintenance of the dwellings, post-retrofit evaluation and monitoring data), as well as points along the retrofit process at which this information should be provided to the household (inception of the project, the completion of the improvement option evaluation, the completion of the retrofit design, shortly after handover of the completed installation). The document specifies that different ways should be considered to deliver such advice, including web forums, open home events and community meetings.

As such, policy advice based on results obtained when meeting the second thesis objective can be used to affirm the current policy direction.

7.1c. The importance of the implementation experience and suggestions for the reduction of associated difficulties

The third objective of the thesis is to identify ways to minimise implementation difficulties associated with low-carbon retrofit, and consider implication for the transition to a low-carbon housing stock. To address this objective, the thesis evaluated the impact of implementation experience on the diffusion of low-carbon home innovation. The thesis findings suggest that the effect of the experience is twofold. First, the findings suggest that a positive retrofit experience is paramount to achieve post-retrofit reduction in energy use. This insight is in line with finding by Owen and Mitchell (2015), who report that the retrofit experience influenced the householders' beliefs of the effectiveness of the installed technology in the studied sample. In one of the cases, a particularly bad experience of an air source heat pump installation led the householder to believe that there was no reduction in energy use and that the equipment was not working properly. In another case, the householder found the installation process well managed, and as a result had "affectionate feelings" towards the technology, and even was willing to overlook some operational problems (ibid.: p. 931).

Second, the findings in this thesis suggest that both the retrofit process and its final outcomes are important to generate a positive word of mouth for low-carbon home retrofit. It can help to persuade others to retrofit their homes, which in turn has the potential to accelerate the overall transition to a low-carbon housing stock. This insight is in line with findings by Mlecnik (2010, 2013), who observed that the owners in some of the studied cases would not recommend the experience to others specifically because the projects were too demanding. Such insights are also consistent with other innovation diffusion studies, which highlight the importance of innovation attributes on adoption of energy conservation interventions (Völlink et al., 2002). Darley and Beniger (1981) concluded on the basis of literature review that the skills and effort involved in the installation of the innovation are important attributes needed to describe diffusion of energy conservation technologies.

Current governmental policies that aim to encourage low-carbon retrofit among homeowners, recognise the importance of good quality construction on the formation of the positive impression of low-carbon retrofit in the population. However, there is no recognition of the importance of a pleasant retrofit experience on the sustained reduction in post-retrofit energy use, as well as on the positive impression of the retrofit outcomes. The findings from this thesis suggest that for greater success, the policies also need to support homeowners in their retrofit journeys to ensure that the associated experience is pleasant. The rest of the subjection makes policy suggestions on how implementation difficulties, associated with-low-carbon home retrofit, can be minimised, to ensure a positive retrofit experience for the household.

<u>Outline routes for a step-by-step low-carbon home retrofit approach</u>

The thesis findings suggest that one way to ease the implementation burden associated with low-carbon construction is to do the works step-by-step over a period of time. Support for incremental retrofit is also found in the literature. First, most retrofit works tend to be gradual or incremental with a timespan of years or even decades (EST, 2011, Fawcett and Killip, 2014, Sunikka-Blank and Galvin, 2016; Vlasova and Gram-Hanssen, 2014). Second, an incremental approach reflects the evolving nature of household needs and allows time for the household to get ready for larger decisions (Fyhn and Baron, 2017). Third, a step-by-step retrofit approach might assist a more incremental behavioural change, necessary to assist fundamentally new and lower resource consumption (Vlasova and Gram-Hanssen, 2014). Killip (2011) argues that the market potential for the incremental retrofit can be up to 45% of the entire domestic repair market.

However, a step-by-step retrofit approach is not without drawbacks. This thesis identified another interesting dilemma between an in-depth retrofit approach and a step-by-step retrofit approach, with potentially significant impact on the process of the overall transition towards a low-carbon housing stock. As discussed in *Chapter 2*, one of the main methods to speed up the innovation adoption rate in the system is to shorten the decision-making process of individual agents (Rogers, 2003). In the context of home retrofit this logic implies that the sooner individual homeowners refurbish their homes to low-carbon standards, the sooner they will form a critical mass of people to spread information about such retrofit to others, and the sooner the rest of the population will follow suit.

Measures and technologies, necessary to achieve low-carbon settings in one’s home, can be adopted simultaneously as part of a single, deep retrofit project, or can be adopted incrementally over a period of time. A single step, in-depth retrofit takes a shorter period of time for individual houses to becomes low-carbon ones, at which stage individual homeowners can communicate to others their experience of living in such dwellings. As a result, a critical mass of people living in such houses is formed quicker, which can lead to a faster overall transition to a low-carbon housing stock. However, the thesis findings as well as current literature suggest that a one-step deep retrofit is likely to result in a negative retrofit experience and a subsequent negative word of mouth regarding such retrofit (Table 7.1). Such negative word of mouth could potentially increase the length of the persuasion stage for potential adopters of discourage them completely.

A step-by-step retrofit approach might ease the implementation burden associated with low-carbon construction, which can result in a more positive word of mouth regarding retrofit process. This result has the potential to accelerate the overall transition towards a low-carbon housing stock. However, a step-by-step retrofit approach might imply that individual homeowners take a lengthy period of time to retrofit their homes to low-carbon standards, up to three decades as in case H, which slows the formation of a critical mass of people, who already live in low-carbon houses, which can ultimately slow down the diffusion of the idea of low-carbon living in the population.

Table 7.1. Effect of the retrofit strategy on the rate of adoption

Effect on the rate of adoption	**Retrofit strategy**	
	In one go	**Step-by-step**
Shortening	A possibly shorter period of transition of individual houses to low-carbon standards implies a quicker formation of a critical mass of people living in such houses and talking about their experience to others, which can, ultimately, accelerate the transition to a low-carbon housing stock.	A step-by-step retrofit is likely to result in a positive retrofit experience, thus, contributing to the formation of a positive word of mouth, needed to persuade other to retrofit their homes.
Lengthening	Retrofit in one go is likely to result in a formation of a negative experience of the retrofit process, which can potentially increase the length of a persuasion stage for potential adopters or discourage them altogether.	A step-by-step retrofit might imply that individual homeowners take a lengthy period of time to retrofit their homes to low-carbon standards, which slows the formation of a critical mass of people, who live in such houses, which can slow the diffusion of the idea of low-carbon living in the population.

Current UK policies that focus on low-carbon domestic retrofit emphasise the need to support both one-step deep retrofit and step-by-step incremental retrofit approaches (British Standards Institution, 2019a). As mentioned earlier, the PAS 2035 document requires an outline of a medium-term pan (20–30 years) to improve energy efficiency and reduce carbon emissions of a dwelling, when retrofit works are carried out (ibid.). This strategy helps to identify appropriate order of implementation and helps to avoid suboptimal solutions and lock-in for future retrofit opportunities.

However, it is not clear how many steps are necesary to have an optimal impact on shortening the overall transition period to a low-carbon housing stock, and how big such steps should be to provide the least stressful retrofit experience for the homeowners. The problem is complex and future research, potentially including computer simulation, is recommended to investigate, whether there is an optimal size and number of steps, as well as an optimum order (technically and economically) in which to install retrofit measures.

Ensure control over the retrofit experience

Fatigue related to the retrofit process has been revealed as one of the reasons for the formation of a negative impression regarding low-carbon home retrofit. Hockey's theory of psychological fatigue has been used to develop an endogenous causal explanation of the development of retrofit-associated fatigue, formalise the explanation into a system dynamics model and explore the model via simulation (Hockey, 1997; 2013). Scenario exploration via simulation revealed the trade-off between the dynamics of effort, performance and fatigue. A constant pace of work during a one-step retrofit ensures a higher productivity, but is more likely to lead to stress, a subsequent feeling of fatigue, and its negative association with the retrofit experience for homeowners. In contrast, a combination of regular small and occasional big breaks during a step-by-step retrofit ensures that the feeling of fatigue is neutralised, and homeowners have a more positive experience. However, it will take longer to retrofit to low-carbon standards. Thus, the interpretation of the results of the simulation model confirms the results obtained via qualitative analysis of the interviews using Rogers' innovation diffusion theory.

Scenario exploration via simulation also revealed the dynamics between resources, control and motivation, necessary to establish healthy work patterns (Figure 7.3). Intrinsic rewards are paramount for an individual to engage in a difficult self-initiated project. It is also necessary to have adequate coping resources and control over the situation to ensure a pleasant experience during project implementation.

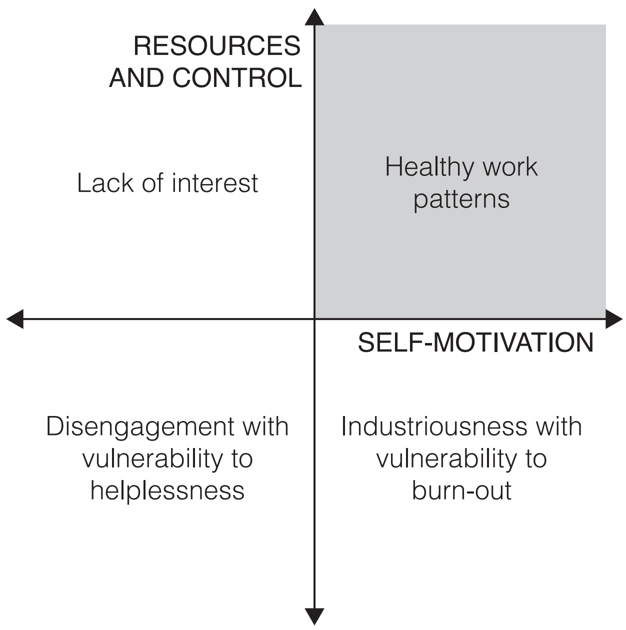

Figure 7.3. Dynamics between resources control and self-motivation in different work patterns

The simulation results can be interpreted as follows for policy recommendation on low-carbon home retrofit. First, a homeowner needs to be truly engaged in the retrofit, which further highlights the need to understand the diversity of homeowner goals and motivations. In this thesis, home-meanings are used to bring insights in such diversity. Related policy implications are discussed in subsection 7.1a.

Second, a homeowner needs to be in control of the situation to have a pleasant retrofit experience. The thesis findings highlighted the importance of a good relationship and a high level of trust between the builders and the owners for the owners to feel in control of the situation and have a good retrofit experience. This finding is in line with the literature project management in general (Laan et al., 2011), and retrofit projects in particular (Fawcett and Killip, 2014). The thesis findings also revealed that the owners felt more in control, when they carried the projects themselves (DIY retrofit) as compared to outsourcing it to the tradespeople.

Current policy direction does not favour DIY retrofit for safety reasons, as well as to ensure construction quality (British Standards Institution, 2019a). The UK Government commissioned Each Home Counts review, which recommends the establishment of a quality mark for domestic retrofit as a way to improve trust of homeowners in the domestic retrofit industry (Bonfield, 2016). The TrustMark quality scheme was subsequently established as this quality mark (British Standards Institution, 2019a). Further research is necessary to understand what else, except of trust, makes a homeowner feel more or less in control of the retrofit activity, and whether the TrustMark scheme provides enough support to eliminate trust issues among homeowners.

This section summarised insights generated from data analysis in this thesis and discussed policy suggestions in light of the obtained results. Some of these results are used to affirm current policy direction, including: (i) the use of enhanced feelings of comfort, safety, security and control to promote low-carbon retrofit; (ii) provide different types of information at different retrofit stages for different aspects of a socio-technical system of a low-carbon dwelling; (iii) Support a step-by-step retrofit approach. Other results provided a way for novel policy suggestions, including: (i) promote a recognition of a broader social responsibility associated with low-carbon lifestyle; (ii) support homeowners in their retrofit journeys to ensure that the retrofit experience is pleasant. A step-by-step retrofit approach as well as a sense of control over the retrofit experience were found to result in positive retrofit experience. The next section evaluates theoretical contributions of the current thesis.

7.2. THEORETICAL IMPLICATIONS

7.2a. The contribution to the literature on home-meanings

The notion of home is a multi-dimensional construct (Blunt and Dowling, 2006). Different approaches for understanding the home come from different disciplines, including psychology, sociology, geography and architecture to name a few. Each approach emphasises certain home-meanings and downplays or neglects others (Somerville, 1997). In the absence of an integrative theoretical model that explores the processes by which home comes to have meaning for an individual, this thesis develops a conceptual framework to guide data collection, interpretation and analysis. The data analysis performed with the conceptual framework of home-meanings provided useful insights, but the framework does not allow an understanding of how motivational influences, associated with low-carbon retrofit, develop over time.

A theoretical explanation is necessary for this, and several calls have been made to create an overarching theoretical model of home-meanings (Somerville, 1997; Després, 1991). Future research can take several routes towards this. The conceptual framework of home-meanings developed in *Chapter 2* represents a rich synthesis of current empirical and theoretical literature, which can serve as a basis for an articulation of a theory. Future research can demonstrate the applicability of the framework beyond the focus of the current thesis, and its use to guide a comprehensive inquiry about a range of home-related issues. Future research can start with the conceptual framework as a basis to guide the development of an integrative theoretical explanation of the processes by which home comes to have meaning for an individual (Imenda, 2014).

7.2b. The contribution to the innovation diffusion literature

Innovation diffusion is one of the most established theories of social change (Rogers, 2004). Despite the widespread use of the theory, almost two thirds of all the empirical generalisations reported in diffusion publications deal with the innovativeness of the members of the social system, such as innovators, early adopters, early majority, late majority and laggards (Rogers, 2003: p. 94). Less than 7% of diffusion publications concentrate explicitly on innovation-decision process, with most focusing on the type of different communication channels used at different decision stages (ibid.).

The current thesis contributed to the latter literature stream by emphasising the following topics in the innovation diffusion discourse: (i) disaggregation on a unit of analysis into three levels, when studying low-carbon home innovations as a particular product, a design option and a socio-technical system; (ii) the importance of different interpersonal communication channels in the process of individual attitude formation towards different innovation options; (iii) the importance of a good implementation experience on the successful use of an innovation, the formation of a positive attitude to the innovation itself, and a subsequent positive word of mouth for the innovation; (iv) the difference in the nature of innovation-decision processes of individual agents (adoption of all necessary technologies in one go vs over time) and the associated impact on the overall innovation diffusion in the population. Future research in other areas within the innovation diffusion discourse is recommended to build confidence in the generalisability of the findings.

7.2c. The contribution to the literature on psychological fatigue

Work-related psychological fatigue is a wide-spread problem that affects individuals on a regular basis. Hockey's theory of psychological fatigue (Hockey 1997, 2013) has been used as the basis to explore the development of work-associated fatigue with a system dynamics simulation model. The development of psychological fatigue has been explored through a series of simulation runs. The first set of simulation runs reproduced the wide range of work management patterns from workaholism to a disengagement and burn-out as proposed in Hockey's theory. Hockey theorised three work management modes in his motivation control theory of fatigue: *engaged*, *disengaged* and *strain*. The formalisation of the theory and the simulation of the model confirmed the existence of the described work management modes, which strengthens the internal validity of the theory (Davis et al., 2007). The simulation also revealed two additional, distinct stain work management modes not previously conceptualised by Hockey. *Strain II* work management mode is distinguished by a sustained proactive coping strategy and a stabilisation of fatigue at a constant level. *Strain III* work management mode is distinguished by the oscillations between a proactive and a reactive coping strategy. This insight might be interesting for the researchers in the field of psychology and trigger new ways of thinking about the phenomenon in the field. Future empirical research to confirm findings obtained through model simulation is recommended.

This section discussed theoretical contributions of the thesis. The next section evaluates its methodological contributions.

7.3. METHODOLOGICAL IMPLICATIONS

7.3a. Benefits of a systems approach to understand low-carbon energy use

A focus solely on aspects of retrofit decisions that apply to low-carbon retrofit specifically, poses a risk that important systemic aspects of the complex development of retrofit-decision journeys of individual homeowners, can be overlooked. This thesis intentionally did not distinguish low-carbon retrofit journeys from the general retrofit processes during data collection. Consequently, some thesis results apply not only to low-carbon retrofit specifically, but to retrofit in general, including: (i) the insight that homeowners collect different types of information during different retrofit stages for different aspects of retrofit; and (ii) an understanding of the importance of a pleasant retrofit experience on the homeowner satisfaction with retrofit results. The analysis process revealed how these insights about retrofit generally apply specifically to low-carbon retrofit. For instance, it was shown that a pleasant retrofit experience subsequently leads to a sustained reduction in post-retrofit energy use, and stressed the importance of the formation of such experience for the overall transition to a low-carbon housing stock. Thus, the systems approach to the problem of low-carbon home retrofit revealed some important aspects, which would have been overlooked, if the research focused solely on aspects related to low-carbon retrofit during data collection.

This research was able to capture the temporal sequences in retrofit decisions, by grounding data collection and analysis in *process research* (Langley, 1999), and drawing on relevant and related theories and concepts such as innovation diffusion theory and the idea of stages in retrofit-decision journeys. As a result, it was possible to suggest how to facilitate the transition between the stages of the retrofit-decision journeys. The current thesis revealed the combined importance of the first and second stages of the innovation-decision process (i. *Knowledge* and ii. *Persuasion*). Due to the significant length of these stages, a policy that aims to shorten them, might have a great impact on shortening the overall innovation-diffusion process of an individual, which, consequently, can result in a faster overall transition to a low-carbon housing stock. The identification of these areas would not have been possible with a variance type of research, as it would have focused on the investigation of various low-carbon retrofit drivers and barriers and, thus, overlooked the interaction of various influences between different decision stages (Langley, 1999). Thus, a process research approach enabled to see new areas that current policies should focus their efforts upon, for greater impact.

7.3b. A three-step approach to develop a generic simulation model that can be applied to specific cases

Any research design demands trade-offs among generality and accuracy, as the two tend to conflict with each other (Langley, 1999). The thesis illustrates a three-step approach to build a simulation model that is both generic and can be grounded to cases. First, process research guided a multiple-case study design with qualitative data collection through interviews and analysis via thematic coding. It revealed the behavioural pattern of interest from the case studies: development or non-development of psychological fatigue. Second, Hockey's theory of psychological fatigue was identified as a suitable lens to develop further insights into the phenomenon. The theory was operationalised into a system dynamics model, tested and validated based on a thick textual description of the theory provided by Hockey. Third, further data was collected in a second round of interviews via questionnaires and mapping with the same interviewees the behavioural patterns of interest for some constructs in the model. The model was parametrised for each case and a second set of simulation runs explored the possibility to reproduce the fatigue patterns inferred from the homeowners' interviews. Overall, the model output is consistent with the empirical patterns the interviewees provided.

The range of results obtained from the first set of runs, which explored the replicability of theoretical results by the model, provide a measure of the generality of the model in terms of the theoretical ground and phenomena it covers. The second set of simulation runs, which explored the replicability of empirically observed fatigue development patterns, provides a measure of accountability for various behavioural patterns observed in the case studies. In summary, the developed system dynamics model is (i) case-specific, as the initial behavioural patterns were suggested from the cases themselves and the model was able to re-produce behavioural patterns observed in the cases, when parameterise to each case; and (ii) generic, as it is based on Hockey's theory of psychological fatigue, which is generic in terms of the theoretical ground and phenomena it covers.

This section discussed methodological contributions of the thesis. The next section evaluates its limitations.

7.4. LIMITATIONS OF THE STUDY

All methodologies have their limits (Feyerabend, 2010). The present study has a number of contextual and methodological limitations, which highlight the need for further research on the adoption process of low-carbon home retrofit in the UK. The rest of the section is used to outline the study limitations for each aspect of the study.

7.4a. Limitations associated with the scope of the study

The scope of the study is necessarily limited. First, it focuses exclusively on low-carbon retrofit as a strategy to reduce operational energy use. Nevertheless, energy use is associated with both the energy efficiency of building components and the occupants' behavioural patterns. Current literature highlights that, even when low-carbon home retrofit takes place, it often does not assist new and lower resource consumption (Vlasova and Gram-Hanssen, 2014). The data analysis showed that a successful retrofit experience assists the formation of habits for lower resource consumption. However, no strong links were found between homeowner general believes and their post-retrofit change in energy use. Further research is recommended to bring insights into the phenomenon, possibly with a different theoretical framework, such as social practice theory, and/ or different sample strategy, such as conducting interviews with people, who did not carry out low-carbon retrofit works, despite having access to appropriate information and opportunity to do so. The literature also suggests that installers might play a significant role on the formation of the occupant's behavioural patterns during *commissioning* or, even, *post-commissioning* stages (Owen and Mitchell, 2015). Such interactions have not been observed in the cases, but could be uncovered through further research.

Second, the study does not include the effect of embodied energy associated with low-carbon construction on carbon footprint of dwellings. The study suggests a step-by-step retrofit as an alternative route to achieve significant carbon emission reductions. Further research is needed to investigate the amount of embodied carbon associated with this approach and its contribution to the total carbon footprint of a dwelling.

Third, the study uses meanings people attach to their homes to develop insights into the diversity of low-carbon home retrofit goals, intentions and motivations. Inevitably, considerations that cannot be traced back to home-meanings were excluded. This includes financially-related considerations, which are known to have a prominent role in homeowner retrofit decisions.

Future research is needed to investigate such considerations with a different theoretical framework.

Fourth, the study focuses on owner-occupiers, but not other types of tenure, such as private tenants and social housing tenants. While owner-occupiers account for about 70% of the housing stock in the UK, it seems that a focus on occupants with other types of tenure, as well as landlords, is a worthy area of further research, where limited evidence appears to be currently available. Homeowners retrofit solutions are shaped by various actors, such as builders, planners and conservation officers (Buser and Carlsson, 2017). The thesis sample includes homeowners only, which means that some important dynamics of the creation of the retrofit solution in the process of interaction between different actors might have been overlooked. Future research is recommended to focus on the interaction between different actors, and how such interactions move homeowner decision towards or away from low-carbon retrofit options.

7.4b. Limitations imposed by the chosen research design

Some limitations have been imposed by the chosen research design. The thesis featured a small, UK based study with a limited sample size from representatives of the SuperHomes network. The participation in the SuperHomes network implies that the individuals chose to share their experiences publicly. This might not be the case for other homeowners, who opted not to do so. However, it is difficult to avoid this bias, as there is no central record of low-carbon retrofit activity in the UK, and thus, such activity is not readily visible for the researchers. As a consequence of these limitations, the developed theoretical insights are representative of the sample only. The findings were positioned within a broader literature, which increased external validity of the interpretation. Further research on a wider sample representative of the population could test the developed theoretical insights.

The diversity of affordances provided by one's home is built on the studies carried out in western world. It is possible that an understanding of what home can offer to an individual varies across different social, economic, political and cultural backgrounds. It seems that a focus on people in non-western world is a worthy area of further research, where limited evidence appears to be currently available. Continuous associative experiments on associations with a word 'home' is recommended on a representative sample of the population under investigation.

7.4c. Limitations imposed by data collection strategies

The data collection strategies employed in the thesis imposed some limitations. First, data collection featured sequential associative experiments, which increased the possibility that answers to the sequential experiments were influenced by the responses to the previous ones. To account for this possibility, a variance in the sequence of associative experiments among different cases is recommended for future research. Second, case A in the study sample does not fit the selection criteria, as the retrofit was carried out as part of the day-time job of the owner, who is a professional architect, and she rented out the property after the retrofit was complete. It was possible that the study results could be biased by the insights from this non-representative case. Nevertheless, it was evident that the case does not generate unique insights, which are not already supported by the insights from the other cases in the study. Thus, it is possible that the study insights can be generalised beyond owner-occupied population. For these reasons it was decided to retain the case. Third, it was only possible to sample one case study, which adopted an emergent retrofit strategy over time (case H). This means that some of the insights made in the thesis are grounded a single case. Future research could gather further evidence on retrofit decision journeys with an emergent retrofit strategy over time.

Fourth, data collection featured post-retrofit hindsight interviews, which increased the possibility of retrospective sensemaking by the interviewees of their experiences (Kahneman, 2012). It is suggested that future research incorporates alternative data collection strategies to control for such bias, such as a combination of retrospective and real-time cases. To partially mitigate the recall issue, the interviewees were asked to draw their retrofit timelines, which helped them to recall the sequence of events. Finally, the case studies in the thesis depicted successful retrofit experiences only, so the research findings lack insights from unsuccessful retrofit journeys. Future research could include cases where the retrofit decision-making process resulted in a rejection of a particular measure or technology under consideration.

7.4d. Limitations imposed by data analysis strategies

Finally, some limitations were imposed by the data analysis strategies. First, some associative experiments were carried out for a combination of words, such as ‘low-carbon home’, rather than for an individual word, which increased the possibility that interviewees associations to the whole phrase were affected by the meanings, imbedded in individual words in the phrase, such as ‘carbon’. It is suggested that future research uses associative dictionaries to access the impact of individual words on the meaning of the whole phrase. Second, interviews were coded by one researcher only, which increased the possibility that the results of the qualitative analysis are non-sustainable. This limitation was partly mitigated in the thesis by the chosen strategy for thematic coding with coding categories derived deductively either from an existing theory, or the conceptual framework of home-meanings generated specifically for the study. Clear coding categories increased confidence in overall interpretation of the data, independent on individual researcher's interpretation. It is recommended that future research strategy includes two researchers to code the data independently. Alternatively, external audits can be organised to assess the researcher's interpretation of the data.

Finally, some limitations are associated with system dynamics modelling. System dynamics modelling and simulation proved a useful tool for theory investigation. It reproduced theoretical patterns and led to the discovery of new ones. Moreover, the systematic testing of the model highlighted the trade-offs in the dynamics between effort, performance and fatigue. The model presented in *Chapter 6* can be described as qualitative and exploratory. The focus of model development on simplicity enables the meaningful interpretation of the results in light of theory and empirical evidence. However, it has some limitations. First, the model represents the change in daily performance goals but does not represent the overall project goals and how they change.

Second, the simulation results indicate that the concept of control has important implications on the behaviour of the model. Further exploration and possible elaboration of the structure underpinning the construct would increase the robustness of the results. Third, the model does not represent learning-by-doing mechanisms that could help to increase homeowner competence and the feeling of control over the retrofit. This could increase the effectiveness of the coping mechanisms to fatigue, but it would not change the fundamental modes of work. However, the diversity of the tasks involved in a retrofit process implies very little scope for task repetition so that any learning related to the installation of a particular technology, such as insulation for example, would not be directly applicable or relevant to other technologies, e.g. PV panels. Fourth, the concept of time in the model was used as a proxy for the concept of energetic resources. It is a simplification and further modelling can be done to represent the concept of energetic resources more realistically, for example, include an endogenous mechanism for resource capacity development and depletion. Further exploration and elaboration of the structure of the model is possible and can be recommended. If additional structure is found not to add significant insight into model behavior, a simpler version can be retained, otherwise an elaborate version can be used. However, an increasingly elaborate model, which integrates more theoretical perspectives and addresses all these limitations, would produce results that are increasingly difficult to interpret.

An overview of the major study limitations and how they were dealt is provided in Table 7.2. Despite the outlined limitations, this study offers some valuable insights into the area, where comparatively little research was done so far. The next section concludes the chapter with a summary.

Table 7.2. Study limitations, their impact on findings and mitigation strategies

Limitation	Impact on findings	Mitigation
Delimitations		
Focus on uptake of low-carbon measures and technologies	The behavioural impact on energy use and associated carbon emissions is not addressed.	Future research recommended.
	Effect of embodied energy on the overall carbon footprint is not investigated.	Future research recommended.
Focus on home-meanings as a proxy for retrofit considerations	Financially-related considerations, such as capital costs and investment opportunities, are not considered.	Future research recommended with a theoretical framework that accounts for financial considerations.
Focus on homeowners	The role of occupants with other types of tenure, such as tenants, on the overall transition to low-carbon housing stock is not investigated.	Future research recommended (for private tenants, social housing tenants and landlords).
	A possibility that some important dynamics of the creation of the retrofit solution in the process of interaction between different actors might have been overlooked.	Future research recommended to focus on interactions between different actors that shape the overall retrofit solutions, such as homeowners, builders, planners etc.
Research design		
Small, UK-based sample	The generality of understanding the retrofit decision journeys might be overestimated in the wider population as the study sample is not representative neither of the SuperHomes owners' population nor of the UK owner-occupiers.	Multiple case study design: selection of case studies with different characteristics. Positioning the findings within a broader literature. Future research recommended to test the developed theory.
The sample is from a SuperHomes network	The individuals studied are the ones that chose to share their experience publicly and therefore are visible to researchers. This might not be representative of wider the population.	Future research recommended.

(continued)

Table 7.2. Study limitations, their impact on findings and mitigation strategies *(continued)*

Limitation	Impact on findings	Mitigation
The diversity of affordances provided by one's home is built on the studies carried out in western world.	A spectrum of affordances that exists for people in non-western world is not investigated.	Future research recommended to investigate what homes offers for people from different social, economic, political and cultural backgrounds.
Data collection		
Sequential associative experiments	A possibility that an experience of one associative experiment affected the responses to the next one.	A variance in the sequence of the associative experiments in the future research is recommended.
Case A does not fit the selection criteria.	A possibility that the study results could be biased by the insights from this non-representative case.	Consideration was given to ensure that the insights derived from the case A are not unique and supported by the insights from other cases.
Only one case study depicting emergent retrofit strategy over time	Some generalisations are grounded in the insights of one case study only.	Future research is recommended to bring insights into retrofit decision journeys specific to emergent retrofit strategy over time.
Post-retrofit hindsight interviews	A possibility of retrospective sensemaking by the interviewees of their experiences.	Suggestion for alternative data collection strategy, combining retrospective and real-time cases.
Recruitment of studies depicting successful retrofit experiences only	Potential lack of insight from unsuccessful retrofit journeys.	Future research recommended to include cases, in which a retrofit decision-making process resulted in a rejection or a discontinuity of a measure/ technology.
Data analysis		
Associative experiments carried out for a combination of words, such as 'low-carbon home'.	A possibility that interviewee's associations are affected by the meanings imbedded in individual words, such as 'carbon'.	Suggestion to use associative dictionaries in future research to access the impact of individual words on the meanings of a phrase.
Interviews were coded by one researcher only	A possibility that the results of qualitative analysis are non-sustainable.	Codes for thematic analysis are derived deductively either from existing theory, or a framework generated for the study, increasing confidence in data interpretation. External audits or two independent researchers coding the same data is recommended for future research.
Some structure in the system dynamics model, such as the structure behind the concept of control, is simplistic.	A possibility that simplistic parts of the structure affect the overall dynamics of the model.	A suggestion for further research to investigate the psychological mechanisms of interest, include the respective structure endogenously to see if the model behaviour changes.

7.5. SUMMARY OF THE DISCUSSION

In the context of home retrofit, the transformation of the housing stock to low- and zero-carbon standards will need to accelerate to meet the UK goal to reach net-zero greenhouse gas emissions by 2050. This chapter discusses the steps that can be taken to influence individual retrofit decision journeys at different stages and the implications of such influences on the overall transition to a low-carbon housing stock. An evaluation is made of the benefits of framing the issue of decarbonisation of the built environment as a socio-technical problem and conceptualising home retrofit as a process, situated and shaped by the conditions of everyday life. This focus allows to develop useful insights about individual retrofit journeys, and suggest novel policies, as well as reaffirm current policy direction. Such insights would not have been possible if the analysis had been made under a conventional technical-economic view on the problem of decarbonisation, and used a drivers-barriers framework to understand retrofit decisions.

The following policy suggestions derived from the thesis are used to reaffirm current policy direction. First, it is suggested to use a picture of everyday activities to enhance the feelings of comfort and control, as a type of message to encourage low-carbon retrofit. Second, it is suggested to provide different types of information at different retrofit stages for different aspects of a socio-technical system of a low-carbon dwelling. The research findings also opened a way for novel policy suggestions. First, it is suggested to promote a recognition of a broader social responsibility by others. Second, the findings suggest the need to develop policies to support homeowners in their retrofit journeys to ensure that the associated experience is pleasant. The results of the qualitative analysis, as well as the results of the system dynamics model exploration, suggest that a step-by-step retrofit approach might ease the implementation burden associated with low-carbon retrofit, and thus, generate a more positive impression of the process itself. The system dynamics model exploration also suggested that a positive retrofit experience is also associated with a high feeling of control over the activity. Thus, there is a need to explore further the routes to establish such feeling of control.

The implications for theory development have also been discussed. First, the scope of applicability of the developed home-meanings framework has been considered. It is argued that the applicability can extend beyond the focus of the current thesis, and the framework can provide a basis for theoretical explanation development of the processes by which home comes to have meaning for an individual. Second, the current research makes a contribution to the innovation diffusion discourse, by disaggregating the unit of analysis into three nested levels, when studying low-carbon home retrofit as an innovation: a particular product, a design option and a socio-technical system. The research highlights the importance of different interpersonal communication in the process of attitude formation. It also highlights the importance of the positive experience of the implementation of an innovation on the successful use of an innovation, the formation of a positive experience of the innovation itself, and a subsequent positive word of mouth about the innovation. Moreover, the research highlights the difference in the nature of innovation-decision processes of individual agents (adoption of all necessary technologies in one go vs over time) and the associated impact on the overall innovation diffusion in the population. Third, the thesis makes a contribution to Hockey's motivation control theory of fatigue, by revealing through simulation two additional, distinct work management modes not previously conceptualised by Hockey.

Methodological implications include, first, a demonstration of benefits of a systems approach to understand low-carbon energy use. Second, the thesis illustrated a method to develop a simulation model that is theoretically generic and can simultaneously be applied to diverse empirical cases. The model is generic as it is based on Hockey's generic theory of psychological fatigue and covers a wide theoretical ground and phenomena. The system dynamics model can be case-specific as the initial behavioural pattern was suggested from the cases themselves, and the application of the model to cases was successful, as the model reproduced the behavioural patterns observed in the cases.

The chapter also discussed the limitations of the study: the ones related to the scope of the study, the research design strategy, data collection and data analysis strategies. The impact of these limitation on the findings were considered, and mitigation strategies, which were implemented in this thesis or suggested for future studies, were discussed.

Chapter 8

Conclusions

The conclusions chapter summarises the key findings in relation to the research question and states the significance of these findings in the area of policy in section 8.1. It further discusses the implications of the theoretical and methodological findings in section 8.2 and concludes with the agenda for future research in section 8.3.

CHAPTER CONTENTS

8.1. KEY THESIS FINDINGS AND POLICY IMPLICATIONS

This section summarises the key findings from the thesis in relation to the general research question set in *Chapter 1*:

How can the individual retrofit decisions of UK homeowners be influenced to accelerate the rate of low-carbon retrofit in the population?

To address the research question, the thesis: (i) explored the possibility to use meanings people attach to their homes, to promote low-carbon home retrofit; (ii) captured the dynamics specific to individual retrofit-decision processes, which might have implications on the diffusion of low-carbon retrofit measures and technologies on a population level; (iii) explored the captured dynamics with a simulation model of psychological fatigue development, which helped to identify intervention levers that can support individual retrofit journeys, and by doing so, facilitate the overall transition to a low-carbon housing stock. Several research methods and tools were applied to address the research question: (i) in-depth interviews, associative experiments, questionnaires and visual process mapping with the interviewees for empirical data collection of successful low-carbon retrofit cases; (ii) holistic multiple-case study analysis of the collected data with the use of matrices, process and causal diagrams for analytic display; (iii) the development of a system dynamics simulation model of psychological fatigue to explore the cases further.

The key findings reached in this thesis and the policy suggestions associated with them are laid out in the rest of the section.

Finding 1. The context of a low-carbon home is associated with: enhanced feelings of comfort, safety, security and control, as well as an identity of a broader social responsibility.

The finding suggests two routes to promote low-carbon home retrofit. The first route, already implemented in policy, is to use images of everyday activities to explain how low-carbon dwellings support enhanced feelings of comfort, safety, security and control in relation to these activities. The second route, not yet established in policy, is to target an extra-domestic identity of a broader social responsibility, and delineate circumstances in which such an identity is recognised by others. For example, identity formation can be encouraged on a communal level through peer-to-peer electricity trading, or on a household level between household members through the promotion of low-carbon living as a good formative experience for one's children.

Finding 2. Low-carbon home retrofit as an innovation should be understood as comprised of three imbedded aspects: as a product, a design option and a socio-technical system.

The finding suggests it is necessary to provide information for all aspects of low-carbon home innovation. The suggestion is already implemented in current policy, and thus, the findings are used to reaffirm the policy direction.

Finding 3. Homeowners gather information for these different aspects of low-carbon home innovation at different decision stages through different communication channels.

The thesis suggests to use different information channels at different retrofit-decision stages to deliver information to homeowners. This insight is also implemented in current policy, and the findings are used to reaffirm policy suggestions.

Finding 4. The experience of retrofitting a home to low-carbon standards can affect the satisfaction with results and the associated positive word of mouth that is needed to persuade others to retrofit their homes. Implementation difficulties can be reduced via the choice of appropriate work pace. Such difficulties are also subject to influence by the dynamics between the homeowner's intrinsic motivation and control of the retrofit process.

The finding suggests that a good experience of the retrofit process is necessary for a sustained reduction in post-retrofit energy use. Such experience is also necessary to generate a positive word of mouth, that can help to persuade others to retrofit their homes, which in its turn can accelerate the transition to a low-carbon housing stock. The finding provides a way for a novel policy suggestion to support homeowners in their retrofit journeys to ensure that their associated experience is pleasant. The thesis suggests that a step-by-step retrofit approach as well as a feeling of control over the retrofit process might ease the implementation burden for homeowners.

8.2. THEORETICAL AND METHODOLOGICAL IMPLICATIONS

The study presents a significant advance in understanding the retrofit-decision journeys of homeowners, and their impact on the overall transition to a low-carbon housing stock, despite the limitations outlined in the *Chapter 7*. The key contributions and implications of the research findings in the areas of theory development and innovative methods are outlined in the rest of this section.

The contributions to the area of **theory development** are:

(i) The thesis documents eight successful cases of low-carbon home retrofit and provides a qualitative analysis of the associated retrofit-decision processes.

The qualitative analysis of the cases contributes to the formation of a theoretical understanding of the individual homeowner retrofit-decision process and their potential impact on the transition to a low-carbon housing stock.

(ii) The thesis develops a conceptual framework of home-meanings, depicting different dimensions related to the notion of home.

The conceptual framework of home-meanings represents a rich synthesis of current empirical and theoretical literature and, thus, can be used to guide a comprehensive inquiry about other issues related to home-meanings, not necessarily concerning low-carbon retrofit. The home-meanings framework can also be used as a basis to guide the development of an integrative theoretical explanation of the processes, by which the home comes to have meaning for an individual.

(iii) The thesis applies Rogers' innovation diffusion theory to case analysis and shows that it is a suitable lens to develop insights in how individual retrofit-decision processes can affect the transition to a low-carbon stock. The thesis contributes to the diffusion literature by emphasising the following topics in the innovation diffusion discourse: (a) disaggregation of a unit of analysis for an innovation into three levels: a particular product, a design option and a socio-technical system; (b) the importance of different interpersonal communication channels in the process of individual attitude formation towards different innovation options; (c) the importance of a good implementation experience on the successful adoption and use of an innovation by homeowners, the formation of a positive attitude to the innovation itself, and a subsequent positive word of mouth for the innovation; (d) the difference in the nature of innovation-decision processes of individual agents (adoption of all necessary technologies in one go vs over time) and the associated impact on the overall innovation diffusion in the population.

Other innovation diffusion researchers might find that insight interesting, and it could prompt them to suggest new ways to accelerate the innovation diffusion in the system in the areas of their research.

(iv) The thesis identifies the issue of psychological fatigue as one that can affect the homeowner impression of a retrofit journey in a negative way. Hockey's theory of psychological fatigue is used to pursue further analysis and insights. The theory is operationalised and formalised into a simulation model, which increases the internal validity of the theory.

Theory formalisation and simulation provide a measure of the model generality in terms of the theoretical ground and phenomena it covers. It also shows which aspects of Hockey's theory may need further clarification and structural exploration. For instance, the modelling process suggests that further development of the structure underpinning the notion of *Perceived Control* could bring further insights and increase the robustness of the theory.

(v) The simulation results revealed two additional, distinct behavioural patterns not previously conceptualised by Hockey: strain work management mode II (sustained proactive coping) and strain work management mode III (oscillations between proactive to reactive coping). Thus, the results extend Hockey's theory and provide theoretical patterns for empirical exploration.

The insights might be interesting for the researchers in the field of psychology and might trigger new ways of thinking about the phenomenon in the field.

The **methodological** contributions are:

(vi) The thesis develops and applies a multi-method sequential approach to develop insights on individual retrofit-decision processes and their implications for the overall transition to a low-carbon housing stock. This approach illustrates: the integrated use of in-depth interviews, questionnaires, associative experiments, visual process mapping for data collection; holistic multiple-case studies for qualitative analysis; system dynamics modelling of psychological fatigue; thematic coding to support case study analysis and simulation model development; the use of matrices, process and causal diagrams for analytic display.

The process highlights the complexity associated with qualitative research, and suggests methodological steps specific to the topic. However, these methodological steps can be generalised and used in different combinations in other studies, thus, the process can be of interest to researchers involved in qualitative analysis.

(vii) The thesis illustrates a three-step approach to develop a generic simulation model that can be applied to specific cases. First, process theory guides a multiple-case study research design. It reveals a behavioural pattern of interest observed in the cases: the development or non-development of psychological fatigue. Second, Hockey's theory of psychological fatigue is identified as a suitable lens to develop further insights in the phenomenon. The theory is operationalised into a system dynamics model, that is tested and validated based on a thick textual description of the theory provided by Hockey. Third, further data from the same participants are collected via interviews, questionnaires and mapping the behavioural patterns of interest for some model variables. The model is adjusted and parametrised to each case. The simulation results show that the system dynamics model is both (a) case-specific, as it can reproduce the behavioural patterns inferred through interviews in the case studies; and (b) generic, as it reproduces the three fatigue modes proposed by Hockey, and reproduces behavioural patterns described by Eisenberger's theory of learned industriousness, Seligman's theory of learned helplessness and Sonnentag's theory of psychological detachment.

The process illustrates a way to develop a generic simulation model for application to specific cases. The method might be of interest to other researchers that aim to develop generic but also case-specific theories.

8.3. FUTURE WORK

The limitations of this study have been highlighted and the corresponding areas for future research have been outlined in *Chapter 7*. The research findings have also highlighted new gaps in current knowledge, which should be addressed in future research. A range of areas considered worthy of further investigation are listed below.

The first suggestion for future work is to investigate whether there is an optimal number of retrofit steps, as well as an optimum order, technically and economically, in which to install retrofit measures in similar material arrangements. The thesis findings suggest that a step-by-step retrofit approach might be less tiring and result in a more positive word of mouth regarding retrofit process, which is necessary to persuade others to retrofit their homes. However, it is not clear how many steps are needed to have an optimal impact on shortening the overall transition period to a low-carbon stock. The smaller the duration of the steps, the less is the implementation burden for the homeowners, and the more positive is the word of mouth regarding the retrofit process. However, small steps mean that the overall individual decision-making process of low-carbon retrofit is extended. The transition of individual homeowners to low-carbon living may take longer, or they may never complete such transition. Thus, it will take longer to form a critical mass of people, who have retrofitted to low-carbon standards and can talk to others about their experience of living in such houses. A critical mass of adopters is needed for the innovation diffusion to be self-sustaining (Rogers, 2003). The slow formation of a critical mass of homeowners, who retrofitted their homes to low-carbon standards, might slow the overall transition to a low-carbon housing stock. The problem is complex and it is possible that modelling is required to properly address it.

The second suggestion for future work is to investigate whether some configuration of material structure and technology can facilitate a lower-energy use by the occupants. Data analysis revealed that some technological configuration might shape low-energy use. For instance, the owner in case D made sure that the household altered their shower habits during the summer to ensure that the water tank is heated by the renewable energy only during summer months. Further research is needed to understand which measures and combinations of measures can naturally direct occupants behavior towards behavioural patterns, characterised by low-energy consumption. *Social practice theory* can be used to structure inquiry regarding the relations between agency, material structure and social practices (Gram-Hanssen, 2011; Shove et al., 2012; Warde, 2005; Reckwitz, 2002; Schatzki, 2002).

The third suggestion for future work is to investigate how motivational priorities regarding low-carbon retrofit develop over time, and how the formation of these priorities can be strengthened and accelerated. The current thesis develops a conceptual framework of home-meanings and uses it to gain insight into homeowner retrofit goals as well as living experiences. Even though interesting insights were developed, the framework does not enable an understanding of how various motivational influences develop over time. Such understanding is needed to suggest how these influences can be strengthened. Ford's (1992) *motivational system theory*, which is based on Bertalanffy's (1969) *general system theory*, can be used as a meta-theory to structure the process of developing such understanding.

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Glossary

This glossary clarifies some of the vocabulary used in this thesis. There is ambiguity about many terms used within social science and built environment research. It is hence not suggested that the following definitions are hold in general. Rather, the glossary serves to state how certain terms are understood within this thesis.

A/ AA/ AAA+ rated appliances EU Directive 92/75/EC established an energy consumption labelling scheme. An appliance or a dwelling must have an EU Energy Label clearly displayed when offered for sale. The energy efficiency is rated in terms of a set of energy efficiency classes from A to G on the label, A being the most energy efficient, G the least efficient. In an attempt to keep up with advances in energy efficiency, A+, A++ and A+++ grades were later introduced for various products.

Abduction *Abductive* reasoning is a form of logical inference that explains a curious observation by the supposition that this observation is a case of a certain general rule, and thereupon it is logical to adopt this supposition. Abductive reasoning provides inference to the best explanation. It should be noted though that a conclusion derived by abductive reasoning is not a proof, but just a proposed explanation and should be supported by evidence, as an explanation derived by abductive reasoning could be built based on very few facts. The words *abduction* and *retroduction* are used to describe the same type of inference in different literatures.

Abilities (theory of affordance) In the theory of affordance, abilities are defined in contrast to dispositions. *Abilities* are functional properties. An ability to ride a bicycle does not mean that one will not fall from the bicycle, even in the ideal conditions for cycling. In contrast, *dispositions* are guaranteed to become manifest, if enabled by the right conditions. For instance, a cube of sugar will always dissolve in water in suitable conditions. Affordances arise along with the abilities of animals to perceive these functional properties and take advantage of them.

Actor Real individuals or groups of individuals which act in the real world.

Affordance The theory of *affordance* describes an ontology of the *meaning* of human perceptions, in which meanings are real entities that do not exist in the mind of the perceiver only, but at the same time they are not just the properties of the environment itself. It follows that affordances do not disappear, when there is no animal to perceive and take advantage of them. They do, however, depend on the existence of some animal that might take advantage of them, if the conditions are right.

Agent A representation of actors in a verbal or simulation model, used to represent the most important behavioural differences between actors within a typology. For instance, Hockey theorised three work management modes in his motivation control theory of fatigue: engaged, disengaged and strain. Following this differentiation, the developed system dynamics model was expected to show behavioural patterns for at least three agents: an engaged individual, disengaged individual and an individual under strain.

Air-to-air source heat pump An *air-to-air source heat pump* is a system which transfers heat from the outside air to an indoor space. See *Heat pump*. They can be used as a space heater or cooler.

Arithmetic average See *Lenient compromise*.

Associative experiment

An *association task* or *experiment* is a data collection method, during which the participants are asked to produce responses in association with a specific word or phrase. Association procedures could be differentiated between (i) discrete association tasks, in which participants are asked to produce a definite number of responses for each cue; and (ii) continuous association tasks, in which participants are encouraged to produce as many responses as possible for each cue.

Behavior-over-time graph

A *behaviour-over-time graph* is a simple graphical representation that focuses on the pattern of behaviour over time of a given variable. The construction of such graphs can lead to a rich discussion on why something is changing.

Block diagram (control engineering)

A *block diagram* is a diagram of a system, in which principal functions are represented by blocks that are connected by arrows that show unilateral relationships between the blocks. An arrowhead pointing toward the block indicates the input, and an arrowhead leading away from the block represents the output. The block itself represents the mathematical operation of the input signal to the block that produces the output. Thus, the dimensions of the output signal equal the dimensions of the input signal multiplied by the dimensions of the transfer function in the block.

A *summing point* is represented by a circle with a cross. The plus and minus signs at each arrowhead indicates whether the signal is to be added or subtracted. A *branch point* is a point from which a signal goes concurrently to other blocks or summing points.

Branch point (control engineering)

See *Block diagram*.

Case study

Case studies are rich, empirical descriptions of a particular phenomenon or an instance of a phenomenon.

Causal loop diagram
A *causal loop diagram* (CLD) is a diagram that visualises the causal interrelation of different variables. In CLDs arrows represent the causal relationship between two variables. A positive sign indicates that a change in one variable causes a change in the affected variable in the same direction. A negative sign indicates that a change in one variable causes a change in the affected variable in the opposite direction. The polarity of the causal loops is then identified as reinforcing or balancing, depending on the net change effect in reference to the initial change in the variable chosen as a starting point. Reinforcing loops indicate a change in the net effect in the loop in the same direction and are denoted by **R** in the CLD. Balancing loops indicate a change in the net effect in the loop in the opposite direction and are denoted by **B** in the CLD.

Choice (judgement and decision-making)
During the 1940s and 1950s two foci of judgement and decision-making research, *choice* and *judgement*, were established and continue to dominate the research tradition. One group of psychologists focused on the questions of how do people *choose* what to do next, how rational are their choices, and by what psychological processes do people make their decisions.

Code (qualitative research)
Codes are essentially labels that are attached to the excerpts of descriptive information. Coding is an essential process in qualitative data analysis.

Commissioning stage of the retrofit-decision process
See *Retrofit-decision process.*

Concept
See *Theoretical framework.*

Conceptual framework
See *Theoretical framework.*

Confirmation stage of the retrofit-decision process See *Retrofit-decision process.*

Constant variable (system dynamics) A variable that represent exogenous input to the model.

Construct In a scientific theory, particularly within psychology, a hypothetical *construct* is an explanatory variable which is not directly observable. For example, the concepts of resources and intrinsic motivation are used to explain phenomena in Hockey's motivation control theory of fatigue, but neither is directly observable.

Construct validity *Construct validity* evaluates whether a measure of a concept really reflects the concept it intends to be measuring.

Control theory *Control theory* in control systems engineering is a subfield of mathematics that deals with the control of continuously operating dynamical systems in engineered processes and machines.

Credibility *Credibility* (the quality of being trusted and believed in) strategies in qualitative research are concerned with two key issues — *credibility of procedures* and *credibility of outcome*s.

Credibility of outcomes *Credibility of outcomes* looks into quality and trustworthiness of the research results. Credibility of the results are not deterministic from the credibility of procedures, as it is accepted that the results cannot be absolutely proved.

Credibility of procedures *Credibility of procedures* evaluates how informed, transparent and accountable are methodological strategies and techniques used in the research.

Critical literature review The aim of the *critical literature review* strategy is to critically analyse the extant literature on a broad topic. It goes beyond a mere description and includes a degree of analysis and conceptual innovation. The product of a critical literature review is usually a theoretical or conceptual model, which might constitute a synthesis of current models, or may be a completely new interpretation of available data.

Data triangulation *Data triangulation* is a process of using multiple standpoints to understand the phenomenon under investigation, in which the data is collected from participants with different experience of the phenomenon.

Deduction *Deductive* reasoning is a form of logical inference that shows that a conclusion must be true as long as the premises are true, i.e. it applies a general rule to particular case and states the results. The beauty of deductive reasoning is that it is the only form of inference that guarantees its conclusions to be true.

Decision stage of the retrofit-decision process See *Retrofit-decision process*.

Disengaged work management mode See *Work management mode*.

Dispositions (theory of affordance) See *Abilities (theory of affordance)*.

Energy-efficiency gap *Energy efficiency gap* describes the difference between the cost-minimising level of energy efficiency and the level of energy efficiency actually realised.

Engaged work management mode See *Work management mode*.

Epistemology *Epistemology* is the branch of philosophy concerned with the theory of knowledge.

External validity *External validity* in qualitative research evaluates to which extend the research findings can be generalised.

Extrinsic motivation Within motivation control theory of psychological fatigue, it is emphasised that the development of fatigue is more readily associated with task goals (*extrinsic motivation*) rather than self-initiated (intrinsic motivation) activities.

Fatigue Within motivation control theory of psychological fatigue, *fatigue* is conceptualised as one aspect of the complex set of control mechanisms that regulates performance in light of changing motivational priorities

Features (theory of affordance) In the theory of affordance, features are defined in contrast to properties. *Features* ascribe certain characteristics of the environment without assigning them to any particular object in the environment. For instance, the phrase 'it's raining' describes the feature of the environment, but it does not assign a property to any particular object. *Properties*, on the other hand, are assigned to particular objects in the environment. For instance, a perception of a red car implies a perception that a particular entity (a car) has a particular property (being red). The perception of affordances should be understood as ascribing features, rather than perceiving properties of the environment.

Flow state (psychology) In psychology, a *flow state* describes a mental state in which a person performing an activity is fully immersed in a feeling of full involvement and enjoyment in the process of the activity.

Flow variable (system dynamics) See *Stock and flow diagram*.

Formalisation stage of the retrofit-decision process See *Retrofit-decision process*.

Green Deal *The Green Deal* was a UK government policy initiative that gave homeowners, landlords and tenants the opportunity to pay for energy efficient home improvements through the savings on their energy bills.

Harmonic average See *Strict compromise*

Heat pump A *heat pump* is a system which transfers heat from a source of heat to a thermal reservoir. Heat pumps use external power to move thermal energy in the opposite direction of spontaneous heat transfer, by absorbing heat from a cold space and releasing it to a warmer one. The most common design of a heat pump involves four main components – a condenser, an expansion valve, an evaporator and a compressor. The heat transfer medium circulated through these components is called refrigerant.

Heterogeneity The quality or state of being diverse in character or content.

Home *Home* is a complex, multi-layered, multi-faceted and multi-dimensional construct. In this thesis a conceptual framework of home-meanings is developed to define the notion of home. It distinguishes between five different dimensions associated with a notion of home:
(i) three elements of home environment, including its physical and spatial elements, self and social elements, financial and legal elements;
(ii) two types of affordances home environment can offer to an individual, including behavioural and social-psychological affordances;
(iii) a differentiation between real and imaginative realms; (iv) a temporal dimension; and (v) various social, economic, political and cultural contexts.

Homeostasis The tendency towards a relatively stable equilibrium between interdependent elements, especially as maintained by physiological processes.

Homogeneity The quality or state of being all the same or all of the same kind.

Implementation science *Implementation science* is commonly defined as the study of methods and strategies to promote uptake of interventions that were proven to be effective.

Imported concept (qualitative metasynthesis)

The use of *imported* concepts involves the identification of pre-existing concepts used by the researchers in different reports to interpret their data and, the subsequent use of imported concepts to produce a metasynthesis of findings across all reports.

In vivo concepts (qualitative metasynthesis)

The use of *in vivo* concepts involves the identification of interpretative concepts, developed by the researchers themselves in different reports, to determine whether they can be translated into each other or combined to produce a metasynthesis of findings across all studies in a domain.

Induction

Inductive reasoning is a form of logical inference that shows that a conclusion is probably true, if the premises are also true. It is an inference of a general rule from specific case and observed results. Induction assumes that characteristics, that are true to a number of cases taken at random, are true to the whole population these cases are coming from. It is sometimes called "statistical argument", as arguments derived by inductive reasoning are based on solid empirical evidence and in the long run must generally afford correct conclusions from true premises. However, conclusions derived with inductive reasoning could easily be sound, consistent, but at the same time wrong.

Innovation diffusion theory

The theory of *innovation diffusion* explains how abstract ideas and concepts, technical information or actual practices spread over time through communication channels in a particular social system.

Innovation in low-carbon home retrofit (innovation diffusion theory)

Within innovation diffusion theory, innovation is understood as an idea, practice or object perceived as new by a potential adoption. This thesis suggests that *low-carbon home retrofit as innovation* should be understood as comprised of three embedded aspects: a product, a design option and a socio-technical system.

Installation stage of the retrofit-decision process

See *Retrofit-decision process*.

Internal validity — *Internal validity* evaluates how well a causal relation between the variables is demonstrated.

Intrinsic motivation — Within motivation control theory of fatigue, it is emphasised that the development of fatigue is more readily associated with task goals (extrinsic motivation) rather than self-initiated (*intrinsic motivation*) activities.

Judgement (judgement and decision-making) — During the 1940s and 1950s two foci of judgement and decision-making research, *choice* and *judgement*, were established and continue to dominate the research tradition. One group of psychologists, motivated by the analogy with perception, focused on the questions how people integrate multiple, potentially conflicting cues to arrive to a *judgement* of a situation.

Knowledge stage of the retrofit-decision process — See *Retrofit-decision process*.

Learned helplessness — The mechanism of *learned helplessness* postulates that an individual learns that the outcome of the actions is independent of the responses, when exposed to uncontrollable events.

Learned industriousness — The concept of *learned industriousness* describes an acquired habit to employ high effort strategies, because of the learned association of such strategies with high levels of reward.

Lenient (combination of two variables) — Description: *lenient*. Mathematical construct: *logical OR*. Formula: $x+y-xy$. If one variable is switched off the response follows the full range of the other variable. If however one variable is at its maximum 1, the second variable can have no further effect.

Lenient compromise (combination of two variables) — Description: *lenient compromise*. Mathematical construct: *arithmetic average*. Formula: $(x+y)/2$. This combination describes the averaging between the two variables.

Level variable See *Stock and flow diagram*.

Low-carbon home retrofit There is no agreed definition of what constitutes *low-carbon home retrofit*, in terms of targets to be reached, the measures that need to be installed or the behaviour changes necessary to reach these targets. This thesis draws upon the biggest source of data on low-carbon home retrofit in the UK owner-occupied sector, the SuperHomes database. For this reason, the phrase 'low-carbon retrofit' is used to describe retrofit activities that resulted in at least 60% carbon reductions compared with pre-retrofit emissions in line with the definition developed by the network.

Matrix (qualitative research) A *matrix* essentially represents a cross-tabulation of material in a condensed form.

Member checking strategy *Member checking strategy* is a strategy to deepen the credibility of the outcomes, during which the research findings are taken back to the participants for feedback.

Method triangulation *Method triangulation* is a process of using multiple standpoints to understand the phenomenon under investigation, in which two or more methods are used to bring insights into the phenomenon.

Motivation control theory of psychological fatigue The *motivation control theory of fatigue* conceptualises fatigue development not in terms of energy depletion, but rather as a conflict in the control of motivational choices — an unwillingness to continue with an activity that was unrewarding, rather than an inability to complete one that was too demanding.

Narrative capability The ability to tell the story that enables the representation of the phenomenon by the individual, who experienced the phenomenon under investigation.

Ontological security *Ontological security* is defined as a confidence or trust that the natural and social worlds are as they appear to be.

Ontology — *Ontology* is the philosophical study of being.

Paradigm — A scientific *paradigm* is what the members of scientific community share, including their beliefs, which questions should be studied and what are the appropriate procedures to answer these questions. Competing paradigms are understood to be incommensurable, as the proponents of different paradigms do research in different worlds, with different beliefs on what science is, and what appropriate and legitimate scientific procedures are. For this reason, it is impossible to create a one-to-one correspondence between the ideas in two different paradigms.

Paradigmatic integrity — The questions of *paradigmatic integrity* deal with the aspects of reality that are meant to be communicated to the audience.

Passivhaus refurbishment standard (EnerPHit) — *Passivhaus refurbishment standard* is an international building standard that requires a heating demand below 25 $kWh/m^2/year$, which is calculated by the specialised Passive House Planning Package (PHPP) tool.

Persuasion stage of the retrofit-decision process — See *Retrofit-decision process*.

Phenomenology — *Phenomenology* is the philosophical study of the structures of experience and consciousness.

Pragmatism — *Pragmatism* is a philosophical tradition, which broadly agrees that what is true is what is the most useful. It postulates that cognitive concepts and scientific knowledge should be evaluated in terms of the sensible or tangible outcomes of their use, thus, abstract knowledge that has no tangible outcome of use is considered meaningless. It is argued that the only method to assert the meaning of concepts is an experimental one, and the only way to attain general knowledge of experiential truth is by inductive testing of theories. The process of attaining knowledge is understood to be iterative and in a state of a near approach towards provisional results, as absolute finality of the results can never be reached.

Proactive coping strategy
See *Work management mode*.

Process diagram
A *process diagram* is a visual representation of a particular process.

Process research
Process type of research focuses on how processes emerge, develop, transform and terminate over time. It is well equipped to understand the temporal sequence of events: what are the influences that play a role first, next, and so on, and how each influence in a stage affects the next stage of the process.

Properties (theory of affordance)
See *Features (theory of affordance).*

Psychological detachment
The concept of *psychological detachment*, or an experience of 'switching off' from work, not being busy with job-related tasks during nonwork time and, most important, refraining from job-related task thoughts. It is a skill that people have. Some are better in it than others.

Q-methodology
Q-methodology is a method to study people viewpoints, by having participants rank and sort a series of statements, and using factor analysis to develop a set of shared viewpoints.

Qualitative metasynthesis
Qualitative metasynthesis is a systematic approach to the collection and analysis of qualitative studies with the focus on synthesising the findings from these studies with the use of qualitative methods. The method makes an emphasis on maintaining the richness and essence of the original studies while creating an integrated whole. Metasynthesis

is more than a summary of findings, instead, it offers novel interpretations of findings and a possibility to construct larger narratives than in any individual report. A qualitative metasynthesis of findings is an act of re-representing representations. It constitutes an interpretation at least three times removed from participants' lives.

Rate of change variable See *Stock and flow diagram*.

Reactive coping strategy See *Work management mode*.

Reliability *Reliability* evaluates the level of confidence in data interpretation.

Retrofit-decision process Seven stages are conceptualised in the *retrofit-decision process* in this thesis. (i) At the *knowledge stage*, a household becomes aware of one or another low-carbon home-related innovation. (ii) At the *persuasion stage*, the household forms positive or negative attitude towards the innovation. (iii) Then the household *decides* whether to adopt of to reject the innovation. (iv) During the *formalisation stage* the household acquires specifications and quotes for particular options, gets planning permission and ensures compliance with regulations.
(v) During the *installation* stage the new technology is installed.
(vi) At the *commissioning* stage the new technologies are switched on and tested to ensure they function as expected. (vii) At the final stage of *confirmation*, the household reflects on the experience and communicates messages about his/ her experience to others, thus influencing their persuasion stage.

Right to Buy scheme The *Right to Buy scheme* is a policy in the United Kingdom, which gives council tenants and some housing associations the legal right to buy, at a large discount, the council house they are living in.

Socio-technical system of low-carbon home retrofit A *socio-technical system of a low-carbon home* involves interactions between natural laws, technological characteristics of a building structure and its components, and the action of its occupants, which in combination result in low-carbon operational energy use.

Socio-technical systems approach The *socio-technical systems approach* asks questions how society and technology develop in relation to each other. The key insight is that the society and technology mutually form each other, as different values specific to a particular societal context shape technological change, while technology constantly influence society.

State variable See *Stock and flow diagram*.

Stock and flow diagram A *stock and flow diagram* is a standard diagram in system dynamics. A stock (level or state) represents an entity that accumulates or depletes over time. A flow (rate of change) is the rate of change in a stock.

Stock variable See *Stock and flow diagram*.

Strain work management mode See *Work management mode*.

Strict (combination of two variables) Description: *strict*. Mathematical construct: *logical AND*. Formula: *xy*. If the effect if one soft variable is switched off, the other has no effect.

Strict compromise (combination of two variables) Description: *strict compromise*. Mathematical construct: *harmonic average*. Formula: $\sqrt{(xy)}$. At the extremes of one of the inputs being 0 the response matches the strict case (if the effect if one soft variable is switched off, the other has no effect). However, there will be a point where the response can match the lenient compromise (averaging between the two variables).

Summing point (control engineering) See *Block diagram*.

System In order for a group of elements to constitute a *system*, they have to interact with each other. However, elements interaction is not enough to constitute a system. The idea of a system implies the notion of 'wholeness', where the interaction between elements of the system through feedback mechanisms leads to a change of the initial state of these elements, and, subsequently, a change in the system state. It follows that the system behaviour cannot be understood through an examination of its respective elements in isolation.

System dynamics *System dynamics* is a simulation method suitable to capture dynamic changes over time by simulating the evolving behaviour of interrelated variables.

Taxonomy *Taxonomy* is the science of naming, defining and classifying groups of entities on the basis of shared characteristics.

Thematic coding *Thematic coding* is one of the most common forms of analysis within qualitative research. It emphasises identifying, analysing and interpreting patterns of meaning within qualitative data.

Theoretical framework This thesis differentiates between the notions of *concept*, *conceptual framework*, *theoretical framework* and *theory*. A *concept* is a smallest symbolic representation of an abstract idea. A *theoretical framework* is understood as an application of a *theory*, where the concepts in the framework are derived from the theory. Thus, the concepts and the relations between them are clearly defined. A *conceptual framework* is based on a synthesis of the theoretical and empirical findings in the existing literature concerning a given situation. Thus, the clarity of the concepts and the relations between them might not be ideal. For this reason, a conceptual framework usually has a limited scope and tends to be applicable to a particular study only. With time, a conceptual framework can give rise to a clearly articulated theory.

Theory The word *theory* describes both the type of thinking about a phenomenon of interest, as well as the outcomes of this thinking. A theory structures a systematic view of phenomena with a set of clearly defined interrelated concepts. Explanation of the phenomenon is one of the primary purposes of theory building.

Triangulation — *Triangulation* is a process of using multiple standpoints to understand the phenomenon under investigation.

U-value — Thermal transmittance, also known as *U-value*, is the rate of transfer of heat through a structure divided by the difference in temperature across that structure. The units of measurement are W/m^2K.

Validity — *Validity* evaluates how well the conclusions are grounded in the data.

Variance research — *Variance* type of research focuses on discussing observed inputs (independent variables) and outcomes (dependent variables), and involves data collection and processing aimed to determine the correlations between sets of variables. This research strategy is well-equipped to answer questions 'how often', and 'how many', and questions about relative empirical importance of constructs.

Visual mapping — *Visual mapping* describes techniques of graphical forms of data collection and analysis.

Work-fatigue hypothesis — The *work-fatigue hypothesis* is a widely accepted view on fatigue within psychology, which explains its origin in terms of exhaustion of energy. This hypothesis proposes that prolonged periods of work inevitably lead to energy resource depletion and a reduction in performance.

Work management mode — Hockey (2013) distinguishes three work coping strategies or *work management modes*: (i) *strain*, which refers to the use of a high effort strategy in the absence of control; (ii) *disengaged*, which is characterised by a low effort strategy under low control; and (iii) *engaged*, which is characterised as an effortful strategy under high control. A more traditional classification of work management modes distinguishes between *proactive* (active) and *reactive* (passive) coping strategies. The proactive coping strategy corresponds to the engaged work mode and the reactive coping strategy to the disengaged one. The strain mode is best characterised as a combination of both coping strategies, that shift from initial proactive coping to reactive strategy as the requirements for effortful engagement with the goal increase.

Appendices A

Literature review process

These appendices provide additional detail on the qualitative metasynthesis process carried out for this thesis:

AA. Search concepts used in the metasynthesis
AB. Reading guide for the appraisal of individual reports

Appendix AA
Search concepts used in the metasynthesis

This appendix provides the list of search concepts that were used in the metasynthesis (Table AA.1). Search concepts are different from search filters. The development of search filters is based on the search concepts to perform a search in a specific database. Different databases might require different searching procedures, such as a difference in the truncation symbols used, or different rules for punctuation and capitalisation required to perform a search. The list presented here is a list of search concepts. The list was transformed into search filters specific for *Web of Science*, *Scopus* and *IBSS* databases.

Table AA.1. Search concepts used in the metasynthesis

Search term	Related search concepts
Low-carbon	Energy-efficient, energy neutral, energy saving, environmental, green, high efficiency, low-energy, Passivhaus, passive house, sustainable, thermal, zero-carbon, zero energy.
Home	Domestic, dwelling, house, residential.
Retrofit	Improvement, modernisation, modification, rebuilding, reconstruction, refurbishment, renovation, remodelling, repair, upgrade.
Homeowner	Householder, private household, owner, owner-occupier.
Qualitative research	Case study, constant comparison analysis, content analysis, descriptive study, discourse analysis, ethnography, exploratory, field observation, field study, field research, focus group, grounded theory, grounded study, hermeneutic, interview, lived experience, mixed method, narrative, naturalistic inquiry, participant observation, phenomenology, purposeful sample, purposive sample, semiotics, social theory, thematic analysis, Q methodology.

Appendix AB
Reading guide for the appraisal of individual reports

This appendix provides a reading guide for intra-report appraisals of qualitative research reports. The guide is adapted from the original appraisal guide used in the Analytic Techniques for Qualitative Metasynthesis project (2000 – 2005) developed by Dr. Margarete Sandelowski and Dr. Julie Barroso (Sandelowski and Barroso, 2007). The guide starts on the next page.

AA.1. FACE PAGE

Gathering the demographic features of and reading context for the research report. A basic inventory of such features is created beforehand.

AA.1a. Demographic Features

Complete citation:
Author affiliations, including discipline and institution:
Funding source:
Acknowledgments:
Period of data collection:
Geographic location of study:
Dates of submission and acceptance of work:
Publication type (e.g., authored/ edited book, journal, dissertation, thesis, conference proceeding):
Mode of retrieval (e. g. computer data base, citation list, personal communication):
Key words (as stated in report):
Abstract (copied from report):
Related reports (determined after appraisal of all reports):

AA.1b. Reading Context

Date of reading:
Reader:
Purpose of reading:
Reader affiliations:
Authored by reviewer, or member of review team (Y/N)?

AA.2. RESEARCH AIM

AA.2a. Research problem

Extracting (regular font) or paraphrasing (italics) all statements concerning what the author of the report thinks is wrong, missing or requires changing.

Appraisal parameters	Presence +/–	Relevance +/–	Reviewer comments
1. There is a discernible problem that led to the study.			
2. The problem is accurately depicted.			
3. The problem is comprehensively depicted.			
4. The problem is related to the research purpose and/or the literature review.			
5. The description of the problem establishes the significance of the research purpose, or why the researcher wanted to conduct the study, beyond simply stating that “no one has studied this (qualitatively) before”.			
6. The claim that “no one has studies this before” is accurate.			

AA.2b. Research purpose(s) and questions(s)

Extracting (regular font) or paraphrasing (italics) all statements concerning one or more immediate and long-term goals, objectives, or aims of the study, and/or a list of one or more questions the study will answer.

Appraisal parameters	Presence +/–	Relevance +/–	Reviewer comments
1. There is a discernible set of research purposes and/or questions.			
2. Research purposes or questions are linked to the research problem and/or to the review of literature.			
3. Research purposes and questions are amenable to qualitative study.			
4. Researchers clarify whether the research purposes and questions are those that preceded entry into the field of study or ere altered in the course of study to accommodate data analysis.			

AA.3. LITERATURE REVIEW

Extracting (regular font) or paraphrasing (italics) researcher's discussion of what is believed, known, and not known about the research problem, and of how the problem has been studied.

Appraisal parameters	Presence +/–	Relevance +/–	Reviewer comments
1. Key studies and other relevant literatures addressing the research problem are included.			
2. The review addresses the research problem.			
3. The review clarifies whether it reflects what researchers knew and believed going into the field of study — before and data were collected — or came to know and believe while in or leaving the field of study, after data analysis began or was completed.			
4. The review shows a critical attitude toward the accumulated knowledge about the research problem and toward the methods used to study it, as opposed to indiscriminately identifying or summarising studies in a *he said/ she said* format.			
5. The review shows a discernible logic that points toward the research purpose, and is not at odds with it (e.g., as when researcher used a gap logic to criticise the prevalence of description studies in an area and then report another descriptive study).			

AA.4. THEORETICAL AND PHILOSOPHICAL POSITION

Extracting (regular font) or paraphrasing (italics) all statements indicating the perspectives, assumptions, conceptual/ theoretical frameworks, philosophies and/ or other frames of reference, mindsets, theoretical sensitivities, or orientations guiding or influencing researchers concerning the target phenomenon, or subject matter of a study (i.e., the people, events, or things to be studied), regardless of whether researchers appear to be aware of them.

Appraisal parameters	Presence +/–	Relevance +/–	Reviewer comments
1. There is an explicitly stated or implied frame of reference.			
2. If implicitly stated, the frame of reference is accurately rendered.			

(continued)

Appraisal parameters *(continued)*	**Presence** +/–	**Relevance** +/–	**Reviewer comments**
3. Whether stated or implied, the frame of reference fits the target phenomenon and is not forced onto it.			
4. If explicitly stated as the guiding frame of reference for a study, it played a discernible role in the way the study was conducted and/ or the way the findings were treated. This is in contrast to a frame of reference that is evidently operating in a study, but that is not demonstrably recognised by the researcher.			
5. The presentation of the orientation of the study clarifies whether it influenced researchers going into the field of study — before any data were collected — or after data analysis began or was completed.			
6. The researchers demonstrate awareness of their orientations in their review or in their presentation or discussion of findings.			

AA.5. STUDY METHODOLOGY

AA.5a. Orientation toward inquiry

Extracting (regular font) or paraphrasing (italics) all statements indicating the perspectives, assumptions, philosophies, methods, and/ or other frames of reference guiding or influencing researchers concerning the conduct of a study.

Appraisal parameters	**Presence** +/–	**Relevance** +/–	**Reviewer comments**
1. There is a stated or implied method.			
2. The method fits the research purpose.			
3. The method is accurately rendered.			
4. The method is appropriately used.			
5. The uses of method-linked techniques for other than method-linked purposes are explained (e.g., as when theoretical sampling is used in a qualitative descriptive study, or phenomenological techniques are used to create items for an instrument).			
6. Researchers demonstrate awareness of method choices and their impact on findings.			
7. The study is methodologically qualitative.			

AA.5b. Sampling size and composition

Extracting (regular font) or paraphrasing (italics) all information concerning the people, places, events, documents, and/ or artefacts comprising the actual sources of information of the study, and the actual sites from which people were recruited.

Appraisal parameters	Presence +/–	Relevance +/–	Reviewer comments
1. Sample size and configuration fit the research purpose and sampling strategy.			
2. Sample size and configuration can support claims to informational redundancy, or theoretical or scene saturation.			
3. Sample size and configuration can support claims to the intensive and comprehensive study of particulars.			
4. Sample size and configuration support the findings.			
5. Sample composition is accurately and appropriately displayed in variable- and/ or case-oriented arrangements.			
6. Numbers are used appropriately to describe samples, as opposed to inappropriately used (e.g., as when a designation of "50% of the sample" refers to only two participants, or when only the mean or range is reported for participant ages that range from 18–70).			
7. Features of the sample critical to the understanding of findings are described, as opposed to not described (e.g., as when, in a study of homeowner low-carbon retrofit decision making, no information is offered on the achieved carbon reductions).			
8. The number of and reason why eligible participants refused to participate or left the study are described.			
9. Sites of recruitment fit the evolving sampling needs of the study.			

AA.5c. Data collection or generation techniques and sources

Extracting (regular font) or paraphrasing (italics) all information concerning sources of, or the techniques or procedures used to obtain or generate the data for the study in the following categories: interviews (including focus groups), observations, documents, and artefacts. Extracting or paraphrasing description of the: (a) purpose, place, and number per participant or event of interviews or observations; (b) type of, orientation to, and/ or manner of conducting interviews, observations, document reviews, or artefact study; and (c) (content, timing and sequencing of data collection or generation. Extracting or paraphrasing information about alterations in techniques and procedures made in the course of the study.

Appraisal parameters	Presence +/–	Relevance +/–	Reviewer comments
1. Sources of data and techniques of data collection or generation fit the evolving needs of the study.			
2. The content, sequence, and timing of fata collection or generation techniques fit the purpose and orientations of the study, as opposed to not fitting them (e.g., as when the purpose of the study is to understand homeowner retrofit decisions resulting in low-carbon dwellings, but the only sources of data are people who did not do low-carbon retrofit).			
3. Specific data collection or generation techniques were demonstrably tailored to the reported study, as opposed to the presentation of textbook or rote descriptions of data collection or generation with no application shown to the study reported.			
4. Data collection or generation techniques are accurately rendered, as opposed to inaccurately rendered (e.g., as when the observation of process that occurs during interviews and focus groups is presented as participant observation).			
5. The sources of data presented are demonstrably the basis of the findings, as opposed to not being their basis (e.g., as when document study is presented as a data collection strategy, but there is no evidence of its use).			
6. Data collection or generation techniques are correctly used, as opposed to misused (e.g., as when focus groups are conducted by asking each participant in turn to answer the same question, instead of posing a question to the group to stimulate group interaction.			
7. Sites are conducive to data collection or generation.			

(continued)

Appraisal parameters *(continued)*	**Presence** +/–	**Relevance** +/–	**Reviewer comments**
8. The time period for data collection or generation is explicitly stated.			
9. The timing for data collection or generation is vis-à-vis the target events featured in the study is explicitly stated (e.g., interviews were conducted within a year of retrofit completion).			
10. The timing of use of data collection or generation techniques vis-à-vis each other is explicitly stated (e.g. observations took place before the interviews).			

AA.5d. Data management and analysis techniques

Extracting (regular font) or paraphrasing (italics) descriptions of techniques or procedures used to: (a) create an audit trail of data; (b) prepare data for analysis; (c) catalogue, file, or organise data; and (d) break up, play with, display, and/or reconfigure data. Include the information on whether and how transcripts of interviews and field notes were prepared, whether and which computerised text management systems were used, the specific analytic approaches employed (e.g., content, constant comparison, narrative, discourse, or other analysis), and whether and how coding schemes, data matrices, and other visual displays of data were used.

Appraisal parameters	**Presence** +/–	**Relevance** +/–	**Reviewer comments**
1. Data management and analysis techniques fit the research purposes and data.			
2. Specific data management and analysis techniques were tailored to the reported study, as opposed to textbook or rote descriptions of data management and analysis being offered, with no application shown to the study reported.			
3. Data management and analysis techniques are accurately rendered.			
4. Data management and analysis techniques are correctly used.			
5. Analysis of data fits the data, as opposed to not fitting them (e.g., as when focus group data are analysed at the individual level and the analysis takes no account of group interaction).			
6. There is a clear description of how different data sets were analytically linked.			

AA.5e. Orientation to and techniques for maximising validity

Extracting (regular font) or paraphrasing (italics) information indicating view of, and techniques or procedures intended to optimise validity. Included here is information about the stated strengths and limitations of a study, and discussion of reflexivity, auditability, reliability, rigor, credibility, and plausibility, and of specific procedures implemented, such as member validation or peer review.

Appraisal parameters	**Presence** +/–	**Relevance** +/–	**Reviewer comments**
1. Researchers show an awareness of their influence on the study and its participants.			
2. The distinctive limitations of the study are appropriately summarised (e.g., theoretical sampling could not be fully conducted in a grounded theory study), or opposed to inappropriately summarised (e.g., as when researchers apologise for the so-called limitations of qualitative research).			
3. Techniques for validation are used that fit the purpose, method, sample, data, and findings, as opposed to using techniques that do not fit (e.g., as when reliability coding to ascertain consistency in interview data is used in a study emphasising the revisionist nature of narratives).			
4. Techniques used are tailored to the reported study, as opposed to presentations of textbook or rote descriptions of validation techniques with no application shown to the study reported.			
5. Techniques for validation are accurately rendered, as opposed to misinterpreted (e.g., as when triangulation for convergent validity is confused with using different data sources for informational completeness or to obtain multiple perspectives).			
6. Techniques for validation are correctly used, as opposed to incorrectly used (e.g., as when cases are kept in or dropped from consideration because they conform or do not conform to other cases).			

AA.5f. Protection of human subjects

Extracting (regular font) or paraphrasing (italics) descriptions of issues and practices relating to the recruitment, retention, and well-being of the human participants in a study. Included here is the information concerning how participants were approached and enrolled in the study, the informed consent procedures used, the benefits and risks participants were subjected to be virtue of being in the study, the inducements and protections offered them, and the way they responded to participation in the study.

Appraisal parameters	Presence +/–	Relevance +/–	Reviewer comments
1. Benefits and risks distinctive to the study reported are addressed, as opposed to textbook or rote description of human subjects issues being offered with no discussion of their particular relevance to the reported study.			
2. Recruitment and consent techniques were tailored to fit the sensitivity of the subject matter and/or vulnerability of participants.			
3. Data collection and management techniques were tailored to fit the sensitivity of the subject matter and/ or vulnerability of participants.			
4. Examples of data provided as evidence to support findings have analytical value or presenting participants fairly, as opposed to having only sensational value of presenting participants unfairly (e.g., as when only extreme incidents of events are presented).			

AA.6. RESULTS

AA.6a. Findings

Extracting (regular font) or paraphrasing (italics) all statements of what researchers "found" from the data they collected, or the results or interpretation of these data.

Appraisal parameters	Presence +/–	Relevance +/–	Reviewer comments
1. The report contains findings, as opposed to having no findings (e.g., as when data are presented with virtually no interpretation of them).			
2. Findings are distinguishable from other elements if the research report.			

(continued)

Appraisal parameters *(continued)*	**Presence** +/–	**Relevance** +/–	**Reviewer comments**
3. Interpretations of data are demonstrably plausible and/ or sufficiently substantiated with data collected for or generated in the study reported.			
4. Data is sufficiently (i.e., neither over- nor under-) analysed and interpreted.			
5. Findings address the ultimate purpose of the study reported, as opposed to not addressing it (e.g., as when the stated purpose of a study was to bring insights on how to promote low-carbon retrofit among UK homeowners, but the findings make no such attempt).			
6. Variations in findings by relevant sample characteristics are addressed.			
7. Variations in findings by time (in event and research trajectory) are addressed.			
8. Analysis is largely case-oriented, or oriented to the study of particulars, as opposed to variable-oriented, or quantitatively informed.			
9. Quantitative transformations of data are demonstrably in the service of qualitative interpretation.			
10. Ideas (e.g., concepts, themes) are precise, well developed, and linked to each other.			
11. The results offer new information about, insight into, or a reformulation of the target phenomenon.			

AA.6b. Logic and form of findings

Evaluate the presentational logic and form of the findings, including the literary and visual devices used to resent the study and its findings. Classify the findings as: (a) no finding (exclude from integration study); (b) surveys (topical or thematic); (c) synthesis (conceptual/ thematic descriptions or interpretive explanations).

Appraisal parameters	**Presence** +/–	**Relevance** +/–	**Reviewer comments**
1. The overall presentation of the study fits its purpose, method, and findings.			
2. Given the reporting style, elements of the research report are placed where readers are likely to find them.			

(continued)

Appraisal parameters *(continued)*	**Presence +/–**	**Relevance +/–**	**Reviewer comments**
3. Data are transformed into findings			
4. There is a coherent logic to the presentation of findings.			
5. Findings are organised in ways that do analytic justice to them, as opposed to not doing them justice (e.g., as when, in a rendering of retrofit experience, highly disparate ideas are dumped into one section, because all the experiences happened during the retrofit period).			
6. Visual displays, quotations, cases and numbers clarify, summarise, substantiate, or otherwise illuminate the findings, as opposed to being at odds with them (e.g., as when a path diagram shows a relationship between variables at odds with the relationship between them depicted in the text).			
7. The numerical meaning of such terms as “most”, “some”, “sometimes”, and “commonly” is clear.			
8. The empirical referent for a theme or concept is clear, as opposed to theme or concept being conflated with experience (e.g., as when the writer does not clarify whether the themes discussed are strategies to accomplish a goal, outcomes of having engaged in these strategies, typologies of behaviour, or milestones and turning points in a transition).			
9. Findings are presented in a comparative and parallel fashion, as opposed to a noncomparative or nonparallel manner (e.g., as when, in a typology, some types are presented as behaviours, while others are presented as character traits, and each type is not compared to every other type).			
10. Quotations are appropriately staged, as opposed to inappropriately staged (e.g., as when only “one woman said” and “another woman sad” lead into quotations).			
11. Titles of paper and section headers reflect their contents.			
12. The overall presentation of the study is audience-appropriate.			

AA.7. DISCUSSION AND CONCLUSIONS

Extracting (regular font) or paraphrasing (italics) statements summarising or drawing conclusions about the findings of the study, and indicating their transferability and theoretical, policy, disciplinary or other significance.

Appraisal parameters	Presence +/–	Relevance +/–	Reviewer comments
1. Discussion of findings is based on the findings presented, as opposed to being contrary to the findings or introducing new findings.			
2. Findings are linked to findings on other studies or to other relevant literatures either previously discussed or newly introduced.			
3. The policy, theoretical, disciplinary, and/ or other significance of the findings is thoughtfully considered, as opposed to indiscriminately considered (e.g., when repeating a study with other populations and/ or in other settings is recommended with no rationale).			
4. The extension to which the findings are transferable are clarified.			

AA.8. REVIEWER'S ABSTRACT AND SUMMARY APPRAISAL

Annotating the key features of the report without regard to what writers claimed for them.

Research purpose:

Theoretical framework:

Method:

Sample size and key characteristics:

Data collection techniques:

Data analysis techniques:

Primary topic of findings:

Secondary topic of findings:

(*continued)*

Type of findings:

- ☐ No finding (exclude from study);
- ☐ Topical survey;
- ☐ Thematic survey;
- ☐ Conceptual/ thematic description;
- ☐ Interpretive explanation.

Extracted and edited findings:

Evaluation:

- ☐ Acceptable (Signal > noise);
- ☐ Questionable (Noise > signal).

Summary comments:

Appendices B

Data collection process

These appendices provide additional detail on data collection process carried out for the thesis:

Appendix BA
Ethics approval confirmation

The research carried out in this thesis has been:

- Covered by the UCL Data Protection Registration, reference № Z6364106/2018/05/26 social research.
- Assessed for possible risks with Risk Assessment authorised, reference № [RA017999/1].
- Approved by the Bartlett (UCL Faculty of the Built Environment) Ethics Committee.

Appendix BB

Information sheet

This appendix contains a sample information sheet, which was utilised during interviewing. The information sheet sample starts on the next page.

Information sheet for SuperHomes owners

The following research has been approved by the Bartlett (UCL Faculty of the Built Environment) Ethics Committee.

THE ADOPTION PROCESS OF LOW-CARBON HOME RETROFIT AMONG UK HOMEOWNERS

Yekatherina Bobrova
PhD researcher
yekatherina.bobrova.12@ucl.ac.uk

Dr Nici Zimmermann
Lecturer in System Dynamics
n.zimmermann@ucl.ac.uk

UCL Institute for Environmental Design and Engineering

Invitation to participate

Dear SuperHome owner,

You are being invited to take part in a PhD research project. Before you decide it is important for you to understand why the research us being done and what participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

What's the purpose of this project?

There is a pressing need to reduce the greenhouse gas emissions of Britain's housing sector in order to mitigate climate change. Most of the energy used in housing is associated with heating, which is largely attributed to the level of energy efficiency of buildings. The degree to which retrofit in owner-occupied dwellings results in significant reductions in energy use and associated carbon emissions is still unclear. This research will work towards proving a clearer picture of the renovation decision-making process that results in a low-carbon retrofit, potentially clarifying how such decision-making process could be encouraged on a national scale.

Why have I been invited to participate?

You have been invited to participate in this study because you achieved significant carbon reductions in your house as a result of retrofit activities.

Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. You can withdraw at any time without giving a reason. If you decide to withdraw you will be asked what you wish to happen to the data, you have provided up that point.

What will happen if I take part?

You will be asked to participate in two interviews, each of which will take no more than one hour. The first interview will need to take place at your house for the researcher to familiarise herself with the retrofit works carried out. Both interviews will be audio recorded. Participants will be asked to walk with the researcher around the house and show the works that have been done. With your permission, photographs of the house will be taken.

What are the possible disadvantages and risks of taking part?

Taking part in this study involves the time taken for completing the interviews.

What are the possible benefits of taking part in the project?

Your participation is very valuable. By taking part in this study you will contribute towards understanding how we can encourage others to renovate their homes to low-carbon standards.

What if something goes wrong?

If you have any complains, e.g. regarding the treatment by the researcher, you should contact Nici Zimmermann (n.zimmermann@ucl.ac.uk). If you feel that your complaint has not been handled to your satisfaction, you can contact the Chair of the UCL Research Ethics Committee – ethics@ucl.ac.uk.

Will what I say in this study be kept confidential?

All information collected about you will be kept strictly confidential (subject to legal limitations). Your name and other identifiable information will be fully anonymised. You will not be able to be identified in any ensuing reports or publications. The data controller for this project will be University College London (UCL). The legal basis that would be used to process your personal data will be the provision of your consent. Your personal data will be processed so long as it is required for the research project. If you are concerned about how your personal data is being processed, please contact UCL in the first instance at data-protection@ucl.ac.uk. If you remain unsatisfied, you may wish to contact the Information Commissioner's Office (ICO). Contact details, and details of data subject rights, are available on the ICO website at: https://ico.org.uk/for-organisations/data-protection-reform/overview-of-the-gdpr/individuals-rights/

What will happen to the results of the research study?

The results of the research study will be written up as a part of Yekatherina's PhD thesis, who may see to publish extracts from it in reputable academic journals. If you would like copies of these please contact Yekatherina.

Many thanks for your early attention. I am looking forward to the possibility of working with you on this project.

Kind regards,
Yekatherina Bobrova

University College London
Gower Street London WC1E 6BT
W: http://www.bartlett.ucl.ac.uk/iede

Appendix BC

Informed consent form

This appendix contains a sample informed consent form, which was utilised during interviewing. The consent form sample starts on the next page.

Informed consent form

The following research has been approved by the Bartlett (UCL Faculty of the Built Environment) Ethics Committee.

THE ADOPTION PROCESS OF LOW-CARBON HOME RETROFIT AMONG UK HOMEOWNERS

Yekatherina Bobrova
PhD researcher
yekatherina.bobrova.12@ucl.ac.uk

Dr Nici Zimmermann
Lecturer in System Dynamics
n.zimmermann@ucl.ac.uk

UCL Institute for Environmental Design and Engineering

Lee Shailer
UCL's Data Protection Officer
data-protection@ucl.ac.uk

Thank you for your interest in taking part in this research. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you to decide whether to join in. You will be given a copy of the Information Sheet and this consent form to keep and refer to at any time.

PARTICIPANT'S STATEMENT

I confirm that I understand that by ticking/ initialling each box below I am consenting to this element of the study. I understand that it will be assumed that unticked/ initialled boxes mean that I DO NOT consent to that part of the study. I understand that by not giving consent for any one element that I may be deemed ineligible for the study.

- ☐ I confirm that I have read and understood the information sheet for the above study. I have had an opportunity to consider the information and what will be expected of me. I have also had the opportunity to ask questions which have been answered to my satisfaction

- ☐ I understand that if I decide at any time that I no longer wish to take part in this project, I can notify the researchers involved and withdraw immediately. I understand that if I decide to withdraw, any personal data I have provided up to that point will be deleted unless I agree otherwise.

(continued on the other side)

(continued)

- ☐ I consent to the processing of my personal information for the purposes of this research study. I understand that such information will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998. I understand that my data gathered in this study will be stored anonymously and securely. It will not be possible to identify me in any publications.

- ☐ I understand that the information I have submitted will be published as a report and I can receive a copy of it if I wish to.

- ☐ I understand that my participation will be taped recorded and I understand that the recordings will be destroyed when the project is complete.

- ☐ I agree that the research project named above has been explained to me to my satisfaction and I agree to take part in this study

Signature: Date:

University College London
Gower Street London WC1E 6BT
W: http://www.bartlett.ucl.ac.uk/iede

Appendix BD
Interview guides

This appendix contains three sample interview guides that were used for data collection:

BD(I)	Sample interview guide for investigating individual decision-making process resulting in low-carbon retrofit;
BD(II)	Sample interview guide to investigate development of psychological fatigue in the process of low-carbon home retrofit;
BD(III)	Sample interview guide to investigate retrofit goals and motivations leading to low-carbon home retrofit.

Interviews were carried in two stages. First interview guide was used during the first set of interviews, second and third interview guides were used in the second set of interviews. Despite the fact that interview guides two and three were both used during the second visit, the sample guides here are presented as stand-alone guides and can be used independently.

All three guides were developed for the purposes of this thesis. They are based on the original interview guide used in the FLASH project (2010–2012) developed by Dr. Lai Fong Chiu (Chiu et al., 2014).

BD(I). Investigating individual decision-making process resulting in low-carbon retrofit

BD(I) 1. BRIEFING SECTION

Relevant information has been sent to the participants before the interviews via email during recruiting process. Nevertheless, the briefing section is used to remind the participants why researchers are here and what they are going to do. Participants are provided with the Participant Information Sheet and agreement with the option to give their signed consent to participate.

- Introduction and brief chat. A brief summary of the research project and reiteration of its aims. Reassurance that there are no wrong answers and that the degree of their technical knowledge of the retrofit is not important.
- Reiteration that the interview will be recorded, a walkthrough will be conducted and photos may be taken. Permission will be sought for all of these aspects of the interview.
- Explanation of the arrangements for ensuring anonymity and confidentiality.

BD(I) 2. CONFIRMATION OF DETAILS

Some personal information has been obtained beforehand via the official website of the SuperHomes network. This section is used to confirm personal details and gather general information about household.

BD(I) 2.1. Contact Information

Name	…
Address	…
Email address	…

BD(I) 2.2. Household Characteristics

Household characteristics refer to the period of low-carbon retrofit activities only.

Household size	…
Household composition	Children / Adults / Elderly
Any changes in the number of people living here during the retrofit period?	New baby / Adult children living home / Multiple tenancy / …
Occupant(s) background: (What do you do profession-ally? What does your spouse/ partner does professionally?)	…

BD(I) 3. SIT DOWN SESSION

Gathering information on house configuration, structure type, internal and external conditions prior to retrofit; as well as the measures and equipment installed in the process of retrofit. Information is be obtained via asking the participants directly as well as mapping retrofit processes together with the participants.

BD(I) 3.1. Timing of the household's life in relation to the property

- When did you move here?
- How long are you planning to stay here?

BD(I) 3.2. Dwelling characteristics before the retrofit

- Please tell me a little bit more about the physical conditions of the house at the time you moved in order for me to understand the scope of the work undertaken.

Property type	Mid-terrace / End-terrace / Detached / Flat	
Number of rooms	…	
When was it built	…	
	What is it built of	***Insulation***
Wall	Brick / Stone / Wood / …	External / Internal / Cavity wall / …
Roof	…	Loft / External / …
Floor	Timber suspended / Concrete / …	…
Glazing type	Single / Double / Triple / …	
Heating system	Central heating / Gas boiler / Heat pump / … ▪ Do you use any secondary heating sources?	
Ventilation strategy	Natural / Mechanical / …	
Lighting type	Tungsten / Halogen / LED	
Energy generation technologies/ renewables	PV / Solar thermal / …	
Problems	Draught / Damp / Mould / Internal air quality issues / Unusual smells / …	

- When you first moved into the house, what were the physical features of the house you liked and what were the features you didn't like? Which did you want to improve? And why?

BD(I) 3.3. Retrofit process and dwelling characteristics after the retrofit

The participants are encouraged to describe the retrofit in chronological order. Retrofit-associated activities are mapped on the spot in front of the participants. The table of the dwelling characteristics after the retrofit is filled along the way.

- We have talked with you about the things you liked about your house when you first moved in. Now I would want to understand which changes you actually did and when. I would want you to tell me the changes you made in chronological order, so I can map them together with you on a timescale.
- How many phases did it take you to renovate the house?
- *[If the retrofit is done in more than one phase]* Did you plan the whole retrofit from the outset or did you plan each phase separately?

[The following questions are asked for each retrofit phase]

- When did you start this retrofit phase?
- How long did it take you to complete this retrofit phase?
- Which changes did you do and which measures did you install at this retrofit phase?

Wall insulation	External / Internal / Cavity wall / …
Roof insulation	Loft / External / …
Floor insulation	Timber suspended / Concrete / …
Glazing type	Single / Double / Triple / …
Heating system	Central heating / Gas boiler / Heat pump / …
Ventilation strategy	Natural / Mechanical / …
Lighting type	Tungsten / Halogen / LED
Energy generation technologies/ renewables	PV / Solar thermal / …
Problems	Draught / Damp / Mould / Internal air quality issues / unusual smells / …

- Did the sequence of retrofit phases correspond to the originally planned ones? If not, what was the difference?
- After all works were completed, was there anything you would have done differently or additionally?

BD(I) 3.4. Individual decision-making retrofit process

Gathering information regarding different stages of individual-decision making process that result in a low-carbon home retrofit.

- Could you distinguish particular phases in the preparation it usually took before proceeding with the retrofit? Could you please describe in detail such phases for one of the retrofit phases?
  - Why did you choose this particular measure?
  - Where did you find information about this measure?
  - Did you install the measure yourself or with the help of other, i.e. designers, builders, contractors? *[if installed by the interviewee himself/ herself]* How did you find out how this measure should be installed?
- What affected (positively or negatively) your decision processes and at which stages of the retrofit?
- Were there any obstacles you had to overcome to proceed with the retrofit at each retrofit phase and each preparation phase?

BD(I) 3.5. Low-carbon retrofit goals and associated post-retrofit living experience

Gathering information regarding the reasons for participants' intentions to live in low-carbon houses, as well as participants' live-in experiences associated with low-carbon retrofit.

- Could you tell me how the retrofit changed your living experience? I want to get a good understanding of what is it like to live in a SuperHome and how that experience is different to living in a non-energy-efficient house. Could you please try to recall any interesting everyday experiences specific to living in a SuperHome?
- I want to ask about your house being a part of a SuperHomes network. A house is eligible to join the network if at least 60% carbon reductions were achieved as a result of retrofit activities. Nevertheless, all of the houses in the network are unique and so are

individual stories behind each house retrofit. Could you tell me what does it mean specifically to you to live in a low-carbon house? For your house to be called a Super-Home?

BD(I) 4. ASSOCIATIVE EXPERIMENTS

Gathering information on what 'home' means to the participants as well as their feelings regarding the retrofit. Information is obtained via associative experiments.

BD(I) 4.1. Understanding meanings of home

- Could you tell me the first three words that come to your mind in an association with the word 'home'?

BD(I) 4.2. Understanding retrofit experience

- Could you tell me the first three words that come to your mind in an association with the words 'home renovation'?

BD(I) 5. WALK-THROUGH

The walk through allows the participants to recall more memories regarding the retrofit as they see the measures. Further information is collected via observation and taking pictures.

- Would it be ok if you take me/ us around your property? As we walk through could you please try to recall any interesting stories of how you came about thinking about one or another measure? I want to get a good understanding of how your thinking regarding retrofit unfolded over time. Would it be ok if I/ we take some photographs?

BD(I) 6. CLOSE INTERVIEW

- Explain that I/ we might need to get in touch with them to show preliminary results. Ask if that would be okay with them and ask how they are preferred to be contacted. Leave contact details for them.
- Thank them for their time and help.

BD(II). Investigating development of psychological fatigue in the process of low-carbon home retrofit

BD(II) 1. BRIEFING SECTION

Relevant information has been sent to the participants before the interviews via email during recruiting process. Nevertheless, the briefing section is used to remind the participants why researchers are here and what they are going to do. Participants are provided with a new Participant Information Sheet and a new agreement with the option to give their signed consent to participate.

- Introduction and brief chat. A brief summary of the research project and reiteration of its aims. Reassurance that there are no wrong answers.
- Reiteration that the interview will be recorded. Permission will be sought for this aspect of the interview.
- Explanation of the arrangements for ensuring anonymity and confidentiality.

BD(II) 2. CONFIRMATION OF DETAILS

Personal information has been obtained beforehand during the first interview. This section is used to confirm personal details and update if necessary.

Contact Information

Name	…
Address	…
Email address	…

BD(II) 3. CONFIRMATION OF PRELIMINARY RESULTS

This section is used to share the preliminary results obtained from the analysis of the previously conducted interview. The researcher shows and explains the following diagrams specific for a particular case: (i) retrofit process; (ii) five stages of individual retrofit decision-making; (iii) causal map of individual retrofit process. The participants are asked to give feedback on how well the researcher understood their experience. Such feedback is used to increase validity of the derived explanation.

- I would want to share with you the preliminary results obtained from the analysis of the interview that was carried out previously. It is important for me to get your feedback on how well I understood your experience. So, please feel free to provide any comments on the results that I will be presenting. I will present you with three diagrams that show: (i) the timeline of your retrofit activities; (ii) different stages of your retrofit decision-making process, as well as different influences affecting your retrofit decisions at different stages; (iii) a causal map of your retrofit activities.

[The following questions are asked for each diagram]

- Did I interpret your experience correctly? Did I miss anything? Is there anything you want me to remove from the diagram or add to it? And why?

BD(II) 4. UNDERSTANDING RETROFIT EXPERIENCE

Gathering information on the household's experience of the retrofit process, needed to explain why some homeowners developed retrofit-associated fatigue and consequently formed a negative impression of their retrofit experience, while others did not. Information is obtained via asking the participants directly open and closed type questions.

BD(II) 4.1. State of the house before and after retrofit, meeting retrofit goals

Gathering information about the state of the house before retrofit and what has actually been achieved at each retrofit stage (if more than one).

[Question 1. State of the house before retrofit]

- You did extensive retrofit works on the house to make it your own and for it to be able to support your needs. Obviously, before the retrofit, the state of the house (internal layout configuration, state of repair and decoration) was far from what you would have wanted it to be. On a scale from 1 to 7 how would you best describe the state of the house before all retrofit works?

Ability to support household's needs and everyday activities

1 D*	2 D*	3 D*	4 LC*	5 LC*	6 LC*	7 LC*
Unsafe	*Inadequate*	*Non-sustainable*	*Basic amenities*	*Comfortable*	*Pleasant*	*Almost ideal*

A match between the household's taste and the style/ decoration of the house

1	2	3	4	5	6	7
None	*Inadequate*	*Few*	*Neutral*	*Some elements*	*Good*	*Perfect*

* D refers to 'state of disrepair', LC refers to 'liveable conditions'

- Could you say a bit more about why did you choose these numbers?

[The questions in the rest of the subsection are asked for each retrofit phase if more than one]

[Question 2. State of the house after retrofit]

- The overall retrofit was carried out in x-number of stages. On a scale from 1 to 7 how would you best describe the actual achieved state of the house after the retrofit/ each individual retrofit phase?

Ability to support household's needs and everyday activities

1 D*	2 D*	3 D*	4 LC*	5 LC*	6 LC*	7 LC*
Unsafe	*Inadequate*	*Non-sustainable*	*Basic amenities*	*Comfortable*	*Pleasant*	*Almost ideal*

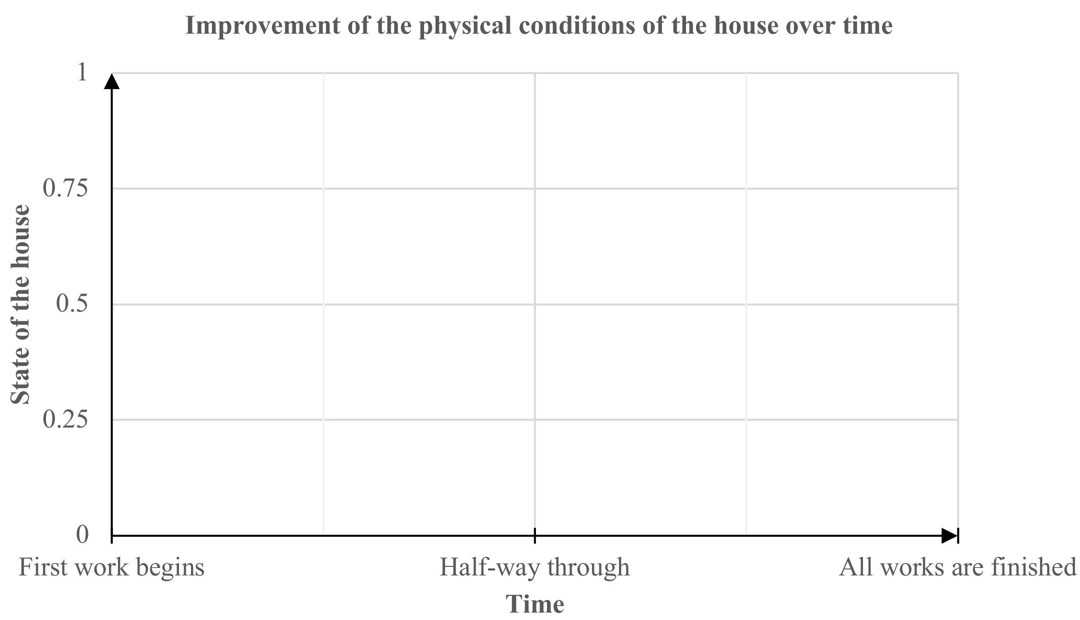
A match between the household's taste and the style/ decoration of the house

1	2	3	4	5	6	7
None	*Inadequate*	*Few*	*Neutral*	*Some elements*	*Good*	*Perfect*

* D refers to 'state of disrepair', LC refers to 'liveable conditions'

- Could you say a bit more about why did you choose these numbers?

- The overall retrofit was carried out in x-number of stages. Let's conceptualise the state of the physical conditions of the house as 0 in the beginning of the retrofit, and as 1 after all the works were complete. Could you draw on the graph below how much improvement has been achieved at each phase of the retrofit?



- Could you say a bit more about this variation?

BD(II) 4.2. Goal erosion

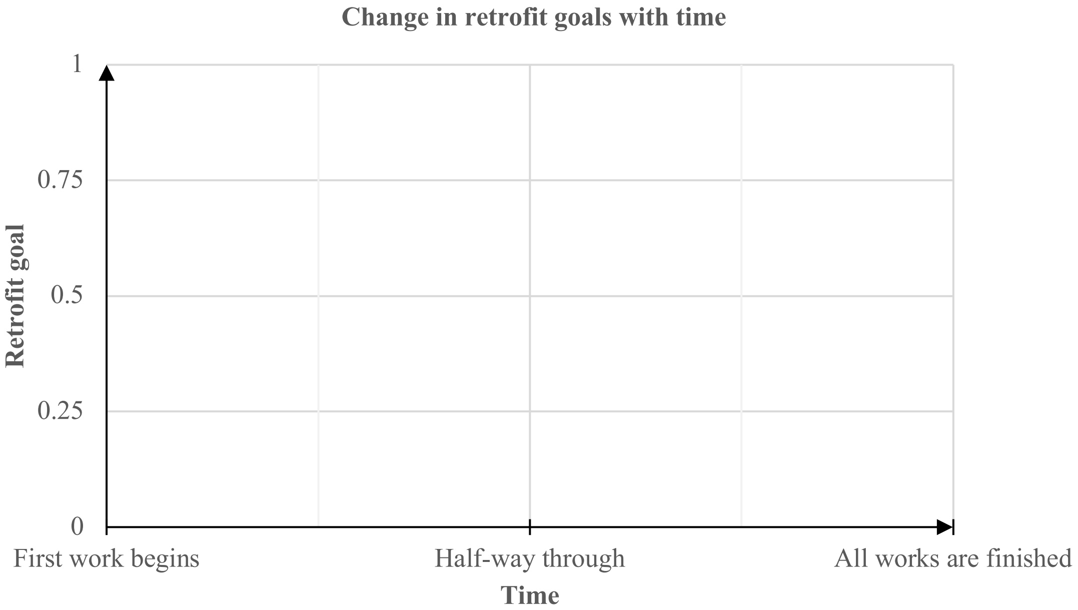
Gathering information about how retrofit goals change with time.

- It is possible that not everything that was initially envisioned got realised during home retrofit. Did you change the scope of the works with time?

[The questions in the rest of the subsection are asked if the scope of the works have been changed]

- Could you describe in a bit more detail what were the ideas that you dropped from the initially planned scope of works? Could you describe in more detail why did you decide not to carry on with these works?
- Could you say that achieved result is less ambitious than what was initially planned? In other words, is it a compromise?

- Let's conceptualise your initially intended scope of works as 1 on a scale from 0 to 1. Which number on the same scale would you assign to the actually achieved scope of works? It probably took you some time to abandon your initial intentions and settle for a lower goal. Could you draw on a graph below the change with time of your initial intentions from ideal 1 to the compromised goal?



- Could you say a bit more about this variation?

BD(II) 4.3. Perceived benefits and intrinsic motivation

Gathering information about perceived benefits of the retrofit outcomes, as well as how much the owners enjoyed the retrofit process itself.

[Question 3. Motivation]

- Home retrofit is a self-initiated activity. Undoubtedly, you embarked on the retrofit journey because you thought it would have been beneficial to you to go through this journey and complete the retrofit. On a scale from 1 to 7 how important was it for you to see the project through to completion?

1	2	3	4	5	6	7
Not important	*Majorly not important*	*Rather non-important*	*Indifferent*	*Rather important*	*Many aspects are important*	*Highly important*

- Could you say a bit more about why did you choose this number?

- All activities come at a cost, usually in terms of effort, time and money required. Could you describe a hypothetical situation when you would have stopped the retrofit after you already started it? What should have happened for you to change the plans and not to pursue the retrofit any longer after the works have already begun?

[Question 4. Intrinsic satisfaction from the process]

- It is possible to enjoy the retrofit activity itself. At the end of the day it is an opportunity to learn something new and build some new expertise. Could you say that you had a pleasure from just doing this project? What was it you enjoyed? On a scale from 1 to 7 how much did you enjoy the project?

1	2	3	4	5	6	7
Absolutely didn't enjoy	*Majorly not enjoyed*	*Rather didn't enjoy*	*Indifferent*	*Rather enjoyed*	*Enjoyed many aspects*	*Highly enjoyed*

- Could you say a bit more about why did you choose this number?

[Question 5. Satisfaction from the job well done]

- It is natural to feel satisfaction with the job well done. On a scale from 1 to 7 how much of this kind of satisfaction did you feel about your retrofit/ retrofit phase?

1	2	3	4	5	6	7
Very dissatisfied	*Dissatisfied*	*A bit dissatisfied*	*Neutral*	*Somewhat satisfied*	*Satisfied*	*Very satisfied*

- Could you say a bit more about why did you choose this number?

BD(II) 4.4. Theoretical and practical knowledge regarding retrofit, and control over activity

Gathering information regarding the pre-retrofit level of homeowners' theoretical and practical knowledge necessary to carry out the retrofit works, as well as the change in such knowledge with time. Information is also gathered regarding the homeowners' perceived control over what, how and when to do.

[The questions in this subsection are asked for each retrofit phase]

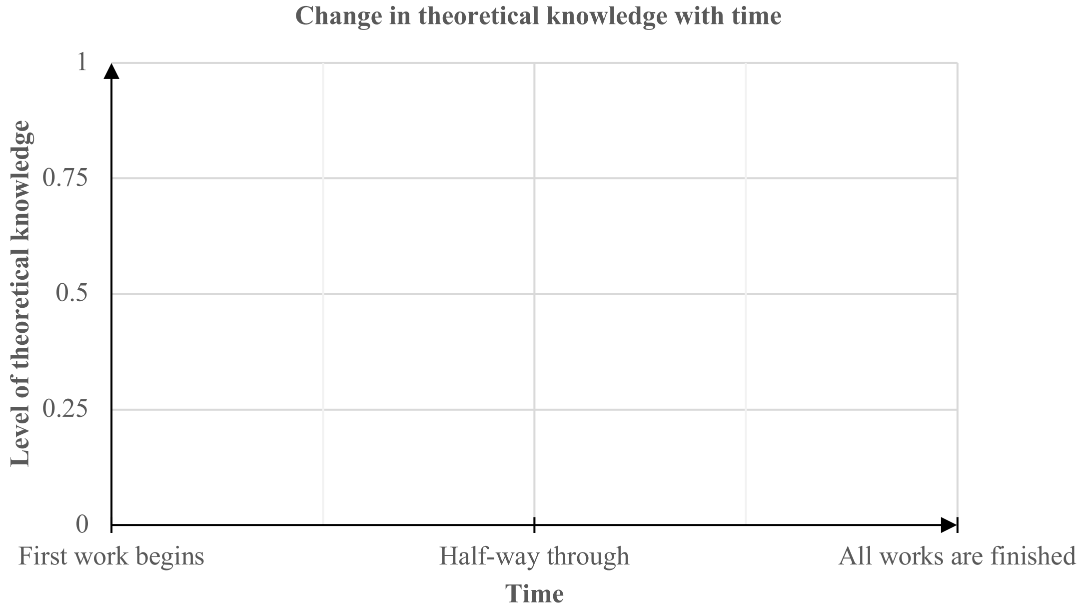
[Question 6. Theoretical knowledge before retrofit]

- Low-carbon home retrofit requires a lot of theoretical knowledge regarding the options available to achieve desired intentions. On a scale from 1 to 7 how good was your theoretical knowledge before you started the project?

1	2	3	4	5	6	7
Dangerously incorrect knowledge	*Majorly incorrect knowledge*	*Somewhat incorrect knowledge*	*No specific knowledge*	*Some useful knowledge*	*Good knowledge*	*Expert knowledge*

- Could you say a bit more about why did you choose this number?

- You have gathered information throughout your retrofit experience and increased your knowledge sufficiently enough to see the works through to completion. Let's conceptualise your initial level of knowledge as 0 on a scale from 0 to 1, and your final level of knowledge as 1 on the same scale. It is very likely that knowledge accumulation did not resemble a linear graph, but rather a steep learning curve. Could you draw on a graph below the change in your theoretical knowledge from 0 to 1 with time?



- Could you say a bit more about this variation?

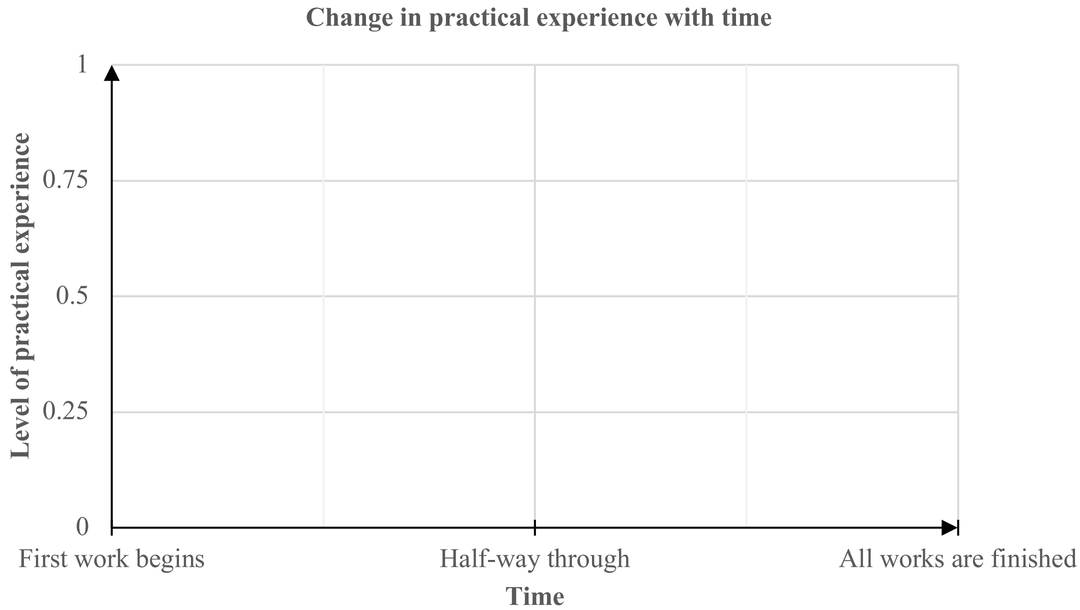
[Question 7. Practical knowledge before retrofit]

- Low-carbon home retrofit requires a good practical experience of such works from the retrofit team. You were an integral part of the retrofit team at least in the tasks of project management and sourcing materials. On a scale from 1 to 7 how good was your practical experience of low-carbon home retrofit before you started the project?

1	2	3	4	5	6	7
Dangerously misleading experience	*Majorly misleading experience*	*Some misleading experience*	*No specific experience*	*Some useful experience*	*Good experience*	*Expert experience*

- Could you say a bit more about why did you choose this number?

- You and your team have learned through the project and your experience was at the end sufficient so the project was completed successfully. Let's conceptualise your initial level of practical experience as 0 on a scale from 0 to 1, and your final level of experience as 1 on the same scale. It is very likely that experience accumulation did not resemble a linear graph, but rather a steep learning curve. Could you draw on a graph below the change in your experience from 0 to 1 with time?



- Could you say a bit more about this variation?

[Question 8. Control of what when and how to do]

- It is important to feel in control of what you are doing. However, in the retrofit project it is not always possible to have full control: sometimes the information is not available to you and there is no understanding how such information could be sourced; sometimes you are constrained to do only the type of jobs your local builder is comfortable doing; sometimes you can not source the right materials at the local market; sometimes you can not postpone the retrofit as you are pressured to finish it as soon as possible to, as prolonging the retrofit would mean you need to pay builders and tradespeople for a longer period of time. Now in retrospect, on a scale from 1 to 7 how much control do you perceive you had over the retrofit, in terms of what to do, when to do and how to do? Please note that I am combining a few concepts on one scale (what to do, when to do, how to do). You can rate them altogether on an aggregate level, or you can rate each of them individually on a scale from 1 to 7.

1	2	3	4	5	6	7
None	*Inadequate*	*Limited*	*Just about adequate*	*Good*	*Very good*	*Absolute*

- Could you say a bit more about why did you choose this number?

BD(II) 4.5. Motivational control and performance regulation

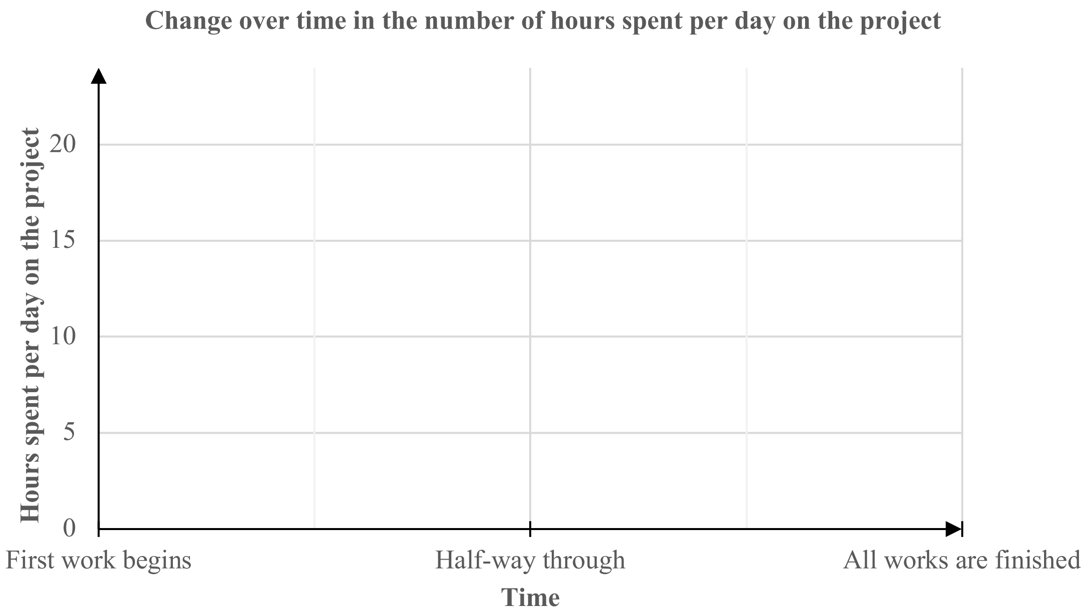
Gathering information regarding amount of effort required to see the project through to completion and strategies employed to reach the goals.

[The following questions are asked for each retrofit phase]

- It is only a limited amount of time in a given day. A lot of retrofit activities are done after a full-time job. How much time per day you initially thought you will need to spend on the retrofit/ retrofit phase? How many days/ weeks/ months did you think it will take you to finish your retrofit/ retrofit phase?
- No project goes exactly as planned. It is usual to plan some extra time for a big project in case something goes wrong and it will be needed. How much of extra time you thought it might be needed and, therefore, planned for it in advance?
- Now after the project is complete could you please reflect on how good was your initial estimation of the time required for the project? How much time did you actually spent on the project (per day, as well as how many days/ weeks/ months)?

[The following questions are asked if more effort/ time is spent than initially anticipated]

- Why did you need this extra time?
- Let's conceptualise the effort you made to finish the project in terms of time per day and overall time required for the project. There are 24 hours in any given day. Could you draw on the graph below how the amount of time per day you allocated to the project changed as the project progressed?



- Could you say a bit more about this variation?
- How long did it take you to free up your time, cancel other engagements and activities and be able to put more time into the retrofit?

- Did it take you overall longer to complete the project? For instance, two years, instead of initially planned one? How long did it take you to understand that the project will need more time than initially planned?
- You chose to spent more time per day rather than taking longer to complete the project (or vice versa, or both). Please explain the choice of the strategy.
- *[If more time were spent per day]* Do you think it was efficient use of the time or do you think you would have done a better job if you were more rested (worked smaller amount of time per day, but greater amount of days)? Now looking retrospectively, what do you think would have been the most efficient way to spend your time on the project? Please explain.

- *[If the retrofit was done in more than one phase]* Did your estimation of time and effort needed for the retrofit improved after each retrofit phase? Please explain.

BD(II) 4.6 Retrofit-related feeling of fatigue

Gathering information regarding the level of stress and fatigue associated with the retrofit experience.

[The questions in this subsection are asked for each retrofit phase]

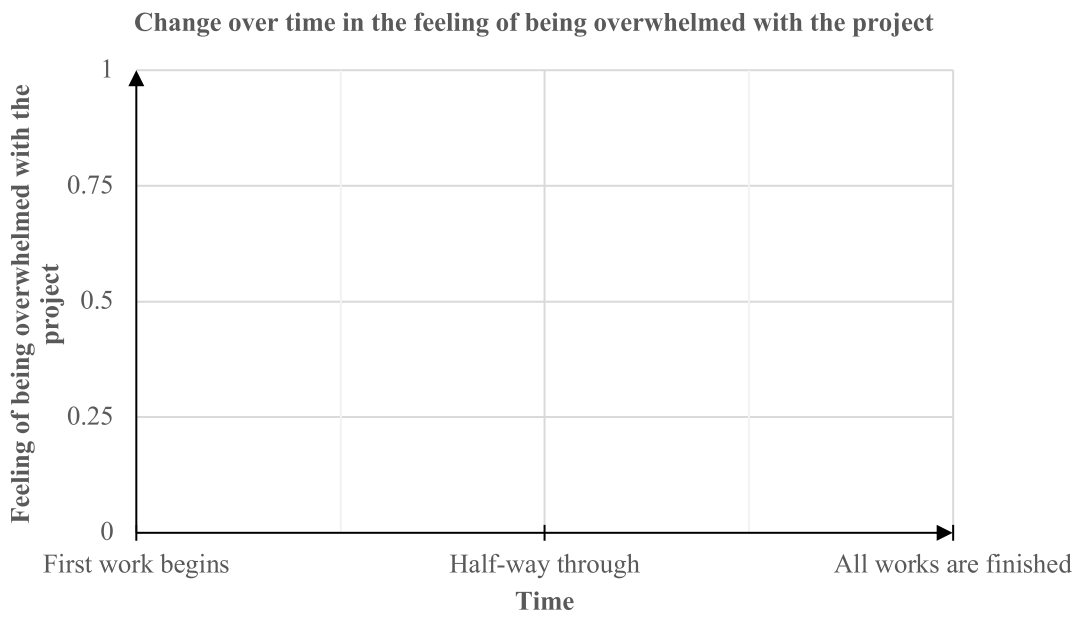
[Question 9. Maximum feeling of fatigue from the project]

- Retrofit could be an overwhelming experience. Did you at any point of the project felt overwhelmed and tired, or even regretted you embarked on the project altogether? On a scale from 1 to 7 how would you rate the feeling when you were the most overwhelmed with the project? Please note that I am combining a few concepts on one scale (being overwhelmed and being tired). You can rate them altogether on an aggregate level, or you can rate each of them individually on a scale from 1 to 7.

1	2	3	4	5	6	7
An easy job to do	*It was a lot easier than I thought*	*It was a bit easier than I thought*	*Neutral*	*A bit tired*	*Very tired*	*Completely unbearable*

- Could you say a bit more about why did you choose this number?

- So, this is how you rated the point in the retrofit when you felt most overwhelmed. It is, however, likely that this feeling varied over time. Let's conceptualise your feeling of being overwhelmed with the project from 0 to 1, with 0 being the state in the beginning of the project, when you just started and were full of energy, and 1 is the point when you felt most overwhelmed. Could you draw on the graph below how this feeling of being overwhelmed with the project varied over time?



- Could you say a bit more about this variation?
- How did you cope with the feelings of being tired and overwhelmed with the project? What kept you going? How did you recover from these feelings?
- After a period of highly demanding activity, such as retrofit project, it is common to disengage from other effortful activity immediately after the current one is finished. Did you feel something like that after the retrofit works were complete? Please say a bit more about it.
- Do you think you will be ready to do such a challenging project again in your life? When do you think it will be? And why?

BD(II) 5. CLOSE INTERVIEW

- Explain that I/ we might need to get in touch with them to show preliminary results. Ask if that would be okay with them and ask how they are preferred to be contacted. Leave contact details for them.
- Thank them for their time and help.

BD(III). Investigating retrofit goals and motivations leading to low-carbon home retrofit

BD(III) 1. BRIEFING SECTION

Relevant information has been sent to the participants before the interviews via email during recruiting process. Nevertheless, the briefing section is used to remind the participants why researchers are here and what they are going to do. Participants are provided with a new Participant Information Sheet and a new agreement with the option to give their signed consent to participate.

- Introduction and brief chat. A brief summary of the research project and reiteration of its aims. Reassurance that there are no wrong answers.
- Reiteration that the interview will be audio recorded, a walkthrough will be conducted and photos may be taken. Permission will be sought for all of these aspects of the interview.
- Explanation of the arrangements for ensuring anonymity and confidentiality.

BD(III) 2. CONFIRMATION OF DETAILS

Personal information has been obtained beforehand during the first interview. This section is used to confirm personal details and update if necessary.

Contact Information

Name	…
Address	…
Email address	…

BD(III) 3. TEN ITEM PERSONALITY INVENTORY (TIPI)

Gathering information on personality traits. Information is obtained via asking the participants directly closed type questions.

- Here are a number of personality traits that may or may not apply to you. Please choose a number for each statement to indicate the extent to which you agree or disagree with that statement. You should rate the extent to which the pair of traits applies to you, even if one characteristic applies more strongly than the other.

1	2	3	4	5	6	7
Disagree strongly	*Disagree moderately*	*Disagree a little*	*Neither agree nor disagree*	*Agree a little*	*Agree moderately*	*Agree strongly*

I see myself as

1. ___ Extraverted, enthusiastic.
2. ___ Critical, quarrelsome.
3. ___ Dependable, self-disciplined.
4. ___ Anxious, easily upset.
5. ___ Open to new experiences, complex.
6. ___ Reserved, quiet.
7. ___ Sympathetic, warm.
8. ___ Disorganised, careless.
9. ___ Calm, emotionally stable.
10. ___ Conventional, uncreative.

BD(III) 4. ASSOCIATIVE EXPERIMENT

Gathering information on what 'home' means to the participants, their feelings regarding the retrofit; the feelings of retrofit associated stress and fatigue. Information is obtained via associative experiments.

BD(III) 4.1. Understanding meanings of home

- Could you tell me all the words that come to your mind in an association with the word 'home'?

BD(III) 4.2. Understanding retrofit experience

- Could you tell me all the words that come to your mind in an association with the words ‘low-carbon home’?
- Could you tell me all the words that come to your mind in an association with the words ‘low-carbon retrofit process’?

BD(III) 5. UNDERSTANDING MEANINGS OF HOME

Gathering information on the meanings participants attach to their homes, needed to get a deeper understanding of retrofit goals and outcomes. Information is obtained via asking the participants directly open and closed type questions.

- What is you like most about your house? Why?
- What is it you are most proud of about your house? Why?

BD(III) 5.1. Aesthetical appeal

- What was it you liked in your house when you bought it [before the retrofit] from the aesthetical point of view? Why?
- What is it you like in the house now [post retrofit] from the aesthetical point of view? Why? What is it you like the most?

BD(III) 5.2. Social practices

- Which are the areas you spend most of your time at home?
    - Which are the areas you spend most of your time individually (alone)? How do you spend your time there? Why do you choose this/ these place(s) to spend you time alone? How does this/ these place(s) help you to enhance the experience of the activities you described?
    - Which are the areas you spend most of your time with your family? How do you spend your time there? Why do you choose this/ these place(s) to spend you time with your family? How does this/ these place(s) help you to enhance the experience of the activities you described?
    - Which are the areas you spend most of your time with your friends? How do you spend your time there? Why do you choose this/ these place(s) to spend you time with your friends? How does this/ these place(s) help you to

enhance the experience of the activities you described?

BD(III) 5.3. Dream home

- Could you please describe what your ideal home looks like?
  - How does it look?
  - Who lives there?
  - What do you do there? Alone/ with the family/ with friends?
  - What are the spatial arrangements of your ideal home? How do these spatial arrangements support the activities you described earlier?

BD(III) 6. UNDERSTANDING PRACTICES AFFECTING DOMESTIC RESOURCE USE

Gathering information on domestic practices that affect resource use. Information is obtained via asking the participants directly open and closed type questions.

- Home is a place of comfort. However, comfort is not something given, but rather something people achieve through performance of different routines. These routines often require the use of resources, such as energy, water and materials. I would like to ask you some questions about different routines you use to achieve comfort, the associated use of resources to achieve such comfort and the role of technology as well as behavior in reducing resource use.
  - Let’s talk about thermal comfort. What are your heating/ cooling routines? How do you minimise energy use associated with these routines? How do you see the role of the physical structure of the house and technology in minimising associated energy use while achieving thermal comfort? How do you see the role of behavioural adaptation in minimising associated energy use while achieving thermal comfort?
  - Let’s talk about indoor air quality. What are your routines for ventilation and moisture control? How do you minimise energy use associated with these routines? How do you see the role of the physical structure of the house and technology in minimising associated energy use while achieving good indoor air quality? How do you see the role behavioural adaptation in minimising associated energy use while achieving good indoor air quality?
  - Let’s talk about lighting comfort. There are many routines both individual

and social that would require comfortable lighting conditions. How do you minimise energy use associated with lighting? How so you see the role of the physical structure of the house and technology in minimising associated energy use while achieving comfortable lighting conditions? How so you see the role of behavioural adaptation in minimising associated energy use while achieving comfortable lighting conditions?

- Let's talk about electricity use by appliances. There are many routines both individual and social that would require the use of electrical appliances. How do you minimise energy use associated with the use of electrical appliances? How do you see the role of the physical structure of the house and technology in minimising associated energy use while achieving maintaining comfortable level of appliances use? How do you see the role of behavioural adaptation in minimising associated energy use while achieving maintaining comfortable level of appliances use?
- Let's talks about water consumption. There are many practices such as cooking or showering, that require water use. How do you minimise water use in your house? How do you see the role of the physical structure of the house and technology in minimising water use? How do you see the role of behavioural adaptation in minimising water use?

BD(III) 7. WALK-THROUGH

The walk through allows the participants to recall more memories regarding the places and features they like in the house. Further information is collected via observation and taking pictures.

- Would it be ok if you take me/ us around your property?
  - As we walk through could you please try to recall any other interesting stories about what you like about your house, why and how does your home support you in your day-to-day needs? I want to get a good understanding of what you value in your home in both: sustainability and non-sustainability-related dimensions.
  - Could you show me which part of the home's decoration/ layout is truly representative of who you are as an individual? Which part of the home that say "it is you"?
    - Could you tell me a bit more about the magnets on the fridge? What

are they and what do they mean for you?

- Would it be ok if I/ we take some photographs?

BD(III) 8. CLOSE INTERVIEW

- Explain that I/ we might need to get in touch with them to show preliminary results. Ask if that would be okay with them and ask how they are preferred to be contacted. Leave contact details for them.
- Thank them for their time and help.

Appendix BE
Example of behaviour-over-time graph

This appendix gives an example of behaviour-over-time graph from case G. The participant was asked to draw the development of her feeling of being overwhelmed with the project during the time course of the retrofit (Figure BE.1). The graph is displayed on the next page.

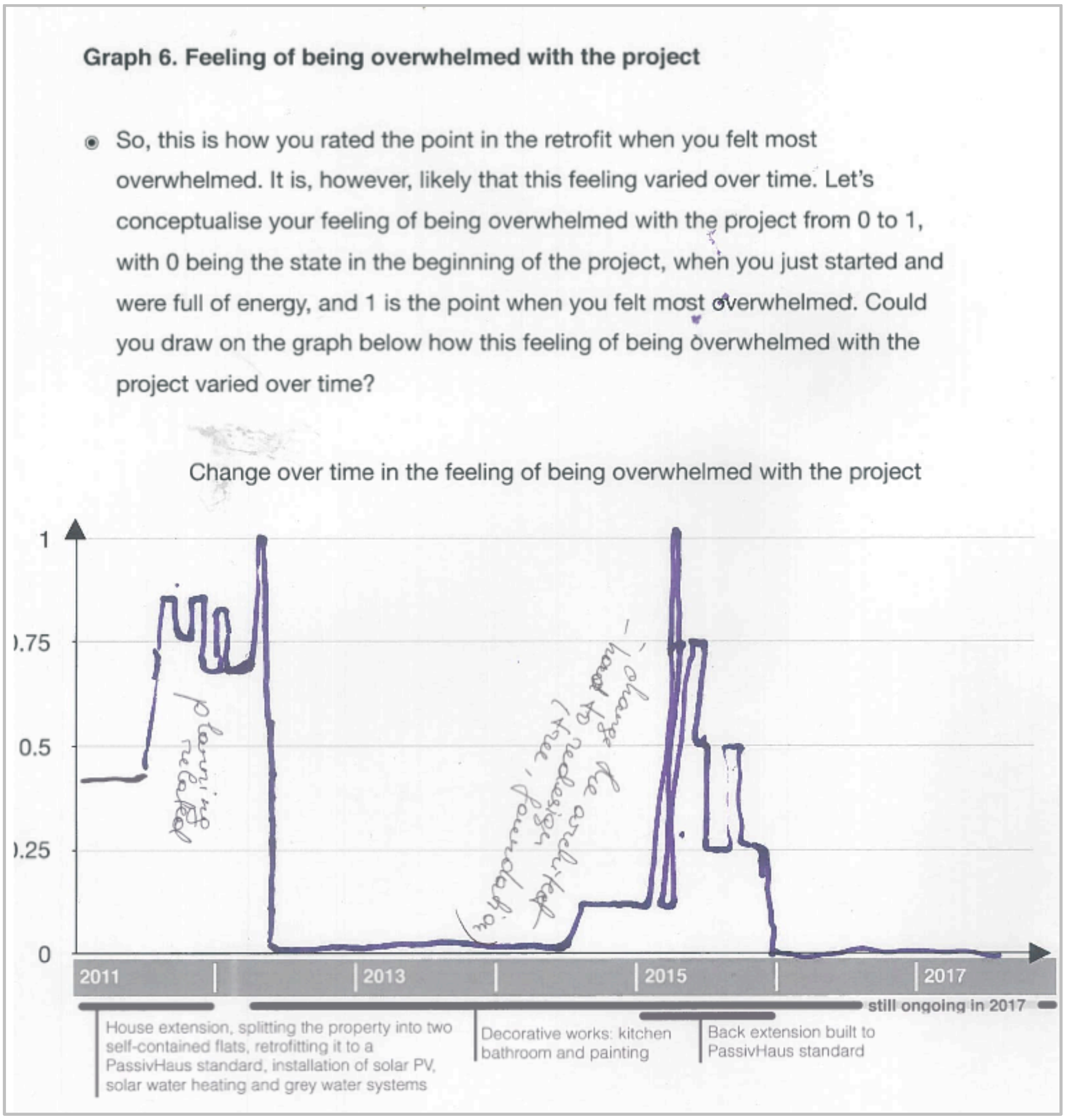


Figure BE.1. Behaviour-over-time graph of the feeling of fatigue, drawn by the participant in case G during the interview

Appendices C

Qualitative analysis process

These appendices give an insight in the qualitative analysis process, by exemplifying the type of records generated by the process:

CA.	Sample/ population comparison
CB.	Case reports
CC.	Example of an interview transcript
CD.	Example of an analytical matrix
CE.	Example of an analytical causal diagram
CF.	Retrofit-decision process diagrams

Appendix CA
Sample/ population comparison

This appendix provides a comparison of dwellings and households characteristics between the project sample and the SuperHomes population (Table CA.1). The data for the SuperHomes population is compiled based on the survey results, carried out by Fawcett and Killip (2014). The survey sample is 57 households. The questionnaires were completed during July 2013. At the time of the survey, the total number of SuperHomes owners were 130. The recruitment target was 50 completed questionnaires. Respondent numbers reached 57 after 70 SuperHomes owners had been contacted (81% response rate).

Table CA.1. Comparison of the project sample with the SuperHomes owners population

Typological and physical characteristics of the dwellings		Project sample (8 households)	Population sample (57 households)
Conservation area		A, B, D, F	11 (19%)
Dwelling type	Detached house	F	18 (31.5%)
	Semi-detached house	C, G, H	22 (38.5%)
	Terraced house	A, B, D, E	9 (16%)
	Other		8 (14%)
House age	Before 1919	A, D, E	29 (51%)
	1919–44	B, C, G, H	10 (17.5%)
	65–80	F	7 (12%)
	Other		11 (19.5%)
Number of bedrooms	2	A	5 (9%)
	3	B, C, D, G, H	24 (42%)
	5+	E, F	14 (24.5%)
	Other		14 (24.5%)
Characteristics of the household		**Project sample (8 households)**	**Population sample (57 households)**
Adults living in the house	1	D	3 (5.2%)
	2	B, C, F, G	34 (61%)
	3	E, H	16 (28%)
	4	A	3 (5.2%)
	No answer		one
Children living in the property	0	A, C, H	29 (54%)
	1	D	10 (18%)
	2	B, E, G	14 (26%)
	3	F	0 (0%)
	4		1 (2%)
	No answer		three
Employment	Full time paid work	A, B, C, D, E, F, G	25 (45%)
	Retired	H	9 (16%)
	Other		22 (39%)
	No answer		one
Ethnic background	White – British	C, D, F, H	47 (84%)
	White – Other	A, B, E, G	6 (11%)
	Other		3 (5.2%)
	No answer		one

Appendix CB
Case reports

This appendix provides reports of each case with the information about the household, the state of the dwelling before and after retrofit, description of the timeline of each retrofit as well as the stages of individual decision processes according to Rogers (2003): *knowledge*, *persuasion*, *decision*, *implementation* and *confirmation*.

CB.1. CASE A

CB.1a. Dwellings and households' characteristics, timelines. Case A

<u>Information about the household</u>
The owners do not live in the property, but rent it out. The owner is an architect, who intends to rent out the apartment for at least next 10 years. There are four individuals living in the apartment. The owner has professional knowledge and experience of retrofit.

<u>Information about the house and its state before the retrofit</u>
The house is an end of terrace Victorian Mews House located in a conservation area in Camden, London. The original building built in late 19th century consisted of a home and a hay store. The layout of the property has changed since then a number of times. By the time the property was purchased by the current owner, the first floor and the hay loft were converted into a flat, in which living and sleeping spaces were mixed between the two floors. This layout was significantly changed during the renovation. The property retained many of the original features of the Victorian Mews house, which charmed the owners into purchasing it in the first place. They wanted to preserve the original fabric as much as possible while bringing the building closer to the modern standards of sustainability and energy efficiency.

The house was not energy-efficient, but it was not in a bad state of repair and was perfectly liveable. The property featured solid brick walls and single glazed sash windows. There was no insulation throughout and there was no heating on the ground floor. There were no problems with mould or condensation.

The retrofit timeline

The owners bought the house in late 2011, but the works did not start until February 2012. The owners took their time to plan the works ahead as well as to obtain the planning permission. The property was retrofitted in two stages. During the first stage the ground floor was converted into an architectural studio and during the second stage the upper two floors were converted into a four-bedroom, two bathrooms' maisonette. Apart from the layout, the structural changes included an introduction of an additional dormer upstairs. Original Victorian features were reused and upgraded to higher thermal performance criteria. Draught-proofing was carried out throughout. Thin double-glazed units were fitted for the windows, doors were insulated with vacuum-based insulation materials. All external walls and roof were internally insulated with foil-sided polystyrene insulation, which improved not only the level of insulation, but also the level of air-tightness. The new mechanical services included solar thermal and two MVHR units. Energy-efficient fluorescent lighting and A-rated appliances were introduced throughout. All the works were completed in August 2012, at which point the first new tenants were moved in.

The state of the house after the retrofit

The energy efficiency improvements throughout the property resulted in comfortable thermal conditions and minimal use of heating, even during the winter. After the retrofit the building was up to Level 4 standard for the Code for Sustainable Homes. 75% of carbon savings has been achieved as a result of the retrofit. The house has been visited and assessed by a representative of a SuperHomes network, who confirmed the values achieved.

There is no separate utility room and the tenants have to dry their clothes in the bedrooms or bathrooms. Regardless of that fact, the property is well-ventilated and completely condensation and damp free. Having an open plan kitchen and living room upstairs meant that the kitchen/ living space area benefit from light throughout the day, while bedrooms remain smell free.

CB.1b. Stages in retrofit decision-making process. Case A

Felt needs

The owner thought that the building was used inefficiently both spatially and pragmatically, and was looking to redesign it spatially, so it could accommodate a family of four and a work studio.

She planned to rent the property out from the beginning. The owner took the opportunity to improve the energy efficiency of the building. The owner is a professional architect and she took this opportunity to improve her portfolio and increase her professional credentials. The owners wanted to retain the character of the building, upgrade it to a modern standard of energy efficiency and maintain a good quality of indoor air. These considerations together with a desire to change the layout of the property was seen as an opportunity to increase the property's value. The character of the building was maintained through recycling, reusing and restoring original features.

<u>Knowledge, persuasion, decision and implementation stages</u>

The owner of the house is a professional architect. She planned it and carried it out as a usual project. She had to obtain a planning permission, come up with a conceptual idea of the design, make detailed plans of the renovation details and supervised the construction. There were some elements in the projects that required some research, but there were no problems reported. The owner needed to acquire planning permission for the retrofit as the property is located in the conservation area.

<u>Confirmation stage</u>

The tenants are happy with thermal comfort and indoor air quality. They also report that the property feels bright and spacious. MVHR unit is used in the property for ventilation. The unit requires some easy maintenance, such as filter replacement twice a year, which is done by the owner. The tenants do not engage with the ventilation system.

CB.2. CASE B

CB.2a. Dwellings and households' characteristics, timelines. Case B

<u>Information about the household</u>

The household consists of a couple in their late 30s/ early 40s and their two children under the age of ten. There is no immediate plan to expand the family. They plan to stay in the property for good. They used to live on numerous boats for almost two decades before moving to the current property. The owners have practical experience of altering, fitting and designing their boats, which helped a great deal in their house retrofit.

Both owners work in furniture restoration. One of the owners is a builder and used to supervise the building of high-quality energy-efficient homes. This owner also shows a huge interest in renewable energy, keeps up to date with news and trends, as well as attends public lectures on related subjects at least a couple of days a week. The family has a wide network of connections in sustainable energy and renewables sectors.

Information about the house and its state before the retrofit

The property is a mid-terrace house, located in the conservation area in Hammersmith and Fulham, London. It is a 1920 brick cottage style dwelling, typical to the area. The back side of the house is facing south east. Originally, the house was a two-storey building, featuring three bedrooms upstairs and kitchen, and a dining/ living area downstairs. During the renovation the main layout of the property remained intact. The only changes included the loft conversion and adding a conservatory at the back of the house. The owners were fond of the original features throughout the house such as fire places, which helped preserve the unique character of the place. Not all of the decoration was up to owners' liking, however they were keen on keeping the original features. They also left some decorative elements they did not originally like as they were, and gradually grew into liking them.

The house was in a good condition when the family moved in and was perfectly liveable. The property features composite walls — cavity brick on the outside and light concrete on the inside. This combination allowed to achieve a very good level of insulation at the time. The windows were single glazed. The house had no insulation when the owners bought it except of some insignificant roof insulation. The property was heated with gas. The house relied on non-renewable energy sources, which was something the homeowners wanted to change. Tungsten bulbs were used for lighting.

The retrofit timeline

The owners moved into the property in 2009 and did several renovations and improvements in the house. Firstly, the owners built the conservatory in 2012 over a period of three months. Despite the fact that they live in a conservation area, the owners obtained a planning permission for it easily, as it was just a conservatory and not a full house extension. Afterwards, internal wall, ceiling, roof and loft insulation was installed. The work began in 2009, it took a total amount of approximately a few hundred hours, and was gradually completed over the span of four years. Consideration was taken for draught proofing. During the renovation and redecoration of the property, energy-efficient LED lighting and energy-efficient appliances such as energy-efficient fridge freezer and induction cooker were installed. As the owners insulated the floor, they also installed energy-efficient underfloor heating. The system is zoned and has a separate control in every room. The wood burning stove installed in the living room serves for decoration purposes only. The owners also took steps to minimise water use and installed a 10 kW instantaneous water heater, which regulated the temperature with water flow.

In 2012 the owners installed a 3.34 kW PV system. The owners got a loan through the bank to finance the installation. The capital costs were paid back through the Feed-in Tariff. At the time of the interview, the homeowners estimated that it will take them another two years to recover the investment costs. In 2014 the owners installed by themselves an air-to-air source heat pump, which is used not only for heating in the winter, but as an air conditioning unit in the summer as well. In May 2016, a 5 kWh battery tank for the PV system was installed. The system was not properly installed initially, which resulted in a drop of the amount of generated energy. It took significant time and effort to resolve the problem, however the owners are reasonably happy now about the installation. The owners plan to change the glazing in the conservatory to the triple glazing in the near future.

The owners first installed window film on the single glazed windows. It reduced the heat loss and improved the U-value from 5 to 3 W/m^2K. They were satisfied with the thermal comfort achieved. Over the years the noise from the adjacent road became an issue and they decided to change the windows. Double glazed windows were installed in 2014, which reduced noise levels tremendously. On some windows additional sheeting was installed to help with the noise insulation. The windows open inwards, allowing the homeowners to reach the shutters they installed earlier. The shutters serve to soundproof the property in the summer, when the windows are open, serving as shading devices as well.

<u>The state of the house after the retrofit</u>

The owners practically achieved a zero net energy living through a combination of good insulation, passive heat gains via conservatory, energy-efficient lighting and appliances, efficient electrical underfloor heating system, solar PV system, air source heat pump and behavioural adjustments. The necessary behavioural changes include being thoughtful of the thermostat settings during the winter, taking shorter showers, as well as not using several electrical appliances at the same time. Some of these adjustments, such as shorter and colder showers during the winter, effect owners' level of comfort and they are thinking of improving the system in the future. The owners managed to achieve a reasonably comfortable indoor thermal environment. The are no problems with condensation and mould.

The owners did the retrofit at a cost of around £4,000, excluding the installation of the solar PV. This number accounts for the capital costs of the measures only, as the whole retrofit was done DIY. The owners took a loan to finance the installation of the solar PV, costs from which are expected to be paid back through Feed-in-Tariff. The homeowners also report around 50% of savings on energy bills, which equates to around £500. The savings are calculated based on the installation of the energy efficiency measures only, excluding the PV installation. Together with the PV installation the overall setup is carbon neutral. The family lives comfortably using the dishwasher, washing machine etc. 67% of carbon savings has been achieved as a result of the retrofit. The house has been remotely assessed by a representative of a SuperHomes network.

CB.2b. Stages in retrofit decision-making process. Case B

Felt needs

The owners aimed to achieve a carbon neutral setup. Another important goal was a preservation of the original features of the house and its 1920s character. One of the owners had to extinguish quite a lot of fires in his past, so he made sure they installed a good fire extinguishing system even though it was not required by the regulations.

Knowledge stage

The husband is a builder himself and had a previous experience of altering, fitting out and designing boats/ barges, which helped a great deal in the house retrofit. He also had supervised the construction of high-quality prefabricated homes in Europe. His professional background helped him to gain sufficient knowledge to come with a good conceptual understanding of how different retrofit goals could be achieved.

Persuasion stage

The owners had previous experience of some of the measures they installed. For instance, the insulation installed in the property was the same kind of insulation the couple installed previously on the boats they lived on. The owners also chose to install a relatively expensive LED technology, due to the fact that the husband had an experience with this particular LED technology at work and thought it had a good balance between the appearance, energy efficiency and colour rendering. Even though the objective for the owners was to do the retrofit as cheap as possible, they also appreciate that in a long run it is better to pay extra for a better quality product that is more durable and will last longer. For instance, the LEDs they installed are more expensive but are of a great quality and are worth that investment. The owners decided to go for an expensive material for the underfloor heating system as it looked robust and was made out of recyclable and sustainable materials. However, it proved to be a disappointment. The material happened to be really sensitive to water, making it very difficult to maintain. As a result, the floor in the bathroom is swollen.

The husband is interested in technological developments and regularly attends lectures and seminars on sustainability to keep up to day with the current trends. One of the reasons to join SuperHomes network was to share the owners knowledge and experience with others, showing that it is possible to achieve net zero energy living on a budget.

<u>Decision stage</u>

Achieving an energy and carbon neutral setup means that the total amount of energy used by the building on an annual basis is roughly equal to the amount of renewable energy created on the site. A conventional advice to achieve such goal is, firstly, change wasteful behaviour to reduce demand; secondly, to improve energy efficiency of the building fabric and building services; and finally, meet the remaining demand with renewable energy. Practically, the advice is widely interpreted as super insulating the property first, in order to almost eliminate heating demand.

The homeowner takes a different approach. He does not believe that superinsulation is necessarily a good option. He thinks that better results could be achieved with less insulation via a combination of other measures. One of the main considerations that should be taken into account when making a property super insulated and airtight, is retaining good indoor air quality and, thus, adequate level of ventilation. Providing an adequate level of insulation in an airtight property often means installing mechanical ventilation system, which requires a lot of ducting work, that increase the capital costs of the installation. As one of the main goals was to renovate on a budget, it was decided to count on passive strategies to maintain the adequate level of ventilation in the house. Therefore, the owners took steps to keep some level of air permeability in the property, for instance they did not block or seal the chimneys.

The owners decided to use electricity to meet all energy needs in the house. They installed solar panels to generate it. The roof of the house is facing southeast, which means that the installed system achieves only 82% of its potential performance. The owners were also restricted by the size of the roof. They used all the space available to them. Installed solar panels were more expensive than some of other options available, but they showed the best performance in hot weather as well as cloudy conditions. Air-to-air source heat pump was installed to improve efficiency of the heating and provide cooling in the house.

The owners did the renovation over four years slowly but steadily. The order of the measures installed was the most logical to make it comfortable to live in. The owners also chose the measures that will require minimum maintenance to ensure comfortable living conditions. The owners used to live on different boats for 17 years, before they moved to this house and enjoyed their lifestyle. They felt a luck of light in the house and decided to install a up a conservatory to bring some light in. The owners checked the wall materials before proceeding with the works. It helped to ensure that the choice of insulation materials will not create new problems or unintended consequences such as internal wall condensation, as a result of a wrong combination of materials.

Implementation stage

The owners installed two inches of internal wall insulation. The house is located in a conservation area. Therefore, they were not allowed to alter the physical appearance of the dwelling and, thus, external insulation was not an option. The layout of the property was not altered during the retrofit. On one hand, it helped to preserve the original character of the property; on the other hand, the rooms remained relatively small by current standards. The installation of internal insulation requires additional internal space. As the lack of space was already an issue, the owners decided to go for a relatively thin amount of insulation — about two inches. The retrofit was designed as a budget retrofit; therefore, a commonly used affordable board insulation material was used. Nevertheless, the house was insulated enough to ensure a uniform temperature distribution from the underfloor heating system.

Confirmation stage

As mentioned earlier the house is also not perfectly sealed to allow for natural ventilation. Installing internal wall insulation meant that the house could be quickly heated from 13 to 18/19 °C in 20/30 minutes in winter. However, a relatively thin amount of insulation and airtightness meant that once the heating is off, the heat escapes through the fabric relatively quickly. The owner says it drops down to 13 °C overnight and to about 16 °C during the day. The owner adjusted his everyday routines to switch the heating on before the family gets up to ensure comfortable environment for them by the time they get out of their beds.

Behavioural adjustment was needed to retain the level of thermal comfort in the conservatory as well. The glass conservatory helps to bring light into the property and increase passive solar gains. It is double-glazed and has a U-value of 1.4 W/m²K, and adds significantly to the heating of the whole house during winter times. Even though an increase in solar gains could benefit during winter months, it could lead to an overheating of the property during summer. During the summer the owners keep the conservatory doors open, to allow cooling via natural ventilation. On a particularly hot day, they shut the doors, close the blinds and cool the property via mechanical air-conditioning, the energy for which comes for free from solar PV. The owners plan to replace all the windows in the conservatory with triple-glazing units in due time in order to reduce energy losses during winter times. As the building is located in a conservation area, they owners needed to obtain a planning permission for the conservatory.

Previous experience of the measures installed allow the occupiers to set expectations of what kind of benefits should be expected from further installations. If the system does not perform as expected, the owners take actions to check the set up of the system to optimise its performance. For instance, after the installation of the battery storage, the solar panels started producing less energy. The owners had to report the issue to the installation company, and they sent an engineer, who found out that the problem was due to the incorrect installation.

CB.3. CASE C

CB.3a. Dwellings and households' characteristics, timelines. Case C

Information about the household

The homeowners are a couple in their 30s. They do not consider the property as their long-term home and plan to stay there for only another five years. The husband is an architectural technologist and a principal energy specialist in an energy charity, which specialises on energy use improvements in buildings. The wife is a dental nurse. It is their first property and a first step to 'climb the property ladder', so they had no previous experience of building retrofit. Even though they do not plan to stay in this property for good, they were keen to invest in tools, necessary to carry out DIY retrofit, which they hope to use not only in this property but in future ones as well.

Information about the house and its state before the retrofit

The house is a semi-detached council house located in Buckinghamshire, England. It was built around 1930s and it was sold under the Right to Buy scheme in 70s. It is a two-storey building typical for the time period, featuring 3 bedrooms upstairs and 2 reception rooms and a kitchen downstairs. The owners were attracted by the affordability of the property, its location, its general appearance and a sense of character. They also saw the potential for financial investment.

It is very likely that the previous owners did not have the means to maintain it, and the physical state of the house deteriorated over time. The property featured solid brick walls, timber suspended floors, single glazed windows. Some of the window panes were broken, which undermined the overall security of the place. There was no insulation throughout the property except for some insignificant loft insulation of 15mm. There was no central heating system, and the boiler that was installed at the time did not have enough capacity to adequately heat the whole house. The property felt cold and uncomfortable. There were problems with mould and condensation. Overall, the house needed a major refurbishment by the time of the purchase.

The retrofit timeline

The owners bought the house in 2014. Since then, they did several renovations to make the house comfortable and affordable. The works were spread over two years, within which the owners had intense periods of renovation activity. They installed double glazed windows and composed external doors in February 2014. The primary pipework was re-routed and a condensing combination boiler was installed in March 2014. In May 2014, floor insulation was installed for the suspended floors. From summer 2014 to summer 2015 the owners refurbished all the rooms in their house. It took them about 2 weeks per room. The refurbishment included re-doing the ceilings, installing vapour controls, redecorating the rooms and installing low-energy lighting. The owners made sure that newly insulated fabric is as airtight as possible. In summer 2015 they installed external wall insulation. During this time, they did re-rendering of the façade, installed new soffits and gutters.

In 2016 they did some decorative works such as kitchen and bathroom works. Low-energy appliances were installed throughout, e.g. fridge, washing machine. At some point during 2016 the owners readjusted their ventilation strategy for it to become passive stack ventilation. It now included chimney stack passive heat recovery ventilation alongside upstairs trickle vents and wet room extracts. In summer 2016, the owners additionally insulated the external floor perimeter. They do not have any further renovation plans at the moment.

The state of the house after the retrofit

The installation of double-glazed windows and composite external walls improved the security of the place. The insulation of the fabric improved and, as a result, the house became warm and comfortable. The owners enjoy stable indoor temperatures and the absence of draughts. Even though some consideration was given to ventilation strategies, it was never obvious how to achieve any specific results. Currently, the owners find indoor air conditions comfortable, even though they are not sure how well the ventilation works. They report that sometimes it gets stuffy in the bedrooms upstairs in the mornings. They are sensible about the moisture they produce in the house and they do not dry clothes in the house. There are no reported problems with condensation and mould. 70% of carbon savings have been achieved as a result of the retrofit. The house has been remotely assessed by a representative of a SuperHomes network.

CB.3b. Stages in retrofit decision-making process. Case C

Felt needs

The primary interest for the owners was to increase the value of the property through retrofit, which provided them with the opportunity to upsell the property in the future and move up the property ladder. They aimed to improve the security of the place, the level of indoor comfort as well as to improve a general state of repair.

Knowledge stage

A certain level of theoretical and practical knowledge regarding retrofit is needed to achieve an optimal retrofit outcome. One of the owners had a professional background in energy and a good understanding of building physics, so they had a good platform to start from. They were also keen to embark on the project themselves, as it provided an opportunity for one of the owners to accumulate such practical knowledge and increase his professional credibility. They were initially thinking of hiring contractors for doing the actual works. Ultimately, they realised that tradespeople are only interested in the narrow field they work in and are not interested in the bigger picture. The owners expected the tradespeople to have sufficient practical knowledge regarding retrofit. However, after the initial interaction with the contractors and official bodies the couple felt that tradespeople and professional bodies did not have sufficient knowledge about energy efficiency retrofit and improvements. There were not many places to get some advice. The owners did not rush into things and dedicated a lot of time to educate themselves on different options available to improve the energy efficiency of their home. They proceeded to do a lot of works DIY. Acquiring sufficient knowledge to do energy efficiency retrofit DIY proved to be such a difficult task, that after completing the project the owners were keen to join the SuperHomes network as a means to share their knowledge with others.

Persuasion stage

Fabric efficiently retrofit, especially internal wall insulation, is associated with a high level of disruption to everyday life. The owners needed to do retrofit to bring the house to liveable conditions anyways, therefore there were no added disruption associated with energy efficiency retrofit per se. The owners would have been hesitant to inflict that level of disruption, if the needed to do energy efficiency improvements only. Therefore, they feel it is best to integrate the energy efficiency retrofit with the wider refurbishment.

Decision stage

The owners were keen to improve the energy efficiency of the house as cost effectively as possible. They limited the scope of works to those from which they could make a return of investment within the time they intended to stay in the property. For this reason, renewable energy technology installation was ruled out as not cost efficient. The retrofit costs include not only the capital costs of retrofit measures, but also installation costs. The owners installed a lot of measures themselves, thus minimising installation costs, which ultimately allowed them to achieve higher energy efficiency within the same budget. The owners used governmental grants to offset the capital costs of some measures, such as the external wall insulation.

Implementation stage

The owners had different goals they wanted to achieve through the renovation of the property: increase its security, increase its thermal comfort, increase its value, and make the place their own. They were also keen to do all these at a reasonable budget. In order to ensure that all their goals are met, they had to keep a bigger picture in mind and plan ahead, making sure that the steps they took did not limit their future opportunities. The owners took special consideration to coordinate the sequence of works. Energy efficiency measures were done along with other structural and decorative works that needed to be done anyways. Every single measure was seen as part of the bigger scheme. The husband reports that coordination, planning and the logistics of the works were one of the hardest tasks they had to accomplish.

Unforeseen circumstances emerged during the retrofit, increased the scope of the retrofit, and the time required to finish it. Unforeseen circumstances were inevitable during retrofit, as it was sometimes impossible to know the condition of the physical structure of the house until after the works began. However, the scope of unforeseen circumstances seemed to diminish as homeowners acquired more theoretical and practical knowledge of the retrofit.

Confirmation stage

The owners are pleased with the results they achieved: the place is secure, its value increased by a considerable margin and in the process of retrofit the house became their home, something they are definitely can grow into. The owners made an effort to improve the airtightness of the property in order to reduce draughts, and thus increase indoor thermal comfort. They understood that increased airtightness means less air movement, which might cause some problems with condensation and mould growth. Therefore, the owners aimed to ensure that the house is sufficiently ventilated after the renovation. The couple were aware that they could only achieve a controlled level of ventilation with mechanical ventilation. However, they were reluctant to proceed with this option because of all the ducting required. The couple decided to install passive ventilation instead, even though it would mean that they would have no control of the actual level of ventilation achieved after the retrofit. At the end, they achieved higher level of airtightness than they initially anticipated. The bedrooms upstairs get stuffy sometimes, however no other problems, such as mould, have been reported, as the owners are sensible about the moisture they generate and reduce the risk of associated problems with sensible behaviour.

CB.4. CASE D

CB.4a. Dwellings and households' characteristics, timelines. Case D

Information about the household

The household consists of two members: a mother in her 40s and her son in his early teens. They are planning to stay in the house for at least another five years. The owner works as a manager in an organisation, which focuses on improving the use of energy in buildings. The owner owned a similar Edwardian style house before in the same area. The owner was always keen on improving the energy efficiency of the house and had some work carried out such as installing loft and floor insulation, secondary glazing and replacing the gas condensing boiler. The house had a lot of original features, which were carefully preserved by the previous owners, and the current owner did not want to damage or alter them as a result of retrofit. As a result, only the measures that did not result in the alteration of the original features were carried out.

Information about the house and its state before the retrofit

The property is a mid-terraced house, located in a conservation area in a small town in Buckinghamshire. The back side of the property is facing south. Built in 1907 the building is an Edwardian two-storey high house, and features 3 bedrooms upstairs and living/ kitchen areas downstairs. The layout of the property has not been changed during the retrofit. Even though the property is located in the conservation area, it lacked a lot of original features. The current owner saw it as an opportunity to do internal works without compromising the aesthetical value of the property.

The house was dated, however, the overall physical condition of the house was satisfactory, when the owner purchased it. The house featured brick solid walls, original single glazed sash windows in the front and double-glazed windows in the back. The house had originally some insignificant loft insulation, but was otherwise uninsulated. The house was originally heated with open fire. The original fire places downstairs were all removed by the previous owners and the ones upstairs were boarded over. The property was heated with an old-fashioned wall mounted gas fire. The previous owner sold the property without the appliances, so new ones had to be purchased. The decoration was dated and not up to owner's liking.

<u>The retrofit timeline</u>

The family moved in the property in February 2015 and over a couple of years did several renovations and improvements on the property. The chimney breast upstairs was boarded over by the previous tenants, but was not completely removed. The current owner saw an opportunity to optimise the internal space by removing the non-functional breast. The work to remove chimney breast was carried out over a few weeks in April 2015. The owner wanted to insulate the property and tried to find out whether she could get a planning permission for a rendered external insulation. She was unofficially told that such permission will not be granted and therefore an official application was never made. Instead, the renovation plans focused on proceeding with internal insulation, which was installed in May 2015.

In order to insulate properly the area around the boiler, it had to be taken out and the pipes had to be extended. The owner took this opportunity to replace the boiler all together to a more energy-efficient one, which also happened in May 2015. Loft and floor insulation work was carried out in June 2015 over a span of 3–4 days. Solar PV was installed in September 2015 and wood burning stove — in November the same year. Decorative works have been carried for about two years and finished in March 2017. Future planned improvements include an installation of secondary glazing and a replacement of the backdoor.

<u>The state of the house after the retrofit</u>

After the improvement in building fabric the house overall feels warmer and less draughty and the energy bills are lower. The owner constantly monitors the amount of electricity generated by renewables. She also reports a feeling of satisfaction in taking the bath in water that is heated by solar electricity. The is no reported problems with moisture and mould. The owner took her time to redecorate the place. 78% of carbon savings has been achieved as a result of the retrofit. The house has been remotely assessed by a representative of a SuperHomes network.

CB.4b. Stages in retrofit decision-making process. Case D

<u>Felt needs</u>

The owner had a professional interest to do the renovation. As part of her job the owner works on the projects which aim to encourage people to do energy-efficient retrofit. She was interested to improve her professional credibility by undertaken an energy-efficiency retrofit project herself. She considered installing measures that she advised others to install as part of her job. She knew that such measures would help her to improve thermal comfort of the property and reduce energy bills, however she did not have any particular targets in mind. The house overall was in a good state of repair, however its decoration was dated and the owner knew she wanted to decorate throughout.

The owner was keen to improve the thermal comfort of the property, however she would not have been comfortable doing it, if it meant destroying the original features of the house. The house is located in a conservation area, which meant that the permission to install external insulation would not be granted. A lot of original indoor features were already absent by the time the owner purchased the property. She saw it as an opportunity to improve energy efficiency of the house and install internal insulation throughout. She also saw it as an opportunity to install a wood-burning stove, which she felt adds a character to the place.

<u>Knowledge stage</u>

Due to her professional background, the owner had a good conceptual understanding of which measures should be installed, and she hired professionals to carry out all the works. She knew these professionals either through work or personal recommendation.

<u>Persuasion stage</u>

The owner installed some of the measures in her previous house, which informed her retrofit choices for the current property. For instance, she was not fond of the secondary glazing installed in the previous property; therefore, she postponed installing such measure in the current house. Some of the specialists she hired to install the measures she came across through her work, others she hired through recommendation. For instance, the builder who removed the chimney flue was recommended by a neighbour.

Decision stage

The sequence of works has been coordinated. The owners ensured that they did structural works first, so future work will not be compromised. Any structural work requires redecoration afterwards. The interior of the house was dated and the owner was intended to redecorate the property anyways. One of the first structural works that has been done in the property is the removal of a chimney breast in one of the bedrooms upstairs. After the removal it was possible to proceed with the insulation and redecoration of the room.

The homeowners had to consider several things before investing in energy efficiency measures. The capital costs of the investment were one of the considerations. The major retrofit works were financed through the mortgage. The owner expected that she might ran out of money and not be able to do all the planned works in one go. She prioritised the works and eventually, she indeed ran out of money and had to postpone some of the plans, such as the installation of the secondary glazing. The installation of the internal wall insulation was financed through the governmental subsidies scheme — the Green Deal. The capital costs of the PV system are expected to be paid off via Feed-in-Tariff.

Implementation stage

Despite the previous knowledge and experience, it is still not possible to think of all the details in advance, which might result in undesired results. For instance, the installers left a return where the internal insulation finishes. The owner now thinks, it might have been worthwhile extending the extension, so there would be no return.

Confirmation stage

Phasing the sequence of works meant that at some point different surfaces of the house reached different levels of fabric efficiency. Some of the windows in the house are still single glazed and the owner reports the problem of condensation during winter months. The owner understands that with time it could result in rotting of the structure. The owner lived in a similar property before and they used less water than they did in the property. That mismatch helped her to understand that there might be a leak somewhere in the property. She got the plumbers to come over to check the property. Two leaks were identified eventually. After they were fixed, the water consumption reduced to the amount the owner initially anticipated it to be.

Some of the retrofit resulted in unanticipated benefits. For instance, the owner has now windowsills as a result of internal wall insulation. Some other decisions required a change in habits to use the equipment. The owner installed a learning thermostat, she tried to adjust her habits to the logic of the thermostat, but eventually felt out of control and thought it was a bad investment from her side.

CB.5. CASE E

CB.5a. Dwellings and households' characteristics, timelines. Case E

<u>Information about the household</u>
The household is a working couple in their 40s with three children in their mid/ late-teens. The family does not have any plans to move and see the house as their family home. The husband has a business in environmental consultancy. The wife currently works as a service manager for the NHS. She used to work as a sustainability consultant in the built environment for more than 7 years, collaborating with developers, planners and local authorities on both new and retrofit projects. The family owned a property before. They have done some aesthetic improvements to it, however they never did any major works.

<u>Information about the house and its state before the retrofit</u>
The house is a mid-terraced house in Lambeth, London. The property is Victorian, built in 1890s. It has three split-level storeys, featuring a reception room and a kitchen on the ground floor and five bedrooms upstairs. There were some minor layout changes to the property including readjusting some internal walls.

The property was owned before by a single family for three generations, who did not maintain it properly. As a result, the physical conditions of the property were appalling and the house was in need of a major refurbishment. The house featured solid brick walls, which were in poor physical conditions and some of them had cracks. The leaky roof needed to be replaced altogether. There were otherwise no structural issues. The house featured suspended wooden floors. There was no insulation in the property. It had single sash windows throughout and some of them were broken. Every room had a gas heater. The wiring was old and needed to be redone. There were no decorative elements of the interior the owners were keen to keep. The family only moved into the property after the retrofit. The family really liked the volume of the rooms and the overall character of their Victorian house.

The retrofit timeline

The owners bought the house in 2012. They did several renovations, in three stages. The main renovation project lasted for half a year from June to December 2012. As part of the project some walls have been knocked down or moved in order to adjust the layout of the property to the family's taste and needs. The roof, ceiling and floors were insulated. Exposed walls have been insulated internally. Draught proofing was installed around all windows, the front door and below skirting boards on the ground floor. The central heating system was installed with condensing boiler and radiators. The family also installed solar PV panels and solar water heating. They installed energy-efficient lighting throughout.

The family only moved in after these works were completed in December 2012. They then carried out decorative works such as painting and finishes for the kitchen. The family brought some electrical appliances from their previous house and bought energy efficiency appliances for the ones they had to buy. The owners installed rainwater harvesting and use this water for watering the garden. Water saving taps were installed in the bathrooms as well. In 2013 the family carried out works to redesign the garden and build a patio. In the end of 2013 the owners also installed secondary glazing on the windows facing the road. There are no further plans to do other works on the property.

The state of the house after the retrofit

The improvement in the building fabric increased the thermal comfort of the place. Noticeable improvement occurred after the draught-proofing the skirting boards on the ground floor. 68% of carbon savings has been achieved as a result of the retrofit. The house has been remotely assessed by a representative of a SuperHomes network.

CB.5b. Stages in retrofit decision-making process. Case E

Felt needs

Several drivers motivated the homeowners to do energy efficiency retrofit, including desire to improve thermal comfort and reduce energy bills. The owners believe that everyone should do their part to save the planet. They not only renovated the house to higher energy efficiency standards, but also considered using eco-friendly materials in the process.

Knowledge stage

One of the owners had a professional experience in sustainability, helping planners and developers to design more sustainable solutions. Therefore, the owners had a good conceptual idea of what could be improved and where to start from.

Persuasion stage

The owners felt that the advice from the surveyor was really good. The advice gave them enough knowledge to plan detailed solutions, as well as the execution sequence of the different stages of the project.

Decision stage

The owners recognised that their builder does not have enough knowledge regarding energy efficiency retrofit. Therefore, one of the owners invited a sustainability consultant she knew professionally to advise the builder regarding details such as thermal bridging. The owners understood that the house would remain leaky despite the retrofit, therefore they were not concerned with providing any extra means for ventilation. No problems with condensation or mould has been reported.

The homeowners had several things to consider before investing in energy efficiency measures. One of the primary considerations was capital costs. The owners prioritised investment in structural works rather than decorative ones. They wanted a property that would be thermally comfortable. One of the ways to achieve it is to buy a property that is already retrofitted to the required standard. However, it is not easy to access the level of comfort of the property without actually living in it. They owners had a previous bad experience, when they bought a property, which had some structural flaws, which they did not realised until after they lived in the property. Therefore, they preferred to buy a property in a bad physical condition: the capital costs of the property would have been cheaper, the property would have needed works to be done on it, but the owners would have had control over the works that needed to be carried out.

The owners spent £31,000 on the retrofit. The owners had the budget allocated for the retrofit when they bought the house. Money was an issue and the owners tried to partially address it by combining different renovation works. For instance, the setup of scaffolding around the house was used simultaneously for the installation of the PV panels and the rainwater harvesting system. For other works it was not financially beneficial to do them at the same time and, therefore, the owners phased such works out.

Implementation stage

The owners realised that a retrofit project would require a constant attention of one of the owners. One of the owners was not happy with her previous job. She took this opportunity to quit her job, supervise the retrofit project, before finding a new job. The project ran very smoothly. The owner attributes it to the fact that all the specifications were done before starting the project, the project was divided in small tasks and the builder knew exactly what he is working towards at each point of the project. In order not to interrupt their everyday life, the family did not live in the property while it was renovated.

Confirmation stage

The owners made a choice to preserve the windows for aesthetical reasons, however, the restored windows are not as comfortable as the owners would have hoped them to be. The owners think they should have phased out the restoration until they had more money to afford to do the restoration to a better quality.

CB.6. CASE F

CB.6a. Dwellings and households' characteristics, timelines. Case F

Information about the household

The household consists of two adults in their 40s and three children 10 to 12 years old. The owners moved to the property before the children were born, however they had plans to start the family soon after. Thus, the property was seen as a family home from the start and the family plans to stay there long-term, for at least another 20 years. The husband has a degree in IT engineering and computer science, he runs a software developer company. The wife works as a manager. The family had another house before and they carried out some renovation works there. It was however on a much smaller scale.

Information about the house and its state before the retrofit

The house is a detached house, located in the conservation area in the village on the border between Hertfordshire and Buckinghamshire. It was built around 1967 and is facing south. Originally, the house was a two-storey building with two reception/ living areas, a kitchen, and a home office downstairs, and bedrooms upstairs. This layout changed significantly during the renovation.

The house was not in a bad state of repair when the owners moved in. The owners lived in the house for several months before starting the main retrofit. The house had cavity brick walls and a combination of single- and double- glazed windows. Overall, the house was very cold. It had no insulation throughout. The heating system featured a very old boiler and some central heating. The fire tank was only 6 or 7 kW (62% efficiency after being serviced), which was too small to heat the house of that size. The house also had an open fire place. The heating system was inadequate and unsafe, as the old fire tank would not have passed the fire regulations, and electrical wiring was unsafe at places. The property was also not decorated to the owner's liking. The layout of the property was not as efficient as the owners would have wanted to. The owners liked the location of the property, the safety of the area and the fact that the property is south facing. They also saw a huge potential for making the property their own: make it safe, comfortable to live in and alter the décor to match their aesthetic preferences.

The retrofit timeline

The owners moved in the house in June 2004 but they didn't start renovation works immediately. They wanted to live in the house for some time and understand what they really needed. They also wanted to see how difficult the parentage is going to be for them. Their first baby was born in February 2005. Over the years they did several renovations and improvements on the property. The main works were carried out in one go over 14 months from September 2006 till December 2007. Several works were carried out outside the main retrofit activity. The only thing the owners did before the main renovation works began was the cavity and loft insulation, installation of which was carried out in September 2004.

Most of the work done in the house was part of one major retrofit project that started in September 2006 and finished around December 2007. The renovation plans were extensive and included an extension to the house, so the owners had to get a planning permission. Practically, the project included replacing everything but the exterior. The project included significant layout changes. The new layout comprised of 14 rooms. Internal walls, and ceilings were stripped down and completely rebuilt, a kitchen extension was added and the garage extended. The owners installed multi-layered thermal and an acoustic insulation throughout the whole fabric: loft, cavity walls, underfloor and ceilings. They also installed double glazed windows and doors.

The couple installed two wood-burning stoves and chimneys, one in the living room and one in the kitchen/ dining area. They also installed solar thermal and biomass wood pellet boiler, both of which feed a large well insulated thermal storage. It was decided to install underfloor heating throughout the ground floor in 8 zones. Thermal storage feeds into the underfloor heating as well as towel rails in the bathrooms. The decision to have an underfloor heating had challenges of its own. The floor had to be lifted by about 10 cm, which meant that all the doors and windows had to be readjusted accordingly.

The owners put heat recovery ventilation system throughout the house. In each room there was either a supply or an extract. According to owners' observations the ventilation definitely works, though it might not have as high air flow as was originally quoted. Low-energy appliances were used throughout the house. The whole property had new wiring and plumbing. After the retrofit each room had its own wire and data cable outlets. In 2007 the husband built a DIY pergola with solar panels. The owners do not have any immediate plans for further renovation.

<u>The state of the house after the retrofit</u>

The fabric efficiency of the property had been improved, resulting in an increased thermal comfort for the occupants. The property is also mechanically ventilated and one of the owners changes the filters regularly. There are no problems with condensation and mould even though the family has three cycles of clothes washing every day, which they dry in the kitchen. Overall, the family really love living in their renovated property. The extended family of the owners enjoy visiting them during Christmas. The owners attribute it to the special atmosphere that is created in the house during this time of the year. Physical features of the house that contribute to the creation of the atmosphere include open spaces on the ground floor, lots of light, thermal comfort and the beauty of fire in the wooden stoves.

Some building services such as ventilation and heating require some maintenance effort and time. The owner copes very well with that. He himself used to help his dad with the maintenance of the heating system in his parental house. Nowadays he enjoys his own children helping him out in the house. 92% of carbon savings has been achieved as a result of the retrofit. The house has been remotely assessed by a representative of a SuperHomes network.

CB.6b. Stages in retrofit decision-making process. Case F

<u>Felt needs</u>

The husband as part of his A-levels at school did a project aiming to design an environmentally friendly house. Ever since that he always wanted to have an opportunity to do a project to minimise energy and water use in the house and overall make a house eco-friendly. As part of the challenge he was interested to achieve his goals by installing the measures from which he could get a return on investment over a period of time they are intended to stay in the property. As a result of a retrofit the owners achieved great reductions in utility bills, which they were really proud of. One of the reasons to join the SuperHomes network was the opportunity offered by the SuperHomes network to make a formal assessment of the carbon savings. They were really pleased with the results.

Knowledge stage

As the owners have no architectural or sustainability background themselves, they had to educate themselves on the options available for them to reduce energy and water use and achieve sustainable living. In 2004 they went to the Home Building and Renovation show, where they met a large number of renovation practitioners, suppliers and people who make various energy-efficient and sustainable products. It was a starting point for them to familiarise themselves with options available and start thinking how feasible these options are in the context of their home. The rest of the search was done online.

Persuasion stage

The homeowners had to consider several things to invest in energy efficiency measures. One of the primary considerations was financial. The owners were keen to make their house eco-friendly on a reasonable budget. The financial return of investment for most measures were calculated based on anticipated reduction in energy bills. For some measures, governmental subsidies were taken into account. For instance, the capital costs of the PV panels are paid through a governmental scheme called Feed-in-Tariff. At the same time the panels produce enough electricity to pay off the household's electricity bills.

Decision stage

The owners had already retrofit experience with their previous house, albeit not to such a great extend as in their current house. Therefore, they understood that it takes time to settle into a new routine in the house before they can make informed decisions on how things should be re-arranged. So, they decided not to rush into things and live in the house for at least a year before starting the works. Through their living experience the owners found out that the wood burning stove in the living room, which has an open access to the staircase, helps heating the rooms upstairs. It was decided to rely on this stove for the heating purposes. No radiators or any other heating system has been installed upstairs.

It took time to develop a conceptual idea where no previous living experience was involved. The installation of the pergola with PVs on it in the garden was a separate project, which was carried out several years after the initial retrofit. The homeowner came with the idea himself and it took him roughly two years to develop the concept.

Implementation stage

The project was not outsourced to a third party, but rather carried out by one of the homeowners himself together with his builder friend, whom the owner trusted. The builder felt easy to tell the homeowners what could and could not be done and achieved. They were comfortable with experimenting while they were renovating. This enabled them to be very flexible and adapt things as they went along. The owners proceeded to detailed planning without a crystal clear conceptual idea of what should be done. The knowledge and experience of a builder friend was used to both fine-tune the conceptual idea and make a detailed plan of how it should be implemented. The need to fine-tune the conceptual idea on the level of detailed planning probably resulted in the project being longer and more expensive than otherwise could have been. The homeowners intended to stay in the property for a long time, therefore they didn't mind the increased time and costs and they ended up achieving what they really wanted to do.

Some unexpected changes were involved in the retrofit process. For instance, after installing the water thermal on the roof, the owner with his builder friend found out that the roof tiles are rotten. As a result, they had to remove the water thermal panels, re-roof the tiles and re-install the panes again. Another unexpected changes occurred during the kitchen refurbishment. While building the kitchen extension, they found out that they need to replace corrugated steel sheets in the party wall with engineering bricks, altering the layout of the extension. Such unplanned expenses meant that it was not possible to carry out all the originally planned work. For instance, the owners originally planned to do the conservatory and even put the decking for it, but they simply ran out of money and they never completed this part of the project.

Confirmation stage

The owners only have one chance to do the retrofit: after the measures are installed it is prohibitive to redo them (finically or effort-wise) and, thus, the opportunities are locked. The owners, in retrospect understood the shortcomings of their initial solutions and wished they could have done some things differently. For instance, they mentioned that they could have planned the layout of the property differently, in order to minimise costs of the retrofit. Another disappointment was with lighting: fluorescent lights that were initially installed in the living area started quickly dying out. The owners are now phasing them out with the LEDs.

The owners decided to do the whole project at one go, in order to minimise the amount of added disruption associated with individual activities. As the owners embarked on the project without a detailed plan of the works, they underestimated the amount of effort such project required. At the end it took a lot of their time and effort and is still not completely finished. They will not do probably such a project to such extend in their next property just because of the amount of time and effort required. They would, nevertheless, consider doing a lot of the measures. The owners feel it took them a significant effort to learn about the retrofit. They are now happy to share their knowledge with others during SuperHomes Open Days events.

The house provides a framework for the household's personal and social life. For instance, the wood burning stove in the living room operates throughout the whole winter, creating the atmosphere in the house and serving as a pivotal interaction point for the extended family during Christmas. Nevertheless, the building services installed require some regular maintenance. The husband noted that it takes effort to settle into a new routine and it might prove to be quite a challenging transition. The owner, however, notes that it is possible to heat a house via different means, therefore a future owner will be able to choose a technology he or she is more comfortable with, making the transition easier.

CB.7. CASE G

CB.7a. Dwellings and households' characteristics, timelines. Case G

Information about the household

The owners are a young couple in their 30s with two small kids. They plan to stay in the property for good. The husband is a medical doctor and an IT engineer; the wife is an IT engineer. Prior to retrofit they had no specific background in energy/ building physics/ building engineering. One of the owners got certified as a Passivhaus consultant during the renovation project. The family have been renting the properties before. It is the first house they bought and the first retrofit they carried out.

Information about the house and the state before the retrofit

The original house was a semi-detached council house in Ealing, London. It was a typical two floor three-bedroom building and featured a reception room and a kitchen on the ground floor and three bedrooms upstairs. The layout has been dramatically changed during the renovation. The house was built around 1926. The property was not well maintained by the previous owners and was in a need of refurbishment. The property had single glazing throughout and featured solid walls with no insulation. The owners did not live in the property prior to retrofit, but they lived in similar properties prior moving to the new house. They recall these places were cold, and had mould and bad air quality. The property had a central heating system, consisting of a gas-powered boiler and radiators. Gas was used for space heating, hot water and cooking.

The retrofit timeline

The owners bought the property in 2010. Since then they did several renovations, which they carried out in two stages. The first stage was carried out in 2011 over a period of around one year. During this time a two-storey extension was added on one side, extending the property to 125 m^2. The house was split into two self-contained flats. The whole property was retrofitted to a Passivhaus standard. The following measures have been installed: external wall insulation, floor and loft insulation, triple glazed windows and doors. The house has been sealed to be very airtight. The heating system consisted of a gas-fired central boiler and radiators. The overall setup includes mechanical heat recovery ventilation, solar thermal and solar PV systems. New energy-efficient devices were used for the property. A rainwater harvesting system was installed and used to water the garden. In 2015 they did a back extension to the ground floor property, building it to a Passivhaus standard.

The state of the house after the retrofit

Thermal comfort improved significantly. No heating was required in the last four years. The level of insulation and airtightness allowed to maintain constant indoor temperatures throughout the year. There are no signs of mould growth even when drying up the clothes as relative humidity remains low at around 50%. Based on the assessment done by the SuperHomes network representatives, 80% of carbon savings were achieved. The reductions have been assessed remotely. The house has not been visited to verify the measures installed.

CB.7b. Stages in retrofit decision-making process. Case G

Felt needs

The owners took a mortgage to finance both the costs of the house and the costs of the retrofit. They decided to split the property into two, so they could rent out one of the apartments. By doing so they were making sure they could still pay the mortgage or at least part of it, in case something happens to either of them, ensuring long-term financial stability for the household. They also increased the size of both flats, ultimately increasing their value.

The owners redesigned the layout of the property to optimise the use of the space. They were keen to achieve high level of indoor thermal quality and air quality. Even though it is important for the owners to make the house feel like home through decoration, they still have not achieved that level yet. The owners believe that everyone should do their share to reduce their carbon footprint and minimise the environmental damage associated with it. They believe that an individual could contribute by reducing personal domestic and transport energy use, as well as minimising the number of used goods. The owners also planted some vegetation on their roof and got a rainwater collector in a pursuit to contribute to sustainable living.

Knowledge, persuasion and decision stages

The couple lived before in rented accommodation, which had terrible problems with moisture and mould. Therefore, they were keen to proceed with a retrofit, which would guarantee a good level of indoor air quality and thermal comfort. The owners realised that retrofitting their home to a Passivhaus standard would ensure high standards of indoor air quality and thermal comfort. The owners soon realised that the official information available on the topic is detailed enough to plan and carry out a Passivhaus retrofit without previous experience. Therefore, they went along with the concept of a Passivhaus. They gained theoretical understanding through the official information available via the Passivhaus network. Passivhaus standard and software tool proved to be a good framework for the owners to learn and understand what needs to be done for the retrofit. One of the owners proceeded to become an official Passivhaus certifier. In order to minimise the overall expenses associated with the retrofit, the owners carried out themselves a major share of the organisation and research work required by the project. Both owners have engineering background and were overall interested to get involved in the project and gain on-site experience.

The homeowners had to consider several things before investing in energy efficiency measures. One of the primary considerations was capital costs. The owners spent around 10–12% of the total property value on retrofit. They felt it is a justifiable figure to invest in a property development as it involved significant changes to the layout, building fabric and building services, which ultimately raised capital costs.

Implementation stage

The project was one of the pioneer projects for Passivhaus retrofit in the UK, which proved to be a challenge. There were no architects in the UK experienced with the Passivhaus retrofit that the homeowners could afford to employ. The owners employed technical architects without previous knowledge of Passivhaus retrofit and embarked on the project. It was a mutual learning and collaboration experience, and several times things had to be redone.

The owners underestimated the amount of effort required for the retrofit. They did not understand the dependencies that exist between different decisions. They had to put additional time and effort into the project to learn about such dependencies. They were solving practical issues on a day-to-day basis as they came along. The homeowners noted, that the comfortable flow of the renovation process would have been to come up with the general idea of the retrofit first, do the detailed structural design afterwards and only after that commission the builders to start the works. However, the decision to proceed with the Passivhaus standard came late in the project. Therefore, the owners were forced to start the works and figure out the details in parallel. It added extra work and stress. One of the owners worked from home, therefore she was able to allocate extra time to the project. Also, the owner received help from their extended family, who took care of the kids, which released some extra time required for the project. The structural retrofit was highly disruptive to everyday lives of the occupiers. They had to move to the house while the works were still carried out and it proved to be a very challenging time.

Confirmation stage

The project was carried out in two phases: in the first phase a two-storey extension was added, the property was split into two flats and retrofitted to a Passivhaus standard. After living in the property for some time, the owners realised that they would want to extend the property to be able to accommodate their extended family during their visits. The ground floor extension was added soon after and also retrofitted to a Passivhaus standard. Even though the retrofit was not planned to be carried out in two phases from the outset, the owners felt that it was a better decision financially. They felt that after the first retrofit they were absolutely financially broken and would not have been able to afford to carry out all the works at the same time even if they had them all in mind to begin with. At the time of the first interview, all the engineering and structural work were complete. The owners were investing their time in decorative works, and trying to make the house a home. Decorative works are far less disruptive to everyday life and also could be done DIY. As a result, the owners are pacing out the process, and take their time with the decorative works to understand what they really want.

The owners monitor the performance of the building. They use this information to understand how their behaviour affect the performance. Once they detected that they use too much gas, which led them to discover that the solar panels were not working properly. The owners also had to adjust some of their habits to optimise the performance of the house. For instance, one of the owners notes that she is used to sleeping with cooler temperatures during the night, but had to change that habit as the Passivhaus provides them with uniform temperatures throughout the day. The owners are happy with the level of indoor thermal comfort and indoor air quality they achieved. It took them time to warm up the house and get used to the environment, but they are satisfied with it now. The owners joined the SuperHomes network in order to be able to share their knowledge with others on how to do similar works in their homes.

CB.8. CASE H

CB.8a. Dwellings and households' characteristics, timelines. Case H

Information about the household

The homeowners are a retired self-employed couple. They are planning to stay in the property permanently. The husband is a guitar teacher, the wife does acupuncture, medical research and recently started painting. They live together in the house and rent a room to one tenant. They have no background in energy or civil engineering.

Information about the house and its state before the retrofit

The house is a semi-detached house in Lewisham, London. The owners liked the house location on the hill and its view, its proximity to the train station, the space available for having a garden and the fact that they could afford the house. It was originally built as a summer holiday house in 1933 for railway workers and it was never designed to be occupied all-year-round. It was a typical two floor three-bedroom building, with 2 reception rooms, a kitchen on the ground floor, three bedrooms, and a separate bathroom upstairs. The only layout changes that occurred during the renovation was a loft conversion.

The house was not in a bad state of repair when the owners moved in and was perfectly liveable. The house featured solid brick walls, uninsulated loft and uninsulated wooden floors. The windows were single glazed with wooden frames. They were rotten, and there was a condensation problem, with mould growing everywhere. Each reception room had a gas fire located in an old fire place, each upstairs bedroom and bathroom had a radiator, there was no heating in the hallway or landing. The house is located on a hill with one side of the property exposed to wind. The house was very draughty and a cold breeze used to come up from the floor, making it impossible to heat the house. The thermal discomfort even prevented the household members from enjoying the sedentary activities indoors. Not all of the internal decoration was up to owner's liking. For instance, the kitchen had a typical English layout, which included several small cabinets that were not practical or easy to reach.

<u>The retrofit timeline</u>

The owners moved in the property in 1989. Over the years they did several renovations and improvements on the property. The house was retrofitted over many years. The owners had no particular energy performance goal in mind, rather the measures were installed as they became more available on the market. The owners first installed insulation curtains shortly after they moved in. However, and the house became very dark as a result and there was mould growing under the curtains. The curtains were removed. The owners decided to install underfloor heating system to eliminate cold draughts coming from the floor. The system was installed in 1996. At the time of the installation the floorboards were changed, and the boiler was replaced with a condensing one.

In 1997 an accident happened in the kitchen and all the cupboards suddenly collapsed. The owners took this opportunity to redecorate the kitchen. They opened up space for the chimney, installed the wood burning stove and moved the boiler from the kitchen to the first floor. The owners wanted to extend the property and originally applied for a straw bale extension, but permission was not granted as the extension was considered to be out of character with the neighbourhood. Following this, the couple decided to make a loft conversion, which was implemented in 2007. The loft was insulated to meet building regulations at the time. Because of the change of use for the loft the existing water storage tank had to go and was replaced by an unvented water storage, which was moved to the bathroom on the first floor. In 2007 all the bathrooms were changed to wet rooms and the air cabinets were installed.

The owners considered insulating the property. First, they covered one of the internal walls with cork, which had little effect. In 2014 they installed external wall insulation wrapping up the whole house. The owners considered installing renewable technologies and in 2015 they installed a pergola in the garden with solar PV panels on it. Future considerations include the installation of electric battery storage when the technology becomes more efficient and financially affordable.

<u>The state of the house after the retrofit</u>

Initially, the house was very cold, and the installation of a wood burning stove improved the situation during the coldest of winters. Installation of the fabric insulation and the underfloor heating improved significantly the indoor thermal comfort. As a result of the loft conversion, the loft became habitable. The couple find living in the house a much more relaxing experience after the retrofit. They can now do different sedentary activities, such as play guitar and paint. Previously, the cold affected their ability to enjoy these activities. After the retrofit the couple also found themselves in a more relaxed state of mind: they do not argue anymore about open doors and windows, and possible cold draughts. They also wear less clothes indoors. Their extended family also loves coming over for Christmas and Easter. The couple attributes it partly to the comfortable thermal environment of their home. Despite all the improvements, the house remains draughty. The owners did not have any particular ventilation strategies for the house as a whole. They did however install air-cabinets, reducing the risk of condensation and mould. 90% of carbon savings has been achieved as a result of the retrofit. The house has been remotely assessed by a representative of a SuperHomes network.

CB.8b. Stages in retrofit decision-making process. Case H

Felt needs

The house was in a liveable condition when the owners purchased it. It provided the owners with the basic sense of shelter and security and they were happy to have a place they could call their own. It was, however, thermally uncomfortable and had some problems with condensation and mould. The owners were interested to improve the level of indoor comfort. As the homeowners grew older, it became more important to ensure a comfortable indoor environment, as cold is something that is very difficult to tolerate at old age. They would also consider retrofit activities, as one or another part of building fabric or building services came to the end of its lifetime and needed replacement. For instance, they replaced their boiler when it was too old, they also refurbished the cabinets in the kitchen when they collapsed.

The owners wanted to ensure financial stability at old age. They tried to control the costs of utility bills as they grow older. Over the course of their lifetime they got interested in the idea of sustainability and have been looking into making adjustments to live a sustainable life. The owners believe that people should live a sustainable life. They themselves hop to continue to retrofit until they are independent from the grid as long as the technology comes at reasonable cost. The installation of an on-site renewable power generation technology greatly helped to achieve the goal. Taking this attitude into account, it is safe to say that their retrofit project will not be over until they are completely energy autonomous. The husband noted that ‘being in tune’ with the whole idea of sustainability is essential to achieve high energy efficiency results.

Knowledge stage

The owners did not have any background knowledge in neither sustainability nor engineering. They gradually built up their general understanding of what energy efficiency was as the information became more publicly visible and discussed in journals and papers. One of the owners takes pride in being up-to-day with modern technology, and allocates his time to become familiar with the technology.

Persuasion stage

The owners drew some of the ideas from their personal experience. For instance, they decided to proceed with installing underfloor heating after experiencing living in a property with underfloor heating in Japan. They also got advice from the people they trust before planning the retrofit itself. After they formed an initial idea, they started looking for more information in more specialised sources. They found that the information available from the government tends to be very specific and often did not address their needs. The owners tried to get advice on the project from local experts, who they trusted. They felt that the tradespeople should be more proactive in trying to make people aware of the energy efficiency choices available for their properties. Eventually, they would revisit their original retrofit idea, consider turning it into a project and commission the project to contractors they trusted. The retrofit project required time and effort from the owners. They noticed that earlier in their lives they were too busy with their lives to find time for renovation activities.

There are several considerations that the homeowners had to take into account before investing in energy efficiency measures. One of the primary considerations was financial. The owners only did works when they could afford the investment. The capital costs of external wall insulation were prohibitive for the household. However, they received a £6,000 grant from the Energy Company Obligation (ECO) scheme to cover part of the £21,000 cost, which allowed them to carry out the installation.

Decision stage

The owners wanted to improve the thermal comfort of the place, however they were not sure what will it take to achieve their goal. Rather, each renovation project showed them what else needed to be done. For instance, after installing an underfloor heating, they found out that the floor felt warm even when walking barefoot but the air around a standing person would still feel cold. This observation helped them to realise a need for a wall insulation.

Implementation stage

An important constrain was a need to obtain a planning permission for some works. The home-owners were not granted a permission for a straw-bale extension, so they opted for a loft conversion instead. One of the owners highlighted the importance of supervising the builders during the retrofit. He had a bad experience, when the job was not done correctly. The window frames in the loft remained uninsulated, which the owners only found out during the winter. This could have been easily fixed if it was checked on time. After this incident, the owner was always checking builders work.

Confirmation stage

The owners describe how an increase in indoor thermal comfort provide a necessary platform for their day-to-day activities. The owners are pleased with the results they achieved. They do not feel that the level of retrofit they did is exceptional. They actually think that such level of renovations should be the norm, achievable and affordable. One of the reasons they joined the SuperHomes network was to share their experience of energy efficiency retrofit.

Appendix CC
Example of an interview transcript

This appendix gives an example of an interview transcript.

CC.1. EXTRACT FROM AN INTERVIEW TRANSCRIPT

Interviewer: Did you have any previous experience of renovating houses?

Interviewee: Not as large as this, no. But more like having your wall re-plastered, as we did in a flat in [town name]. Yes, we had electricity done, kitchen moved, things like that, but nothing major. But we both liked the idea of thinking about what we could do, how we could change things. I was very excited about being able to walk the talk **[00:20:00]** for once. From having given energy efficiency recommendations for years to actually do this.

Interviewer: Okay. Could we please talk a bit more about your idea to do low-carbon retrofit? How did the idea come about? How did it develop and how you decided to proceed with it? What did you know to begin with and how the knowledge change? What influenced your decisions? Just reflect a bit on your decision journey.

Interviewee: So, we wanted to move and … I guess, in the UK, we find that the housing market is mad, really. You will often find houses with a new kitchen, brand new bathroom, but you don't really know what you are buying. And then you don't have the taste, necessarily, the same taste, as the people from before. And they sell it to you more expensive, because they have done that work, but you might not like it anyways. So, even though it's in a very good condition… or it seems so first. You are not sure it's going to be in a good condition. And second you might not like it anyways. So, eventually, at some point, you will do it again. So, it's kind of you paying twice for it. So, we were looking for a house that needed to be refurbished, because then we knew, what we were buying. Even though it was a wreck, we knew, what we were getting. The house that we had bought before, we had been sort of misled by the people. We had a surveyor come in and tell us, that there were some issues. So, we kind of knew **[00:22:00]**, but still it was a bit disappointing. So, we knew, that it was the way for us do things the way we wanted, really. We put our money. It seemed to be the most efficient use of our money. And also, it was going to be quite expensive in this area, so it seemed the most cost-efficient way, in a way, of doing it. And because I was interested in this field, I wanted to do it and not just ignore it. And because it was such a wreck, it was really the time to do it. It's not like, we will do it one day. If you have a new roof, then you have scaffolding, so you might as well have solar water heating or PV, because it means you never have to pay for scaffolding again. I had this battle in my mind, because the budget is not unlimited for work, so you have to think. Ok, I know that solar PV is not necessarily the best measure of all, energy efficiency is much better. But then, at the same time, I have got the scaffolding here available, and really now is the time to do it, but then it means you can't do the other things. I knew already through my work that it was important to do energy efficiency measures first. I knew, in terms of central heating system, it made sense to, because we are connected to the gas grid, to have a gas boiler, but with an energy-efficient house, so that we reduced the amount of gas used, rather than look for something like **[00:24:00]** wood fuel boiler, that kind of stuff. What are they called again? Sorry, because I don't work in this area anymore, I forgot all the words, but…

Interviewer: Pellets?

Interviewee: Yeah. So, either pellets or wood chips or the electricity. The ones that use electricity, what are they called?

Interviewer: Heat pumps?

Interviewee: Heat pumps, thank you. Yes. So, we didn't hesitate too long on that. When I left my job, they knew I was going to do that, so they gave me a book about energy-efficient refurbishment, which was good, because there is so many different things that you can do and it's still a new field… Builders are not used to that. So, I used that, then came the whole question of… Well, we had a building surveyor. The way we did the work was that we had a building surveyor, who surveyed the house, and we knew, where all the problems were. Then we asked him to build a specification list of all the work that needed to be done. So, we talked with him and told him that we wanted to have insulation in the walls, obviously. Because we were doing a new roof, he mentioned that we needed to have it insulated to building standards, so, that, in a way, was led by the building regulations rather than by us. He wrote a long list like that of all the work that needed to be done. Then, the question was what materials. The big, big question **[00:26:00]** has been for me the type on insulation on the external walls, and that's where there is a lot of questions, and even the book I had was not really responding. And it felt at the time, that no one really knew, what they were talking about. Because they talked about risk of condensation, if you put too much or not the right type, or you don't install it properly. I was really keen to use environmentally friendly products, like cellulose and wood fibres and things like that. But then, what other different systems that exist? And can your builder install it? Do they know how to use these products or not? What is the cost? Is there going to be a risk of condensation or not? All of these. I ended up choosing the standard, the oil based… some foam with plastic boards, because I knew, that my builder was comfortable with it. It was cheaper, than other solutions that were using buttons and rock wool insulation, but I regret this a little bit…

Interviewer: How come?

Interviewee: Because I would have liked to use some environmentally friendly products for health reasons, for all the right things, for avoiding fires, you know… Now we know… Maybe they are right, but it just would have been better **[00:28:00]**, but you kind of have to make a choice because the money is not never ending. That was on the external walls. On the ceiling and under the floor we used rock wool, so that was better. Rock wool seemed to be a good compromise between foam-based and completely cellulose or wood fibres. I guess, in terms of the process, I knew already, what I wanted to do. I knew energy efficiency was going to be on the floor, external walls. I knew, I would have to do the windows, draught-proofing, and change them to double-glazing. The roof was going to be taken care of, because we needed a new roof, and I knew… Well, maybe, I didn't know initially, but then gradually realising, that my builder had no idea about all these things. So, I asked [company name] to make these recommendations about how to do it properly. And then draught-proofing at the end, as well, under the skirting boards. So, that was quite interesting actually, because at the end, when we were living in the house, I could feel really strong draughts on the floor. I was thinking: “what on earth is this?”, because I have spent a lot of money having my house insulated and my floor insulated. I knew that the floor doesn’t give a huge amount of energy savings, compared to walls, for example or roof. But I wanted to **[00:30:00]** have it done for comfort purposes, because you can feel these draughty houses in the UK, where your feet are freezing, because you could feel the draught. I didn’t want that, so, that’s why I wanted it insulted, but the builder came and just put some draught-proofing, you know, some sealant under this skirting board and that stopped it. But it was interesting for me to think that, actually, when you work in this field, the first thing that you see, the most cost-efficient, is to do draught-proofing for windows, for walls and everything. And it proved again, that it’s probably good to have the floor insulated, but it won’t work, if you don’t have also the draught-proofing done. So, that was quite interesting to observe. Then, I suppose, in terms of other measures… water… There is not much you can do on water, really. I did consider grey water harvesting, but it’s very expensive and too complicated. So, that was it then, really. I sort of knew, what I wanted.

Interviewer: What about lighting and appliances?

Interviewee: Yes, and, obviously, all the appliances… Actually, no, we didn’t have to buy all our appliances. The ones we had to buy, we bought energy-efficient, sort of top-rating. But we had a lot of appliances from [town name] that we had kept, and, so, we bought them energy-efficient at the time. Maybe, they are not as efficient, as could be now, but we were not going to buy new ones soon. We still have them now. **[00:32:00]** We have lighting, energy-efficient light bulbs, everywhere. And yes, what else?

Interviewer: Did you think about your ventilation strategies?

Interviewee: No… So, we have extractor fans in the bathrooms. I think you kind of have to. I think, its building regulations. But we didn’t think about a heat recovery. We might have considered, it but not really … seemed to be a bit much for two small bathrooms. In terms of risk of condensation… if we had a really insulated house… Well, we knew, we were not going for Passivhaus. So, it’s not like, there wasn’t going to be any draught at all in the house. So, I was not too worried, really, about it. And we open windows after showers, just to let the fresh air come in and remove excess moisture. I did wonder, whether there would be condensation on the walls, because of the external wall insulation. So far so good. That's about it, really.

Interviewer: So, No problems so far.

Interviewee: No problems so far.

Interviewer: Ok, that's great. Did you make any changes to your final decisions, compared to what you originally planned to do?

Interviewee: Yes, there has been a few things, when we **[00:34:00]** needed to reinforce certain bits of the wall. It was more like structural work that we needed to do. If we remove such wall, we need to reinforce it in a different way. There have been a few things, but nothing major. It went quite smoothly, and the fact that we had this detailed specs done in advance, and I was paying the builder line-by-line, so, there was a price for each line, each item of the spec, and I was paying him only, when it was finished. And so that it made it very clear. He knew exactly, what he was working towards. He knew exactly, what he had to finish and going to be paid then. So, it just made the work happen at pace and quite logically, and so it made it quite smooth. There had been things that were not included, that we had to look at, because you can't plan 100% everything. Some things have been revised also a bit lower, but generally I think that helped to make it work better.

Appendix CD

Example of an analytical matrix

This appendix gives an example of an analytical matrix used for the cross-tabulation of interview information as part of the analytic display (Table CD.1). The example of an analytical matrix starts on the next page.

Table CD.1. Extract from an analytical matrix

CODE	Case F	Case G	Case H
Associative tasks			
Home	family, comfort, place to relax	fun, joy, peaceful, warm, cosy, comfortable, healthy, family, friends, garden, kitchen, cooking	1: family, safe, comfort, responsibility, DIY 2: warm, safe, food, fun, kind of a workshop, children, friends, Christmas, pension, something about old age, continuity
Low-carbon home	n/a	comfort, health, sustainable, proud to have one, comfortable, good air quality It is never cold, not warm, you can control	1: sensible, efficiency. It's a thing to do. There is no reason not to be efficient. 2: responsibility, citizenship. The whole world is safe, protected. It's much more national and global than just us.
Low-carbon-related retrofit goals			
Comfort		… it is also a part of feeling cosy that you… have a constant 20-22 degrees… I think it's a part of feeling cosy, for me at least. The previous rented places, they are all just mouldy. Small places, not good air quality… then to make sure that the air quality is good and you don't have mould, you want to design the air quality, so you will have some kind of ventilation system…	I think we were beginning to get a bit desperate about the house being cold in winter. We had the radiators already, but they didn't seem to be doing anything.

(continued)

Table CD.1. Extract from an analytical matrix *(continued)*

CODE	Case F	Case G	Case H
Control			And also knowing that we also don't have a big pension… and basically, the political situation doesn't fill us with feelings of security. We think prices are going to rise and our income isn't. So, we are worried about being sustainable in our old age. I mean, certain things are guaranteed that you are going to have to pay for, no matter where you are in life. From council tax to energy bills and to utilities. And as you do get to fixed incomes, you get older, and it will be nice to mitigate some of those costs, which is why we got this.
Identity	… I did a project when I was at school during A-Levels and it was to design your own environmentally friendly home. What features would you put it in? I found that so interesting, investigating how you could save the energy and water, and so on. I have always wanted to do a project, where I would have the opportunity to do that sort of experience.	We wanted like a low footprint, really, and we wanted to see how we can achieve that… because it's usually three things: it's a house, transport and then stuff you have got.	…and when you see this kind of stuff, that you are able to help the environment, it just seems to make sense to put those two together: the home and simple things like heat, electricity… If you've got the space and you can afford it, it makes sense to do it, there is no reason not to.
Post-retrofit related experiences			
Comfort			Once the house is all structured, then we could start doing things in it; like I can start painting in it, cause it's warm… With no structure and just open spaces it's hard to really do any development. So, it's a kind of framework for all the other stuff we can do.

(continued)

Table CD.1. Extract from an analytical matrix *(continued)*

CODE	Case F	Case G	Case H
Control	Under-floor heating is hugely more efficient than the radiators. And with little children around you don't have any risks of children getting burned of hot radiators.	[talking about indoor temperatures and overheating] You can control it… this was the day then when I had enough, so I closed that [shades] and opened the windows in the night. Then it didn't warm up that much anymore. So, it's really up to me.	
Inter-personal relations	It is really nice in the Christmas time, when the family comes around. The extended family comes around and you got the fire going and everything. It's a nice, warm and comfortable environment.		[on changes to their living experience post-retrofit] It's so relaxing. We don't have to wear so many clothes. For example, before, everything had to be done in one room and we couldn't spread out. So, everyone was trying to crowd into the same space because, the other spaces were not liveable. And there is less arguing, like: "shut the door", or "you are the one that left it open", all of that sort of thing, which comes from being uncomfortable, physically uncomfortable… I think there is just more relaxed state of mind because it is warmer, it is that simple.

Appendix CE

Example of an analytical causal diagram

This appendix gives an example of analytical causal loop diagram (CLD) used for visual display of interview information as part of the qualitative analysis. CLDs were created for each of the eight cases. This appendix shows a combined CLD, developed based on the common patterns observed in the individual diagrams (Figure CE.1). The example of an analytical causal diagram is presented on the next page.

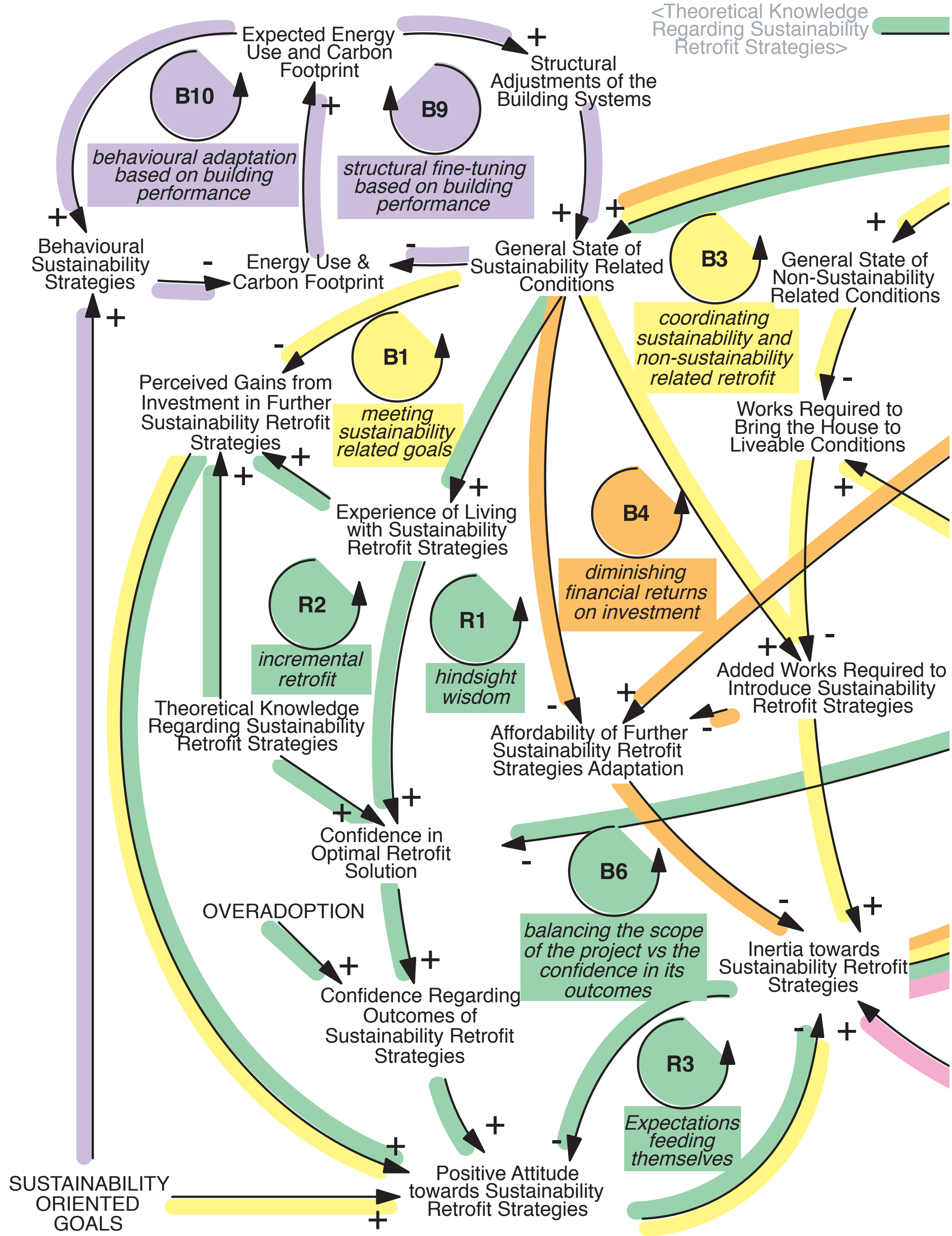
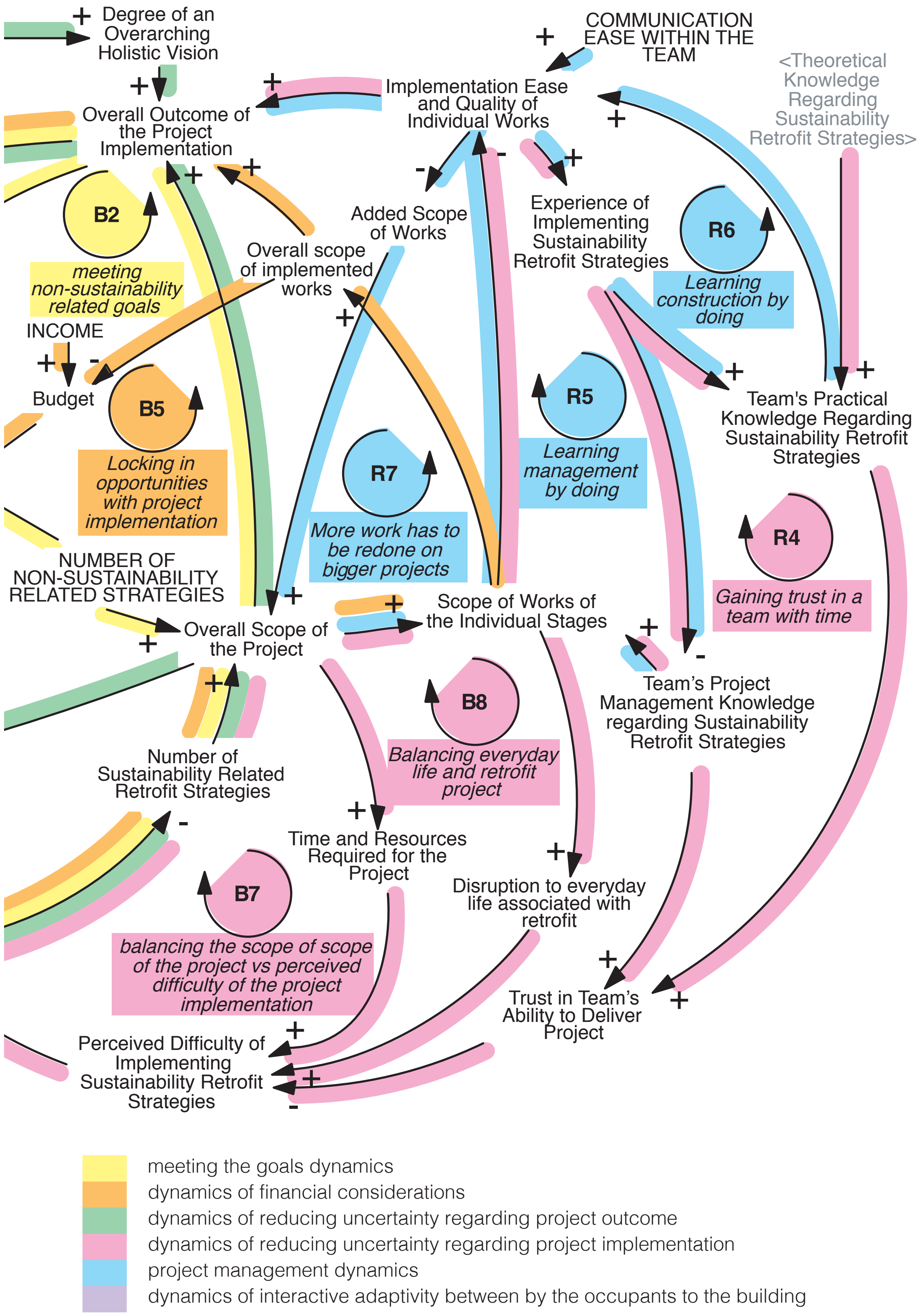


Figure CE.1. Combined causal diagram of common patterns in retrofit-decision processes across eight cases


Degree of an Overarching Holistic Vision
Overall Outcome of the Project Implementation
B2
meeting non-sustainability related goals
INCOME
Budget
B5
Locking in opportunities with project implementation
NUMBER OF NON-SUSTAINABILITY RELATED STRATEGIES
Overall Scope of the Project
Number of Sustainability Related Retrofit Strategies
B7
balancing the scope of scope of the project vs perceived difficulty of the project implementation
Perceived Difficulty of Implementing Sustainability Retrofit Strategies
Overall scope of implemented works
Added Scope of Works
Implementation Ease and Quality of Individual Works
R7
More work has to be redone on bigger projects
Scope of Works of the Individual Stages
B8
Balancing everyday life and retrofit project
Time and Resources Required for the Project
Disruption to everyday life associated with retrofit
COMMUNICATION EASE WITHIN THE TEAM
Experience of Implementing Sustainability Retrofit Strategies
R5
Learning management by doing
R6
Learning construction by doing
<Theoretical Knowledge Regarding Sustainability Retrofit Strategies>
Team's Practical Knowledge Regarding Sustainability Retrofit Strategies
R4
Gaining trust in a team with time
Team's Project Management Knowledge regarding Sustainability Retrofit Strategies
Trust in Team's Ability to Deliver Project
meeting the goals dynamics
dynamics of financial considerations
dynamics of reducing uncertainty regarding project outcome
dynamics of reducing uncertainty regarding project implementation
project management dynamics
dynamics of interactive adaptivity between by the occupants to the building

Appendix CF
Retrofit-decision process diagrams

This appendix provides innovation-decision process diagrams for eight case studies, carried out for this thesis (Figures CF.1–CF.8). Stages of the innovation-decision process are conceptualised from the ones outlined by Rogers (2003). The diagrams start on the next page.

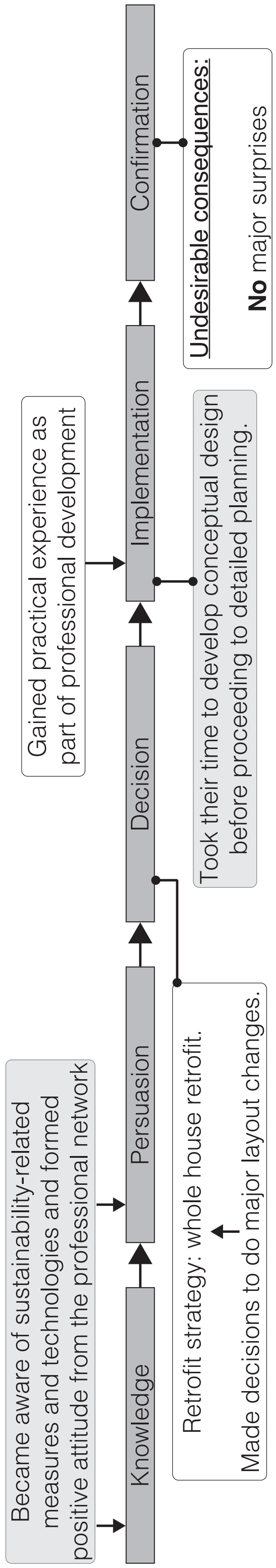


Figure CF.1. Stages in the individual decision-making process. Case A

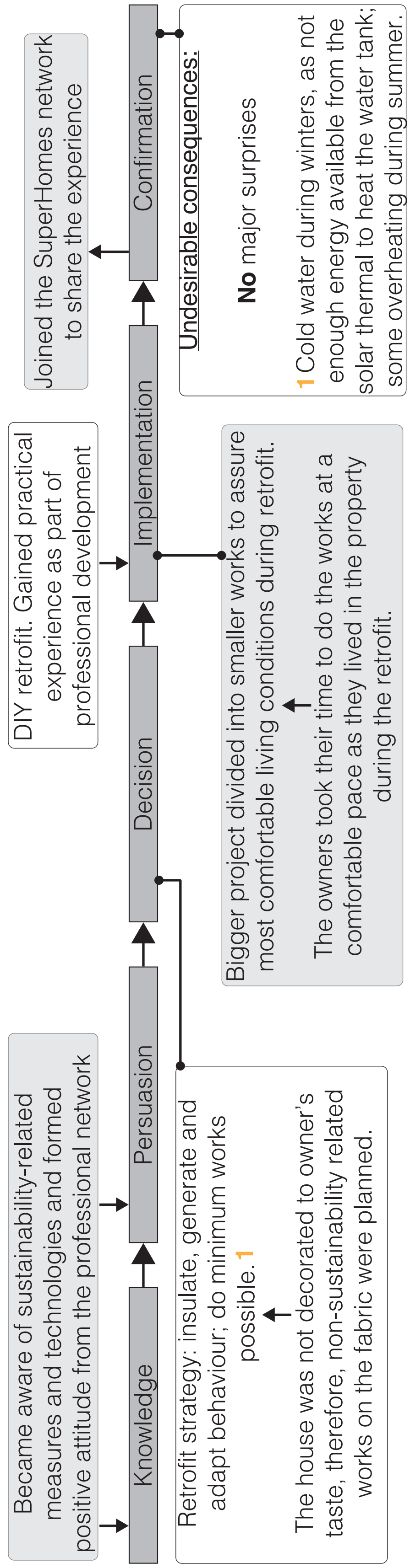


Figure CF.2. Stages in the individual decision-making process. Case B

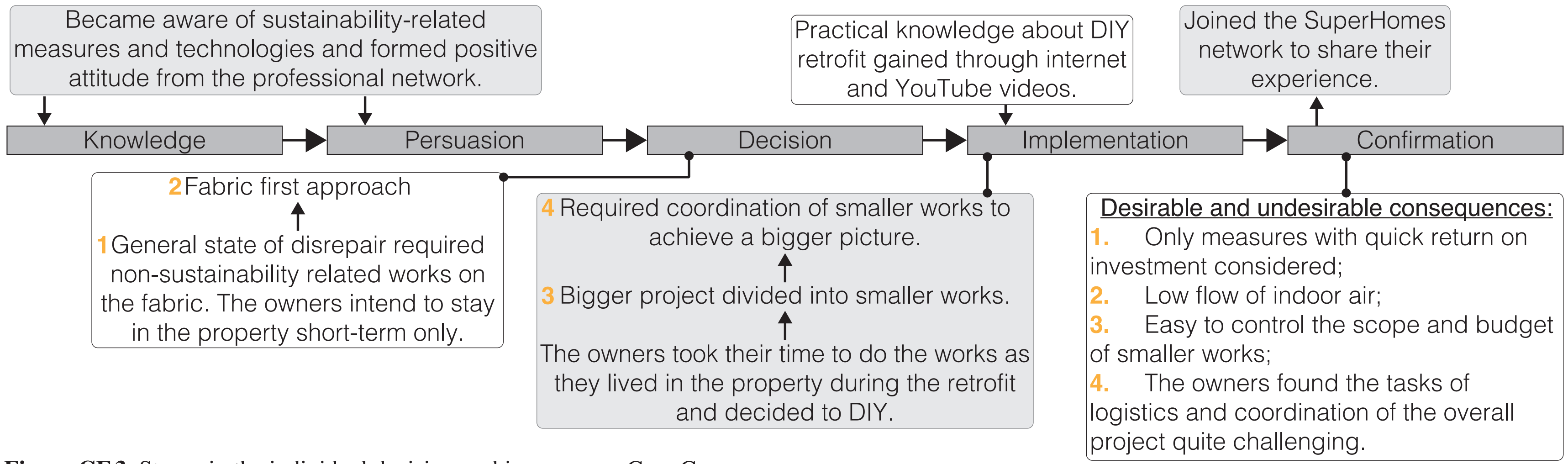


Figure CF.3. Stages in the individual decision-making process. Case C

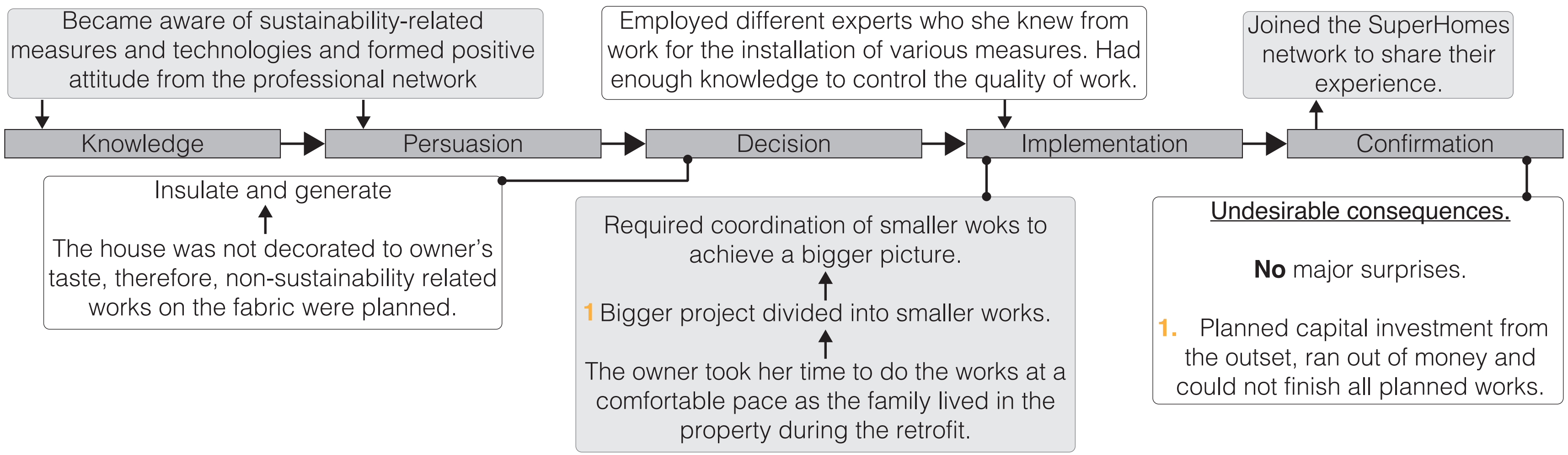


Figure CF.4. Stages in the individual decision-making process. Case D

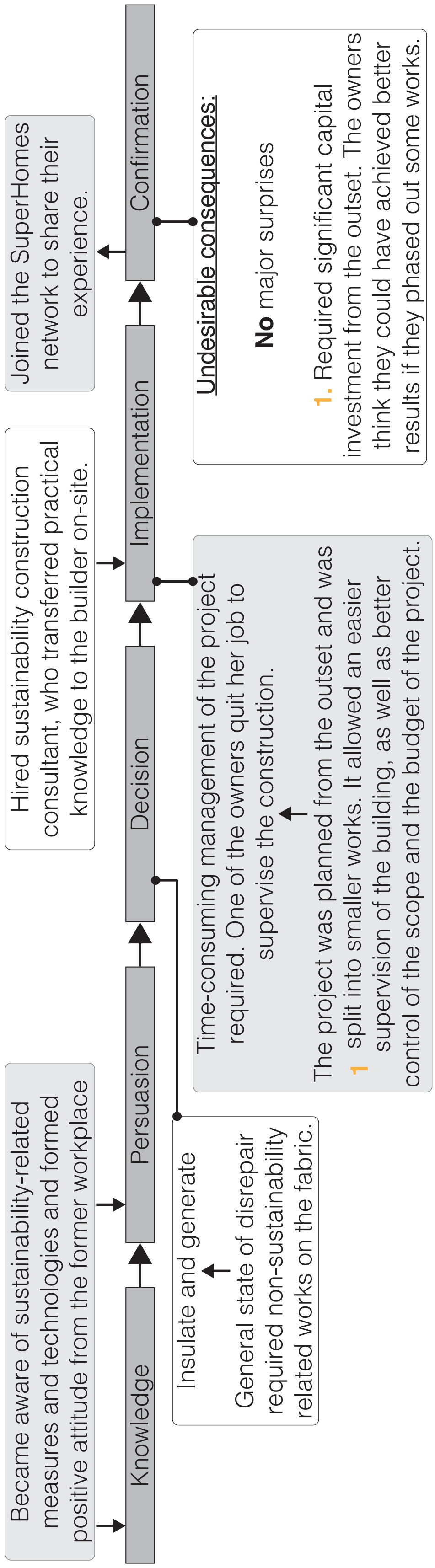


Figure CF.5. Stages in the individual decision-making process. Case E

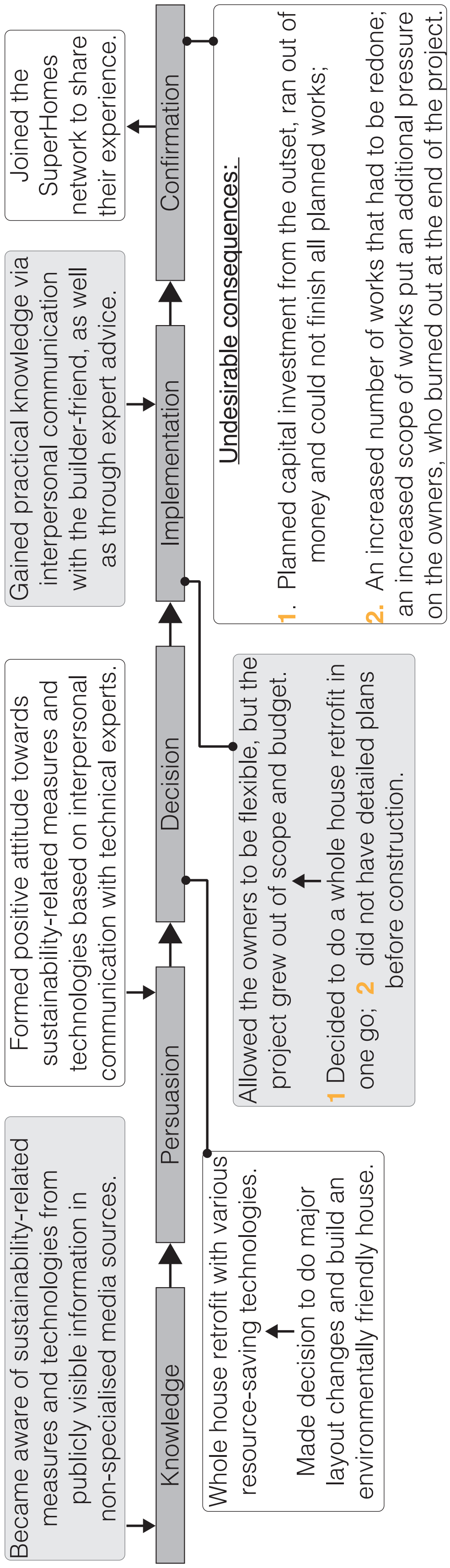


Figure CF.6. Stages in the individual decision-making process. Case F

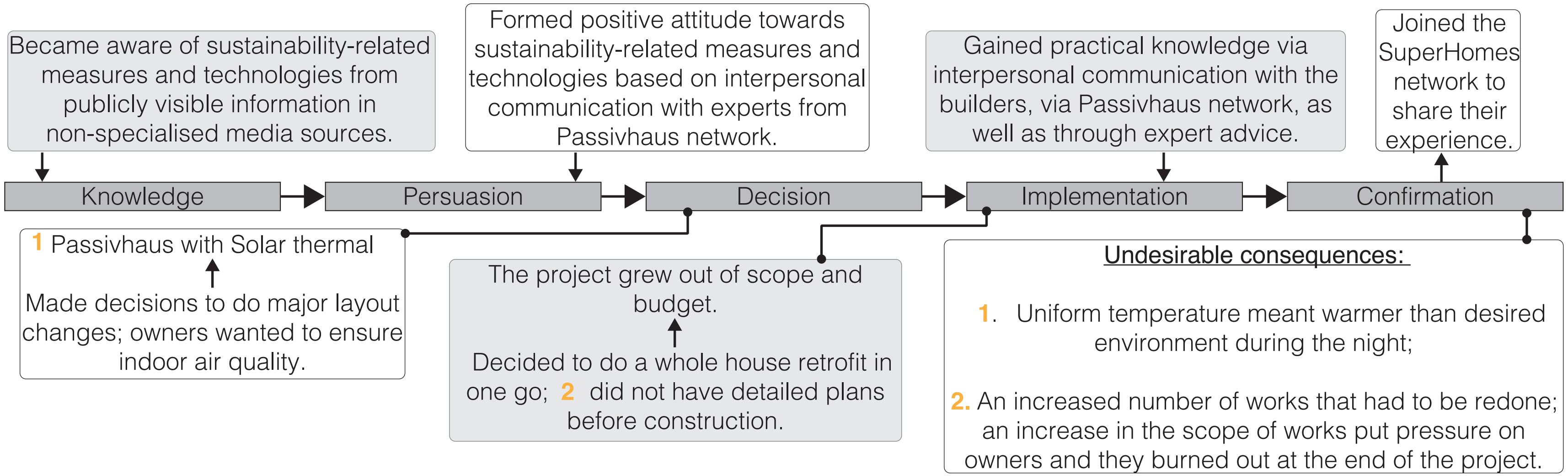


Figure CF.7. Stages in the individual decision-making process. Case G

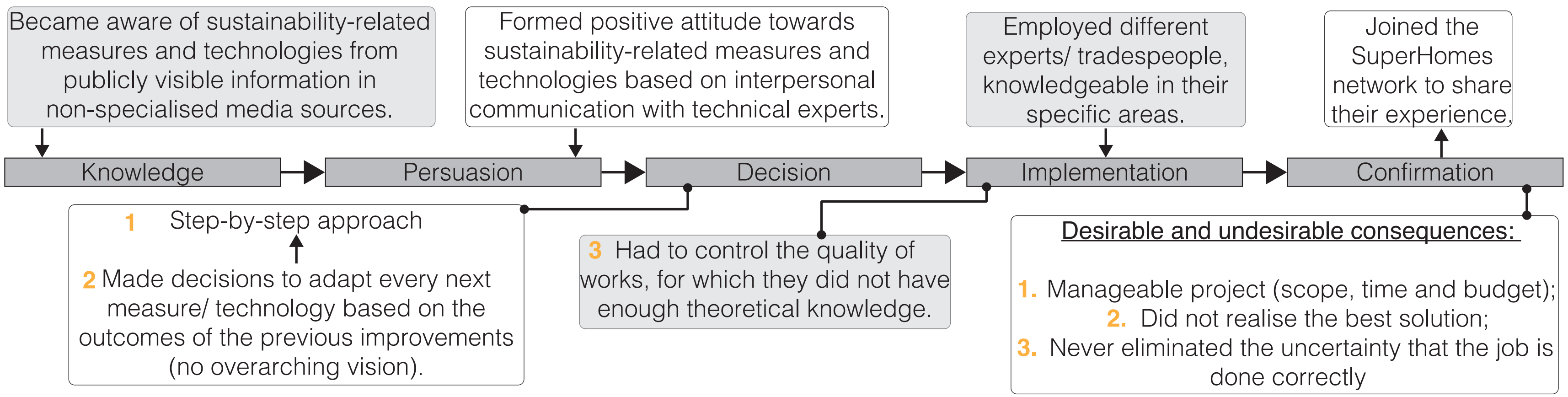


Figure CF.8. Stages in the individual decision-making process. Case H

Appendices D

System dynamics modelling process

These appendices give an insight in the system dynamics modelling process, by exemplifying the types of analytical records generated and used during the process:

Appendix DA
Model documentation

This appendix provides a complete, equation by equation list of the simulation model. The model has five stocks. Documentation follows the same logic and is divided in five sections: *(i) motivation and control, (ii) goal value and performance targets; (iii) resources allocation and effort, (iv) stress, fatigue and recovery* and *(v) activity performance*. The stock and flow diagrams presented in the main text are included here for clarity. Each diagram is followed by the corresponding equations for the variables it depicts. For diagrams that contain stocks, the first equations list the formulations for the state variables, and then corresponding rates of change. Other equations are presented alphabetically. For diagrams that do not contain stocks, the equations are presented alphabetically.

Some functions predefined in Vensim software have been used. A description of the functions used are given in table DA.1. The full list of functions can be found in Vensim documentation (Ventana Systems, 2019).

Table DA.1. List of predefined functions used in the model

IF THEN ELSE (cond, X, Y)	Returns X if condition is non-zero, otherwise Y
INTEG (R,N)	Performs numerical integration of R starting at N (defines a Level)
MAX (A,B)	The larger of A and B.
MIN (A,B)	The smaller of A and B.
SQRT(X)	Returns the square root of X.
ZIDZ(A,B)	Zero (0.0) if dividing by zero (B=0) otherwise returns A divided by B.
PULSE TRAIN(S,D,R,E)	A repeated pulse of height 1.0, starting at time S, lasting B time units and repeating every R time unit until time E.

DA.1. MOTIVATION AND CONTROL SECTOR

This sector is divided in two subsectors: one that depicts variables associated with the *Perceived Benefits of an Active Goal* variable and the one that depicts variables associated with the *Perceived Control* stock.

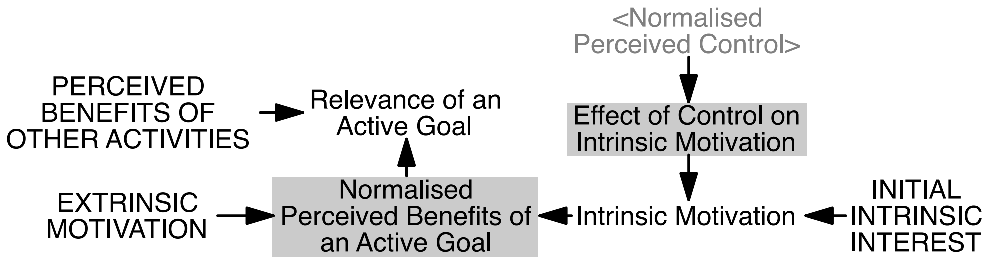


Figure DA.1. SFD for goals and motivation variables

Effect of Control on Intrinsic Motivation

= Normalised Perceived Control

Units: Dmnl

Logic: A linear effect is assumed between the feeling of control and intrinsic motivation.

EXTRINSIC MOTIVATION

Value: 1

Units: Dmnl

Logic: Examples of extrinsic motivation include pay and tangible short-term rewards. The importance of rewards is measured on a scale from 0 to 1, with 0 being no extrinsic rewards and 1 being maximum meaningful extrinsic rewards for an individual.

INITIAL INTRINSIC INTEREST

Value: 1

Units: Dmnl

Logic: Personal goals are driven by intrinsic motivation, “concerned with the pursuit of meaningful, desired activities, and integrated into the developed motivational structure of the individual” (Hockey, 2013: p. 110). The variable describes an initial interest to engage in the activity based on such personal goals.

Intrinsic Motivation

= SQRT (Effect of Control on Intrinsic Motivation * INITIAL INTRINSIC INTEREST)

Units: Dmnl

Logic: The notion of intrinsic motivation is closely linked to a feeling of control. Control is understood as “a sense of self-determination or autonomy in how, when and what work is carried out” (Hockey, 2013: p. 35). Personal goals, driven by intrinsic motivation, tend to have high levels of control, including a possibility to abandon the activity. Thus, when “*want to* goals have lost their earlier reward value and become a chore” (Hockey, 2013: p. 134)., they can be quickly abandoned and the performance drops to zero.

Harmonic average or *strict compromise* (formula: √(xy)) has been used to describe how the feeling of control and initial interest influence the change in intrinsic motivation of an individual. When the parameters have their maximum value of 1, the output will match that of a *lenient compromise* or *arithmetic average* (formula: (x + y) / 2). At the extremes of one of the inputs being 0 the response is also 0, which represents strict case or logical AND (formula: xy) (Hayward et al., 2014: p. 8). Thus, if there is full control and a strong initial desire to pursue the activity, intrinsic motivation equals one. However, if there is no sense of control or no initial desire to engage in the activity, intrinsic motivation is zero.

Normalised Perceived Benefits of an Active Goal

= (EXTRINSIC MOTIVATION + Intrinsic Motivation) – EXTRINSIC MOTIVATION * Intrinsic Motivation

Units: Dmnl

Logic: Perceived benefits of an active goal consist of a combined effect of both intrinsic and extrinsic motivation.

Lenient combination or *Logical OR* (formula: x + y – x*y) has been used to describe how intrinsic and extrinsic motivation are combined to form perceived benefits of an active goal. With lenient combination formulation “if one soft variable is switched off the response follows the full range of the other variable. If however one variable is at its maximum 1, the second variable can have no further effect" (Hayward et al., 2014: p. 9). Thus, if the values of both intrinsic and extrinsic motivation are 1, the overall perceived benefits are also 1. If, one parameter has a value of 1, for instance if extrinsic motivation is 1, the perceived benefits are 1 regardless of whether the activity is underpinned by intrinsic motivation or not. Thus, the value is normalised and is used to calculate the effect of perceived benefits on other variables in the model.

PERCEIVED BENEFITS OF OTHER ACTIVITIES

Value: 0

Units: Dmnl

Logic: Perceived benefits (for both — active goal and other activities) are measured on a scale from 0 to 1. The values above 1 do not have any further effect on a change in individual's behaviour.

Relevance of an Active Goal

= ZIDZ (Normalised Perceived Benefits of an Active Goal, (Normalised Perceived Benefits of an Active Goal + PERCEIVED BENEFITS OF OTHER ACTIVITIES))

Units: Dmnl

Logic: The construct assesses the commitment of an individual to the current activity, relative to other activities. If the perceived benefits of each of the two activities equals 1, it is assumed that they are equally relevant for an individual. "Under most circumstances an increased commitment to task goals is assumed to imply a decrease in the relevance of other personal or biological goals, such as those concerned with leisure, rest or well-being" (Hockey, 1997: p. 78).

A normalised value is used to calculate the effect of relevance of an active goal on other variables in the model.

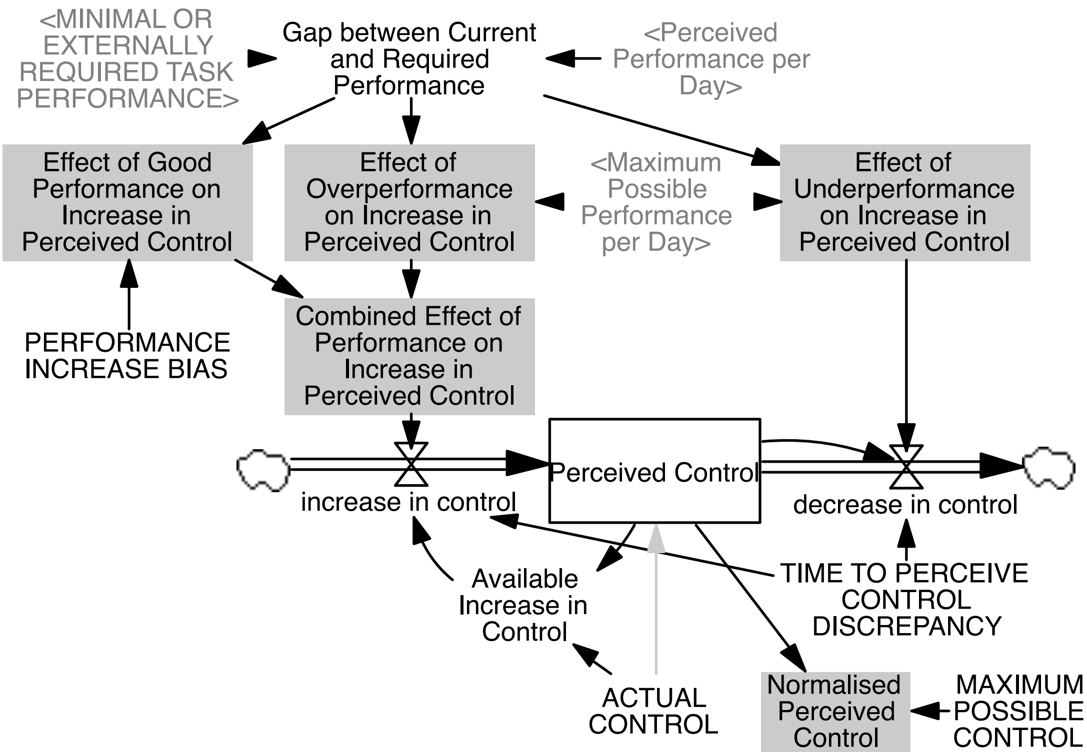


Figure DA.2. SFD for Perceived Control stock

Perceived Control

= INTEG (increase in control – decrease in control, ACTUAL CONTROL)

Units: Dmnl

Logic: Control is understood as "a sense of self-determination or autonomy in how, when and what work is carried out" (Hockey, 2013: p. 35). The concept is closely linked to the notions of "intrinsic motivation and satisfaction from work well done" (Hockey, 2013: p. 41).

increase in control

= (Available Increase in Control / TIME TO PERCEIVE CONTROL DISCREPANCY) * Combined Effect of Good Performance on Increase in Perceived Control

Units: 1/Day

Logic: A change in a sense of control should be understood in relation to performance, stress and fatigue. "…the development of a stress state often precedes fatigue" (Hockey, 2013: p. 94). In its turn, "stress is considered primarily from the perspective of task performance. Stress states are identified with the occurrence of a mismatch between required and prevailing task states" (Hockey, 1997: p. 76).

Such mismatch underpins a sense of control loss over an activity, which can itself act as a stressor: "…for example, high levels of workload may generate anxiety associated with threat to task outcomes or fear of failure from ineffective coping" (Hockey, 2013: p. 86). If an individual performs better than required, the sense of control increases until it reaches its maximum value.

decrease in control

= (Perceived Control / TIME TO PERCEIVE CONTROL DISCREPANCY) * Effect of Underperformance on Increase in Perceived Control

Units: 1/Day

Logic: A change in a sense of control should be understood in relation with performance, stress and fatigue (see logic for *increase in control*). If an individual performs worse than required, a sense of control is gradually lost.

ACTUAL CONTROL

Value: 1

Units: Dmnl

Logic: Control is understood as "a sense of self-determination or autonomy in how, when and what work is carried out" (Hockey, 2013: p. 35). The level of control varies on a scale from zero to one, with one representing full control in how, when or what work is carried out (self-initiated activity without strict deadlines), and zero representing an absolute lack of control.

Available Increase in Control

= ACTUAL CONTROL – Perceived Control

Units: Dmnl

Logic: There is a mismatch between the actual and perceived control over an activity. Perceived control can be lower than the amount of control actually available, but it cannot be higher. This variable determines the discrepancy between the two.

Combined Effect of Good Performance on Increase in Perceived Control

= Effect of Good Performance on Increase in Perceived Control +
Effect of Overperformance on Increase in Perceived Control

Units: Dmnl

Logic: The combined effect of performance is an addition of variables, which determines the effects of good performance and overperformance.

Effect of Good Performance on Increase in Perceived Control

= IF THEN ELSE (Gap between Current and Required Performance <= 0, 1 , 0) *
PERFORMANCE INCREASE BIAS

Units: Dmnl

Logic: If an individual performs as good as required or even better than required, a sense of control increases by a constant amount of *PERFORMANCE INCREASE BIAS*.

Effect of Overperformance on Increase in Perceived Control

= MAX (0, – Gap between Current and Required Performance /
Maximum Possible Performance per Day)

Units: Dmnl

Logic: A normalised value is used to calculate the effect of overperformance, represented by a negative gap, on other variables in the model. The gap is normalised against a value of maximum possible performance. A linear effect is assumed between the performance gap and an increase in the sense of control.

Effect of Underperformance on Increase in Perceived Control

= MAX (0, Gap between Current and Required Performance /
Maximum Possible Performance per Day)

Units: Dmnl

Logic: A normalised value is used to calculate the effect of underperformance, represented by a positive gap, on other variables in the model. The gap is normalised against a value of maximum possible performance. A linear effect is assumed between the performance gap and a decrease in the sense of control.

Gap between Current and Required Performance

= EXTERNALLY REQUIRED TASK PERFORMANCE – Perceived Performance per Day

Units: Accomplishments/Day

Logic: A gap between the current and required performance is determined by subtraction.

MAXIMUM POSSIBLE CONTROL

Value: 1

Units: Dmnl

Logic: Control is understood as "a sense of self-determination or autonomy in how, when and what work is carried out" (Hockey, 2013: p. 35). The level of control varies on a scale from zero to one, with one representing the maximum possible control in how, when or what work is carried out.

Normalised Perceived Control

= Perceived Control / MAXIMUM POSSIBLE CONTROL

Units: Dmnl

Logic: A normalised value is used to calculate the effect of control on other variables in the model.

PERFORMANCE INCREASE BIAS

Value: 0.1

Units: Dmnl

Logic: If an individual performs as good as required or even better than required, then a sense of control increases. An increase is assumed to be constant.

TIME TO PERCEIVE CONTROL DISCREPANCY

Value: 30

Units: Day

Logic: It is assumed to take about a month to adjust the perception of control.

DA.2. GOAL VALUE AND PERFORMANCE TARGETS SECTOR

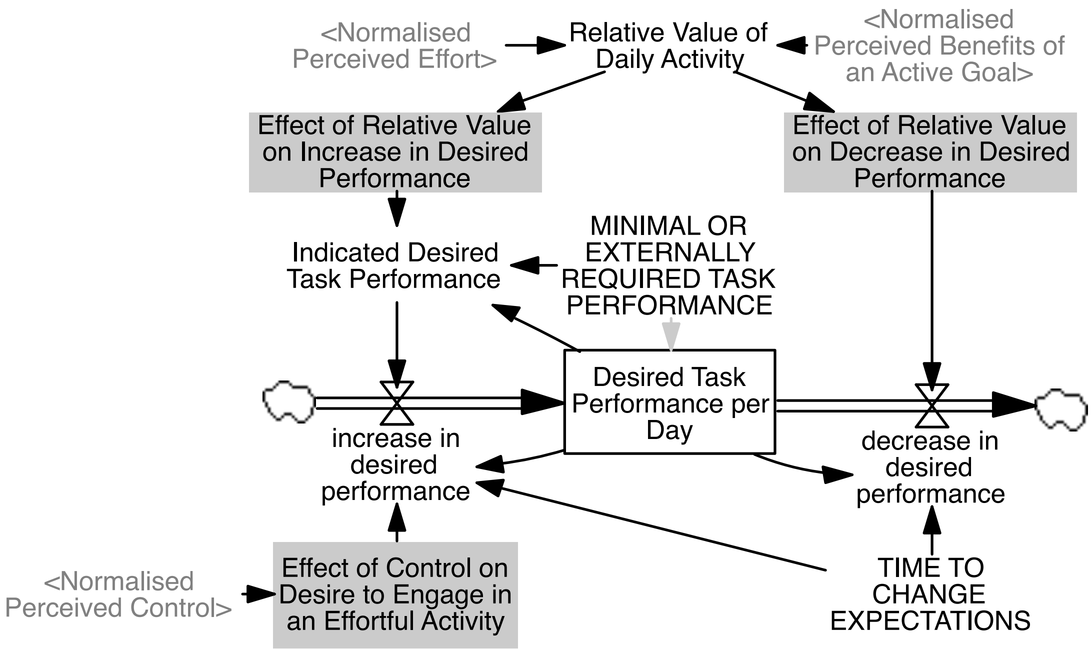


Figure DA.3. SFD for Desired Task Performance per Day stock

Desired Task Performance per Day

= INTEG (increase in desired performance – decrease in desired performance, EXTERNALLY REQUIRED TASK PERFORMANCE)

Units: Accomplishments/Day

Logic: In the current context the term ‘human performance’ refers to “the effectiveness of specific skills in meeting (typically externally-imposed) cognitive goals” (Hockey, 1997: p. 77). Accomplishments per Day are assumed as units of measurement of human performance. The initial level of desired performance is “determined by both long-term and short-term goals, which determine output criteria for behaviour (how fast to work, how much monitoring of accuracy is required, the order in which actions are executed, and so on)” (Hockey, 1997: p. 79).

increase in desired performance

= ((Indicated Desired Task Performance – Desired Task Performance per Day) / TIME TO CHANGE EXPECTATIONS) * Effect of Control on Desire to Engage in an Effortful Activity

Units: Accomplishments/(Day*Day)

Logic: The initial level of desired performance is determined by the goals. However, the level is “assumed to be subject to modification in the light of changes in the perceived costs and benefits of alternative states and actions” (Hockey, 1997: p. 79). If benefits are greater than perceived costs, then the individual raises the level of desired performance.

decrease in desired performance

= (Desired Task Performance per Day / TIME TO CHANGE EXPECTATIONS) * Effect of Relative Value on Decrease in Desired Performance

Units: Accomplishments/(Day*Day)

Logic: The initial level of desired performance is determined by the goals. However, the level is “assumed to be subject to modification in the light of changes in the perceived costs and benefits of alternative states and actions” (Hockey, 1997: p. 79). If costs are greater than perceived benefits, then the level of desired performance gradually deteriorates.

Effect of Control on Desire to Engage in an Effortful Activity

= Normalised Perceived Control

Units: Dmnl

Logic: A lost sense of control leads to an unwillingness to get involved in an effortful activity regardless of perceived benefits or actual control options: “The perceived benefits associated with pursuing effortful goals may become chronically diminished by the increasing costs required to attain them, giving way to an increasing attractiveness of low effort modes of engagement. There is a natural link, of course, with the mechanism of learned helplessness (Seligman, 1975), since the experience with increasingly uncontrollable events is at the heart of the development of reduced expectations of future control. I would further suggest that a strategy of reduced engagement would be very likely to generalize to all tasks, both work and non-work, and also, as the learned helplessness theory predicts, even to activities where control is normally available” (Hockey, 2013: p. 200).

A linear effect between a sense of control and desire to raise one’s performance targets is assumed.

Effect of Relative Value on Decrease in Desired Performance

= 1 – 2* MIN (0.5, Relative Value of Daily Activity)

Units: Dmnl

Logic: The *Relative Value of Daily Activity* is defined as benefits to costs ratio and is determined by the formula x / (x + y). This formulation puts the value on a scale from 0 to 1. When the values are below 0.5, the activity is considered too effortful to pursue and the desired performance targets are reduced. The formula 1 – 2 * MIN (0.5, Relative Value of Daily Activity) puts the effect of such effortful activity on a scale from zero to one. Also, when the benefits associated with the activity equal zero, there is no value to pursue the activity, and the effect on decrease in desired performance is one.

A linear effect is assumed between the value of a current activity and the decrease in desired task performance.

Effect of Relative Value on Increase in Desired Performance

= 2 * (MAX (0.5, Relative Value of Daily Activity) – 0.5)

Units: Dmnl

Logic: The *Relative Value of Daily Activity* is defined as the benefits to costs ratio and is determined by the formula x / (x + y). This formulation puts the value on a scale from 0 to 1. When the values are above 0.5, the activity is more rewarding than effortful and desired performance targets are increased. The formula 2 * (MAX (0.5, Relative Value of Daily Activity) – 0.5) puts the effect of such effortful activity on a scale from zero to one. Also, when the benefits associated with the activity equal zero, there is no value to pursue the activity, and the effect on increase in desired performance is zero.

A linear effect is assumed between a value of a current activity and an increase in desired task performance.

Indicated Desired Task Performance

= MAX (EXTERNALLY REQUIRED TASK PERFORMANCE,
Desired Task Performance per Day *
(1 + Effect of Relative Value on Increase in Desired Performance))

Units: Accomplishments/Day

Logic: The variable sets the goal for an increase in desired task performance, when the desired benefits are higher than perceived effort. The maximum value is chosen between the *EXTERNALLY REQUIRED TASK PERFORMANCE* and the increased performance targets relative to current desired performance.

MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE

Value: 8

Units: Accomplishments/Day

Logic: The variable represents performance targets required by extrinsic goals.

Relative Value of Daily Activity

= ZIDZ (Normalised Perceived Benefits of an Active Goal,
(Normalised Perceived Benefits of an Active Goal + Normalised Perceived Effort))

Units: Dmnl

Logic: The variable is defined as a “ratio of benefits to costs” (Hockey, 2013: p. 102) and is determined by the formula x / (x + y). This formulation puts the value on a scale from 0 to 1. When the values are below 0.5, the activity is considered too effortful to pursue and desired performance targets are reduced. When the values are above 0.5, the activity is more rewarding than effortful and desired performance targets are increased.

TIME TO CHANGE EXPECTATIONS

Value: 10

Units: Day

Logic: It is assumed to take about 10 days to change performance targets.

DA.3. RESOURCES ALLOCATION AND EFFORT SECTOR

This sector is divided in two subsectors: one that depicts variables associated with the *Hours Worked per Day on Current Activity* stock and the one that depicts *effort* variables.

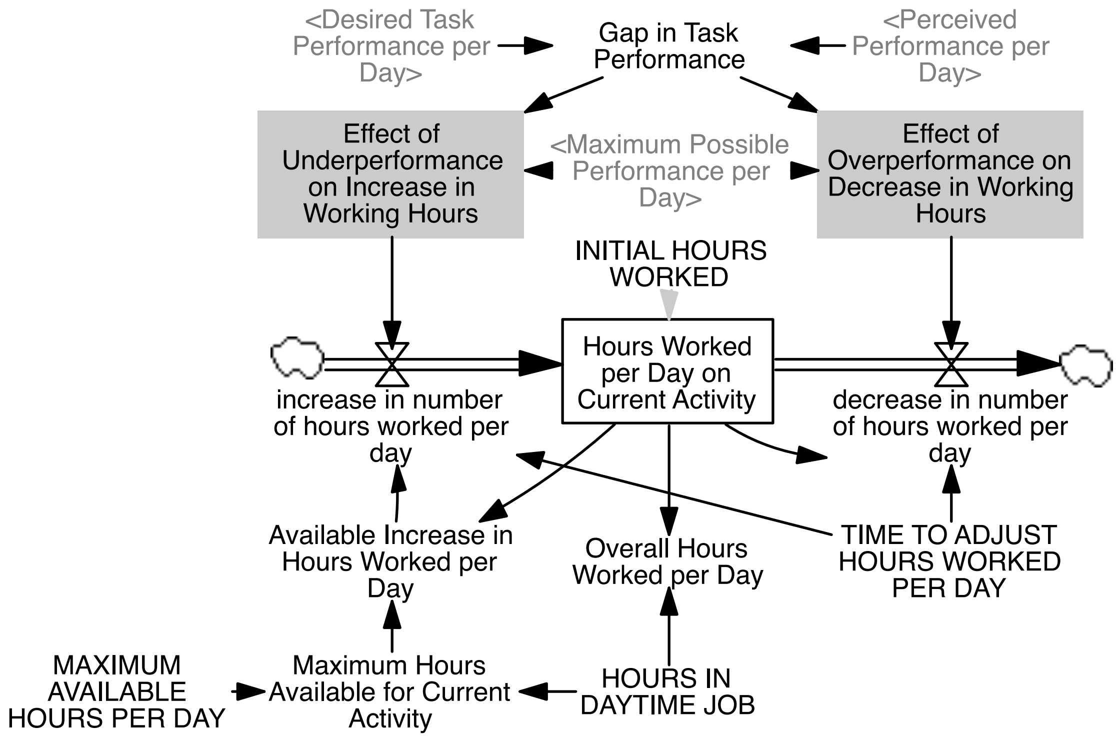


Figure DA.4. SFD for Hours Worked per Day on Current Activity stock

Hours Worked per Day on Current Activity

= INTEG (increase in number of hours worked per day – decrease in number of hours worked per day, INITIAL HOURS WORKED)

Units: Hours/Day

Logic: The construct of resources is central to the development of motivation control theory of fatigue. "[Resources] are conceptualised as the availability of one or more pools of general-purpose processing units, capable of performing elementary operations across a range of tasks, and drawing upon common 'energy' sources. … the resource construct also implies scarcity (the limited capacity assumption), so that simultaneous mental operations making demands on the same pool of resources must compete for processing units" (Hockey, 1997: p. 75–76). The notion of resource capacity has an important implication for understanding performance, as “performance breakdown occur[s] only when the overall capacity is exceeded” (Hockey, 1997: p. 73).

In the current model *Hours Worked per Day on Current Activity* are used as a proxy for the construct of resources. It is a reasonable approximation as the concept of time is consistent with the definitive characteristics of the concept of resources: (i) Allocation of time (resources) to a particular goal inevitable excludes allocation of these resources (time) to other goals. (ii) There is a limited number of hours per day (limited capacity assumption) and the breakdown in performance occurs, when the demand for working hours exceeds the hours available in a day. Initial level of resources allocation is determined by *INITIAL HOURS WORKED.* For simplicity the hours assumed to equal those of *WORKING EFFORT BUDGET.*

increase in number of hours worked per day

= (Available Increase in Hours Worked per Day on Current Activity /
TIME TO ADJUST HOURS WORKED PER DAY) *
Effect of Underperformance on Increase in Working Hours

Units: Hours/(Day*Day)

Logic: A change in the number of hours worked is associated with a perceived discrepancy between current and desired performance: “…deviations from goal criteria are detected via the negative feedback loop, where an action monitor compares the feedback from current output to that specified by the goal” (Hockey, 2013: p. 144). “…performance output values are continually adjusted to match these (goal-driven) target states” (Hockey, 1997: p. 79). If an individual performs worse than required, the number of hours allocated to the activity is increased until all available hours are allocated.

decrease in number of hours worked per day

= (Hours Worked per Day on Current Activity /
TIME TO ADJUST HOURS WORKED PER DAY) *
Effect of Overperformance on Decrease in Working Hours

Units: Hours/(Day*Day)

Logic: A change in the number of hours worked is associated with perceived discrepancy between current and desired performance (see logic for *increase in number* *of hours worked*). If an individual performs better than required, a number of hours allocated to the activity is gradually decreased.

Available Increase in Hours Worked per Day

= Maximum Hours Available for Current Activity – Hours Worked per Day

Units: Hours/Day

Logic: The variable depicts the gap (if any) between the current expenditure of hours and the maximum available hours per day for the current activity. It is not possible to spend more hours on the activity than it is physically available, regardless of the perceived discrepancy in performance.

Effect of Overperformance on Decrease in Working Hours

= MAX (0, – Gap in Task Performance / Maximum Possible Performance per Day)

Units: Dmnl

Logic: A normalised value is used to calculate the effect of overperformance, represented by a negative gap, on other variables in the model. The gap is normalised against a value of maximum possible performance. A linear effect is assumed between the performance gap and a decrease in working hours.

Effect of Underperformance on Increase in Working Hours

= MAX (0, Gap in Task Performance / Maximum Possible Performance per Day)

Units: Dmnl

Logic: Normalised value is used to calculate the effect of underperformance, represented by a positive gap, on other variables in the model. The gap is normalised against a value of maximum possible performance. A linear effect is assumed between performance gap and an increase in working hours.

Gap in Task Performance

= Desired Task Performance per Day – Perceived Performance per Day

Units: Accomplishments/Day

Logic: The gap between the current and desired performance is determined by a simple subtraction.

HOURS IN DAYTIME JOB

Value: 0

Units: Hours/Day

Logic: It is assumed that some activities do not compete for an individual's attention on the same level. For instance, post work activities compete for attention between each other, but not with day-time job activities. However, day-time job activities contribute to the overall feeling of engaging in effortful activities, which underpins the state of stress and subsequent development of fatigue.

INITIAL HOURS WORKED

Value: 8

Units: Hours/Day

Logic: The variable represents the amount of resources an individual initially assumed to be required. The default value is set to be equal to the one of the *WORKING EFFORT BUDGET*.

MAXIMUM AVAILABLE HOURS PER DAY

Value: 16

Units: Hours/Day

Logic: Hockey conceptualised different types of fatigue: mental, physical and sleepiness. Though not conclusive, there is evidence that mental fatigue and sleepiness have different origins in brain processes (Hockey, 2013: p. 175–176). The model only deals with mental fatigue. Thus, thus the maximum hours worked per day are limited to 16 hours, allowing 8 hours for sleep.

Maximum Hours Available for Current Activity

= MAXIMUM AVAILABLE HOURS PER DAY – HOURS IN DAYTIME JOB

Units: Hours/Day

Logic: The variable calculates the maximum hours per day available for current activity, such as retrofit works, assuming that a fixed amount of time is spent on other activities, which do not compete for an individual's attention and resources on the same level, such as daytime job activities.

Overall Hours Worked per Day

= HOURS IN DAYTIME JOB + Hours Worked per Day on Current Activity

Units: Hours/Day

Logic: The variable calculates the overall hours per day spent in effortful activities, such as daytime job and post work effortful activities, such as retrofit works.

TIME TO ADJUST HOURS WORKED PER DAY

Value: 7

Units: Day

Logic: It is assumed to take about a week to adjust working hours.

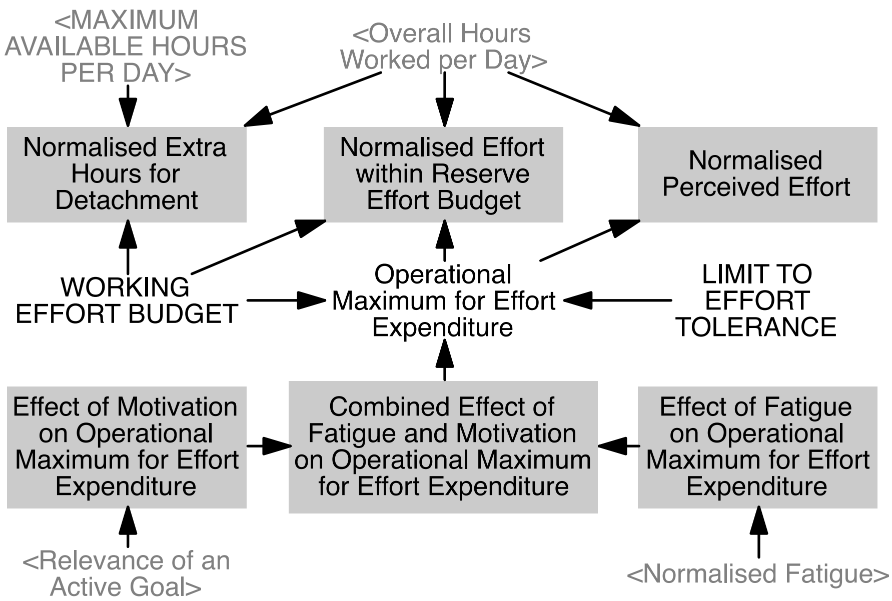


Figure DA.5. SFD for effort variables

Combined Effect of Fatigue and Motivation on Operational Maximum for Effort Expenditure

= Effect of Fatigue on Operational Maximum for Effort Expenditure * Effect of Motivation on Operational Maximum for Effort Expenditure

Units: Dmnl

Logic: The combined effect is calculated by multiplication. "The strict combination of soft variables x and y is the usual multiplication model, and is the equivalent of the logical AND. That is, if the effect of one soft variable is switched off, the other has no effect. If one is set to the maximum value of 1, the combined effect is the full range of the second variable" (Hayward, 2014: p. 8).

Effect of Fatigue on Operational Maximum for Effort Expenditure

= 1 – Normalised Fatigue

Units: Dmnl

Logic: See logic for *Operational Maximum for Effort Expenditure*. A linear effect is assumed between fatigue and *Operational Maximum for Effort Expenditure.*

Effect of Motivation on Operational Maximum for Effort Expenditure

= Relevance of an Active Goal

Units: Dmnl

Logic: See logic for *Operational Maximum for Effort Expenditure*. A linear effect is assumed between *Relevance of an Active Goal* and *Operational Maximum for Effort Expenditure.*

LIMIT TO EFFORT TOLERANCE

Value: 11

Units: Hours/Day

Logic: "The high effort (strain) response to work can be sustained only up to the individual's upper limit for effort tolerance (Cacioppo & Petty, 1981; Dornic, Ekehammar & Laaksonen, 1991)" (Hockey, 2013: p. 199–200).

In the model the *Limit to Effort Tolerance* is assumed to be 11 hours per day, which means that the maximum level of stress can be achieved when a person works 11 hours per day.

Normalised Effort within Reserve Effort Budget

= MIN (1, MAX (0, (Overall Hours Worked per Day –
WORKING EFFORT BUDGET) / (Operational Maximum for Effort Expenditure –
WORKING EFFORT BUDGET)))

Units: Dmnl

Logic: The model formulation ensures that an activity is not perceived as effortful, if performance is below *WORKING EFFORT BUDGET*. The maximum perception of effort is achieved at the *Operational Maximum for Effort Expenditure*. The MAX function ensures that the output is never below zero. MIN function ensures that the output is never above one.

Hockey conceptualises reserve effort budget as a difference between upper and lower set point for effort expenditure: "The lower set point is a default for a given task environment (the working effort budget), based on the anticipated resource needs of the task, level of skill, and so on. Increases in demands below this level are not felt as effortful, and control of performance appears automatic (loop A). The upper set point represents an operational maximum for effort expenditure. The difference between the two providing a reserve effort budget for meeting additional demands, unpredictable changes in the demands-resources balance, or the additional burden associated with stressful environments" (Hockey, 1997: p. 80).

Normalised Extra Hours for Detachment

= MAX (0, (Overall Hours Worked per Day – WORKING EFFORT BUDGET) / (MAXIMUM AVAILABLE HOURS PER DAY – WORKING EFFORT BUDGET))

Units: Dmnl

Logic: The model formulation ensures a possibility of complete recovery, if performance is below *WORKING EFFORT BUDGET*. As an individual starts working above the working effort budget, the possibility for recovery is reduced. The MAX function ensures that the output is never below zero.

Hockey describes the impact of hours worked on a development of fatigue as following: "Overall, there does not seem a strong basis for associating persisting fatigue problems with long working hours or shift work, though it is likely that both are contributory factors in the development of such conditions. More likely, they act as indirect causes, by reducing the opportunity for sleep and recovery from work stress, as well as limiting the buffering effects of family and social activities. There is now abundant evidence of the need for detachment from work and recovery from its effects (Sonnentag, 2011)" (Hockey, 2013: pp. 192–193).

Normalised Perceived Effort

= Overall Hours Worked per Day / Operational Maximum for Effort Expenditure

Units: Dmnl

Logic: In the model the costs of action are determined by the effort required to maintain them. Hours worked are normalised against *Operational Maximum for Effort Expenditure*. A normalised value is used to calculate the effect of perceived costs on other variables in the model.

Desired performance is "assumed to be subject to modification in the light of changes in the perceived costs and benefits of alternative states and actions (Hockey, 1993; Schönpflug, 1983)" (Hockey, 1997: p. 79). "At a first level of approximation, these costs may be interpreted as an expenditure of mental resources" (Hockey, 1997: p. 75).

Operational Maximum for Effort Expenditure

= MAX (WORKING EFFORT BUDGET + 0.5, LIMIT TO EFFORT TOLERANCE * Combined Effect of Fatigue and Motivation on Operational Maximum for Effort Expenditure)

Units: Hours/Day

Logic: In the model *Operational Maximum for Effort Expenditure* is affected by *Relevance of an Active Goal* and the *Feeling of Fatigue*. An addition of 0.5 Hours/Day in the formula means that an individual is only prepared to work half an hour more than initially planned on a demanding task, if fatigued.

Hockey proposes a two-level effort model, which differentiates between two effort set-points: lower and upper set point (Hockey, 1997). "The upper set point represents an operational maximum for effort expenditure. … The upper limit … is more clearly motivational in origin, and more variable. It is assumed to be a function of individual differences in the perceived value of tasks goals, in the response to challenge, in the capacity for sustained work, and in the tolerance of aversive states associated with high levels of strain. It is also likely to change more under the influence of short-term factors such as fatigue (Holding, 1983) and prevailing affective states (Ellis & Ashbrook, 1988; Wiethoff & Hockey, 1996)" (Hockey, 1997: p. 80).

WORKING EFFORT BUDGET

Value: 8

Units: Hours/Day

Logic: The variable represents the amount of resources an individual is ready to spend altogether on effortful activities per day. Thus, it is a working effort budget for all effortful activities, rather than for an individual activity. The terminology is consistent with the one used by Hockey: "the amount of effort allocated to a task is determined primarily by how much the performer assumes will be required, which – through experience with both this and similar tasks – may be estimated quite accurately and implemented in an effort budget" (Hockey, 2013: p. 145).

Effort is an ambiguous construct. In motivation control theory of fatigue effort is interpreted as "the subjective awareness of resource deployment" (Hockey, 1997: p. 80). Hockey proposes a two-level effort model, which differentiates between two effort set-points: lower and upper set point (Hockey, 1997). "The lower set point is a default for a given task environment (the working effort budget), based on the anticipated resource needs of the task, level of skill, and so on. … The lower set point is equivalent to the computational effort associated with task demands. It is determined primarily by an assessment of processing requirements for specific tasks, normally well below the assumed functional limits for effort expenditure, and is likely to be quite stable for a given individual" (Hockey, 1997: p. 80).

DA.4. STRESS, FATIGUE AND RECOVERY SECTOR

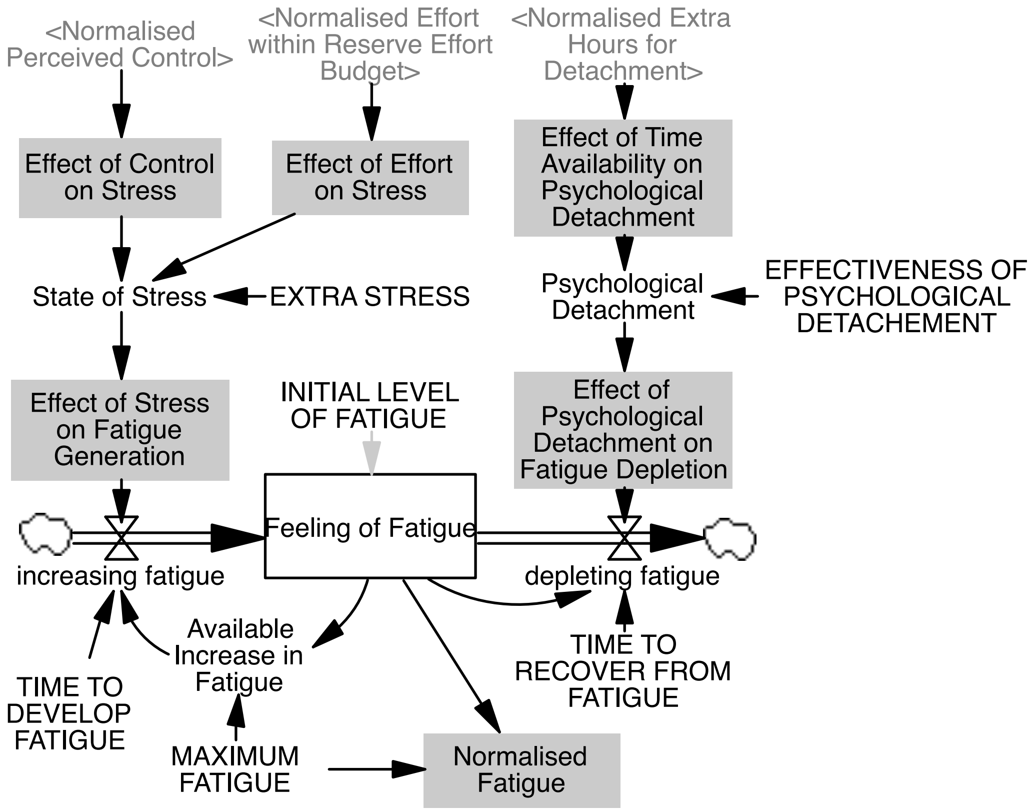


Figure DA.6. SFD for Feeling of Fatigue stock

Feeling of Fatigue

= INTEG (increasing fatigue – depleting fatigue, INITIAL LEVEL OF FATIGUE)

Units: Dmnl

Logic: The variable is modelled as a stock, as the feeling of fatigue accumulated over time and cannot be changed instantaneously.

Hockey understands fatigue as an emotion that serves a function of maintaining motivational equilibrium: "…fatigue may be considered as an emotion…" (Hockey, 2013: p. 132). […] "From an evolutionary psychology perspective (Cosmides & Tooby, 2000; Nesse, 1990) emotions are considered to operate as high level programmes, directing activities of the organism on the basis of current environmental and goal contexts" (Hockey, 2013: p. 99). […] "fatigue … is argued to serve an adaptive function of preventing motivational fixation on current activities, and redirecting behaviour towards those that have a higher utility (greater rewards or lower costs)" (Hockey, 2013: p. 135).

increasing fatigue

= (Available Increase in Fatigue / TIME TO DEVELOP FATIGUE) * Effect of Stress on Fatigue Generation

Units: 1/Day

Logic: In the model an increase in the level of fatigue is proportional to the existence and the strength of the state of stress.

The development of a feeling of fatigue should be understood in relation to state of stress: "…the relationship between fatigue and stress, … it will be clear that the present book also makes no sharp distinctions between the two. Rather, they are considered to be different facets of the same adaptive process…" (Hockey, 2013: p. 4).

depleting fatigue

= (Feeling of Fatigue / TIME TO RECOVER FROM FATIGUE) * Effect of Psychological Detachment on Fatigue Depletion

Units: 1/Day

Logic: In the model a decrease in the level of fatigue is proportional to the effectiveness of psychological detachment strategies.

The feeling of fatigue can be depleted if the stressors are no longer present. In the work environment it means that a person can recover after a stressful day at work after working hours: "Under favourable conditions, after-effects of work may be countered by post-work leisure activities that include desired (want to) goals, such as socializing and personal hobbies, and which also encourage more effective engagement with work on the following day (Bakker & Demerouti, 2007; Sonnentag, 2011; Winwood, Bakker & Winefield, 2007)" (Hockey, 2013: p. 192–193).

Available Increase in Fatigue

= MAXIMUM FATIGUE – Feeling of Fatigue

Units: Dmnl

Logic: The variable determines the discrepancy between the maximum possible level of fatigue and the actual level of fatigue an individual experiences.

Effect of Control on Stress

= 1 – Normalised Perceived Control

Units: Dmnl

Logic: A linear effect is assumed between the feeling of control and the state of stress. A situation is not considered stressful when it is under full control.

Effect of Effort on Stress

= Normalised Effort within Reserve Effort Budget

Units: Dmnl

Logic: A linear effect is assumed between effort and stress.

Effect of Psychological Detachment on Fatigue Depletion

= Psychological Detachment

Units: Dmnl

Logic: A linear effect is assumed between psychological detachment and fatigue depletion.

Effect of Stress on Fatigue Generation

= State of Stress

Units: Dmnl

Logic: A linear effect is assumed between the state of stress and fatigue generation.

Effect of Time Availability on Psychological Detachment

= 1 – Normalised Extra Hours for Detachment

Units: Dmnl

Logic: A linear effect is assumed between time availability and the possibility for full psychological detachment and recovery.

EFFECTIVENESS OF PSYCHOLOGICAL DETACHEMENT

Value: 1

Units: Dmnl

Logic: In the model the *EFFECTIVENESS OF PSYCHOLOGICAL DETACHMENT* is assumed to range from zero to one, with one representing a full ability to switch off from work and detach, and zero representing an absence of such ability.

Psychological detachment is a skill that could be learned. Some people are better in 'switching off' after a stressful work day, others are not: "Dr. Hockey: First, I assume you see detachment as a trained strategy or a skill that people have, rather than as a trait. … So it suggests that what you're looking for is people who have this flexibility of coping strategies, who can use strategies in a context-specific way" (Sonnentag, 2011: p. 268). […] "Maybe for some people, it is easier and for others not. Some people may also want to continue to dwell on all these problems. But at least in principle, you have the possibility to stop it …" (Sonnentag, 2011: p. 270). […] "…they learn to detach from work (e.g., by enacting work–home boundaries or by engaging in mindfulness exercises; Ashforth, Kreiner, & Fugate, 2000; Fredrickson, Cohn, Coffey, Pek, & Finkel, 2008)" (Sonnentag, 2011: p. 262).

EXTRA STRESS

Value: 0

Units: Dmnl

Logic: The variable captures non-job-related stressful conditions, such as worries about one's health or difficulties in personal relations.

INITIAL LEVEL OF FATIGUE

Value: 0

Units: Dmnl

Logic: It is assumed that individuals begin the retrofit processes fully rested. Thus, initial level of fatigue in the beginning of the process is zero.

MAXIMUM FATIGUE

Value: 1

Units: Dmnl

Logic: In the model the level of fatigue is determined on a scale from zero to one, with zero representing no feeling of fatigue and one representing a full state of fatigue.

Normalised Fatigue

= Feeling of Fatigue / MAXIMUM FATIGUE

Units: Dmnl

Logic: A normalised value is used to calculate the effect of fatigue on other variables in the model.

Psychological Detachment

= EFFECTIVENESS OF PSYCHOLOGICAL DETACHEMENT * Effect of Time Availability on Psychological Detachment

Units: Dmnl

Logic: Psychological detachment is an ability to switch off from work and detach.

"Etzion, Eden, and Lapidot (1998) introduced the detachment concept in the literature on job stress and job stress recovery. In a study on military research service as a respite, they defined detachment as an 'individual's sense of being away from the work situation' (Etzion et al., 1998: p. 579). … To emphasize the mental aspect (as opposed to a simple spatial aspect, for instance) of detachment, Sonnentag and Bayer (2005) suggested using the term psychological detachment. Psychological detachment from work during nonwork implies not being busy with job-related tasks during nonwork time and, most important, refraining from job-related task thoughts. In everyday terms, psychological detachment is often experienced as 'switching off' from work" (Sonnentag, 2011: p. 253).

State of Stress

= (Effect of Effort on Stress * Effect of Control on Stress + EXTRA STRESS) – Effect of Effort on Stress * Effect of Control on Stress * EXTRA STRESS

Units: Dmnl

Logic: In the model the state of stress is determined by multiplication between effects of effort and control. The formulation ensures that when one of the soft variables is zero, for instance when an activity is not considered effortful, the state of stress is also zero, regardless of the level of perceived control. Lenient combination or Logical OR (formula: $x + y – x * y$) has been used to describe how job-related and non-job-related stress combine to form the overall state of stress (Hayward et al., 2014).

"Stress is, therefore, a state in which homeostasis is threatened (or perceived to be threatened) by environmental conditions that are unpredictable and uncontrollable, and stabilized through a complex repertoire of both behavioural and physiological adaptive responses, including autonomic, hormonal and metabolic systems" (Hockey, 2013: p. 87).

Within the focus of his theory Hockey talks about stress in relation to commitment to task performance targets and control options: "Within the context of an analysis of the relationship between stress and fatigue, my main focus will be on strain, the effortful state of commitment to task goals that helps maintain them in focal attention" (Hockey, 2013: p. 88). A state of stress and a consequent feeling of fatigue is observed under effortful, low control conditions, where high levels of performance are required: "…fatigue occurs only under effortful, low control conditions, when demanding (normally externally imposed) tasks have to be performed well" (Hockey, 2013: p. 132–133).

TIME TO DEVELOP FATIGUE

Value: 30

Units: Day

Logic: It is assumed to take about a month to develop a full state of fatigue.

TIME TO RECOVER FROM FATIGUE

Value: 30

Units: Day

Logic: It is assumed to take about a month to completely recover from a full state of fatigue.

DA.5. ACTIVITY PERFORMANCE SECTOR

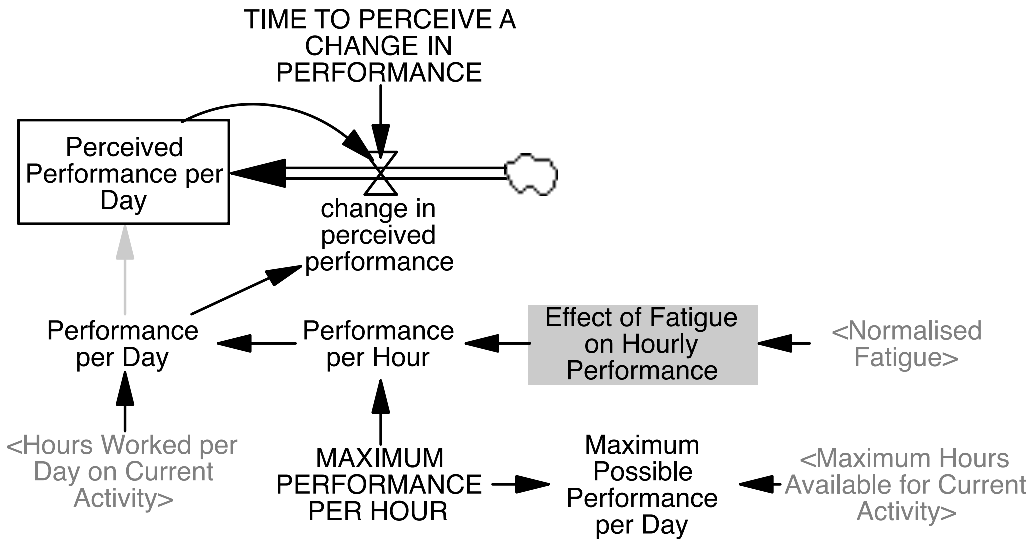


Figure DA.7. SFD for Perceived Performance per Day stock

Perceived Performance per Day

= INTEG (change in perceived performance, Performance per Day)

Units: Accomplishments/Day

Logic: It is not possible to assess performance instantly, so decision-makers are modelled as reacting to perceived performance, rather than to actual performance.

change in perceived performance

= (Performance per Day – Perceived Performance per Day) / TIME TO PERCEIVE A CHANGE IN PERFORMANCE

Units: Accomplishments/(Day*Day)

Logic: The stock of perceived performance is adjusted to the values of actual performance over time. It is an information smooth.

Effect of Fatigue on Hourly Performance

= 1 – Normalised Fatigue

Units: Dmnl

Logic: A linear effect between fatigue and hourly performance is assumed.

MAXIMUM PERFORMANCE PER HOUR

Value: 1

Units: Accomplishments/Hour

Logic: A person is assumed to deliver one accomplishment per hour if fully rested.

Maximum Possible Performance per Day

= Maximum Hours Available for Current Activity * MAXIMUM PERFORMANCE PER HOUR

Units: Accomplishments/Day

Logic: The variable determines the maximum possible performance per day, i.e. the performance, when an individual works with maximum efficiency for the maximum working hours available.

Performance per Day

= Hours Worked per Day on Current Activity * Performance per Hour

Units: Accomplishments/Day

Logic: Performance per day is determined by the multiplication of hourly performance and the number of hours worked per day.

Performance per Hour

= MAXIMUM PERFORMANCE PER HOUR * Effect of Fatigue on Hourly Performance

Units: Accomplishments/Hour

Logic: Performance is affected by the feeling of fatigue: "More effort will be required to maintain task goals under any emotional state, at any level; as long as the goals of this state are incompatible with those of the task a compensatory (high effort) strategy will be required to override them" (Hockey, 2013: p. 99).

TIME TO PERCEIVE A CHANGE IN PERFORMANCE

Value: 7

Units: Day

Logic: It is not possible to assess performance instantly. It is assumed to take about a week to perceive and assess a change in performance.

Appendix DB
Model testing and validation

This appendix presents input model parameters and results of model validation tests. The appendix has two sections:

DB.1. Behavior exploration tests.
DB.2. Theoretical behaviour reproduction and anomality tests.

DB.1. BEHAVIOUR EXPLORATION TESTS

The section lists the results of the behaviour exploration tests under a wide range of parameters with variation in initial values for the constructs of *ACTUAL CONTROL, INITIAL INTRINSIC MOTIVATION, EXTRINSIC MOTIVATION* and *MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE*. For the constructs of *INITIAL INTRINSIC MOTIVATION* and *EXTRINSIC MOTIVATION* three initial input values have been tested, roughly corresponding to minimum, maximum and average values of the constructs (Table DB.1). For the construct *ACTUAL CONTROL* also three initial values have been tested, roughly corresponding to low, high and average value of the construct. For the contract of *MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE* four input values have been tested, ranging from low to high. Overall it amounted to 109 different runs.

Table DB.1. Input parameters for behavior exploration tests

Variable name	Min	Max	Step
ACTUAL CONTROL	0.3	0.9	0.3
EXTRINSIC MOTIVATION	0	1	0.5
INITIAL INTRINSIC MOTIVATION	0	1	0.5
MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE	1	10	3

The model generates various patterns of behaviour, consistent with the logic of the model formulation. Results for the state variables *Hours Worked per Day on Current Activity, Perceived Performance per Day, Perceived Control* and *Feeling of Fatigue* can be found in Figures DB.1–DB.4.

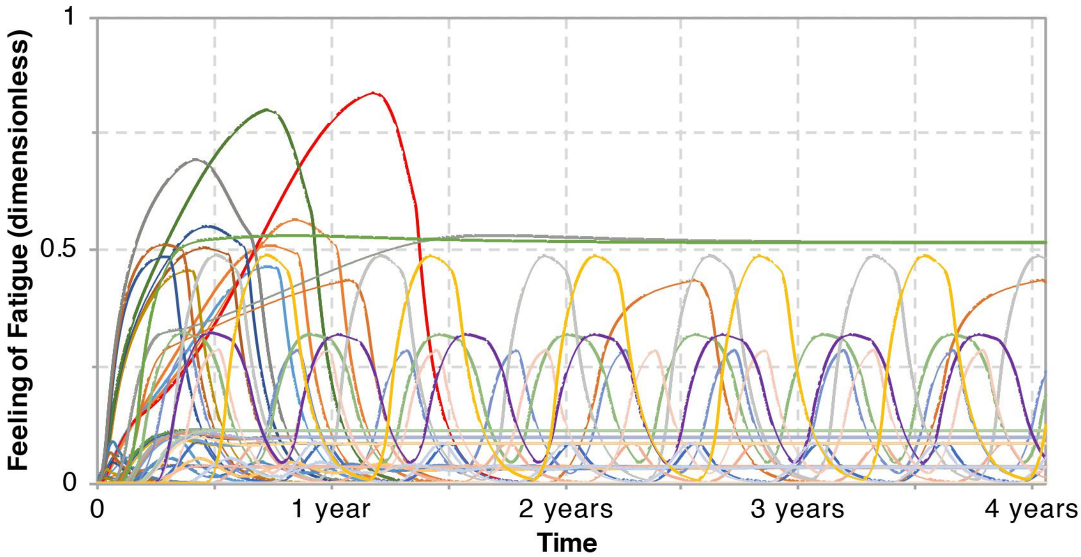


Figure DB.1. Feeling of Fatigue

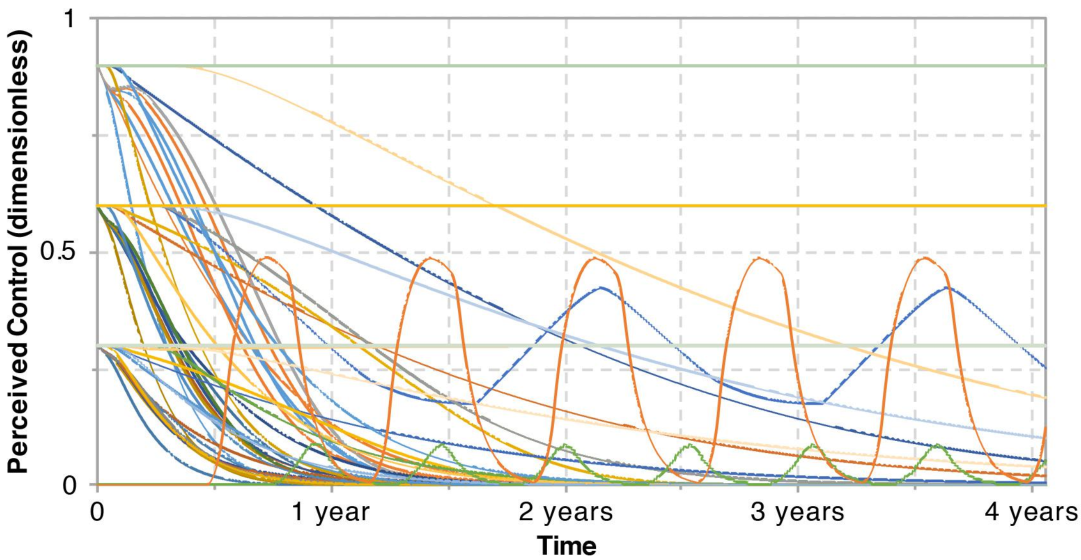


Figure DB.2. Perceived Control

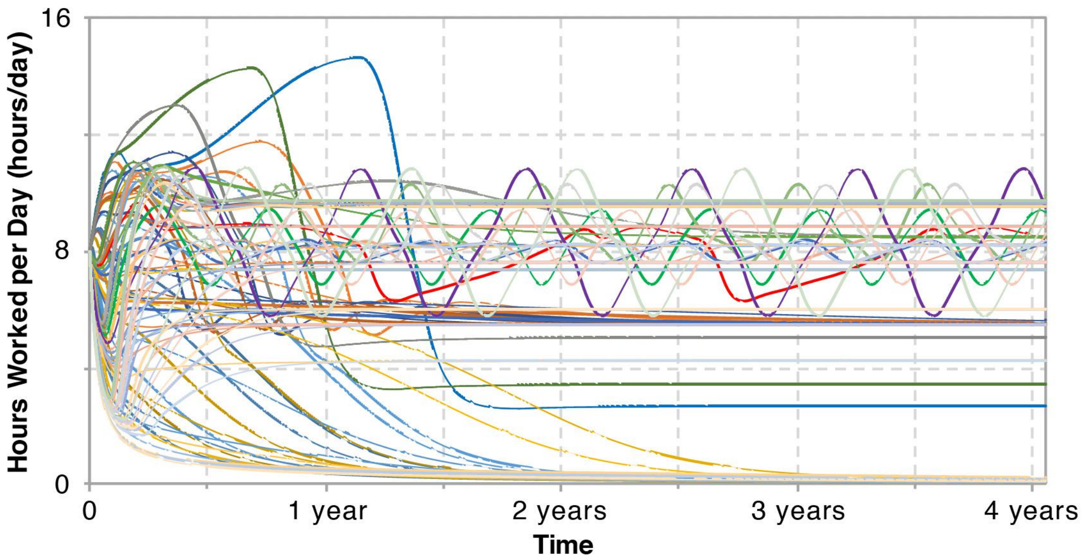


Figure DB.3. Hours worked per Day on Current Activity

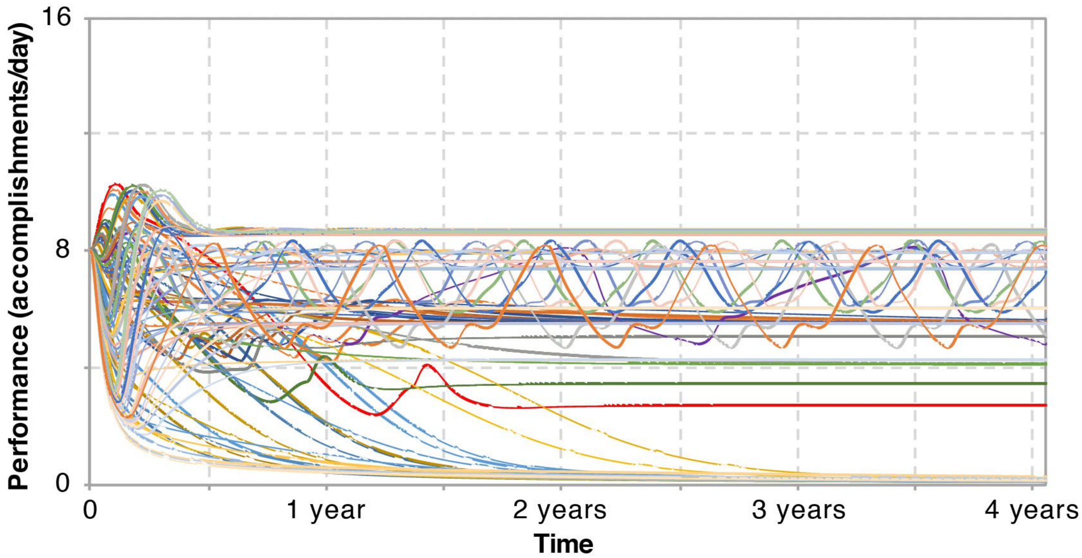


Figure DB.4. Performance per Day

DB.2. THEORETICAL BEHAVIOUR REPRODUCTION AND ANOMALY TESTS

Simulation results revealed five distinct work management modes: three already described by Hockey, and two not previously conceptualised by him. The figures below compare the five different work management modes for the parameters of *Feeling of Fatigue* (Figure DB.5), *Perceived Control* (Figure DB.6), *Hours Worked per Day on Current Activity* (Figure DB.7), and *Perceived Performance per Day* (Figure DB.8). The input parameters for the graphs are given in Table DB.2.

Table DB.2. Input parameters for comparison graphs of five work management modes

Variable name	Work management modes				
	Hockey: Engaged	Hockey: Disengaged	Hockey: Strain I	Strain II	Strain III
ACTUAL CONTROL	1	0.3	0.6	0.9	0.4
EXTRINSIC MOTIVATION	1	0.3	1	1	1
INITIAL INTRINSIC MOTIVATION	1	0.3	1	1	1
MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE	8	7	10	8	2
INITIAL HOURS WORKED	8	8	6	8	2

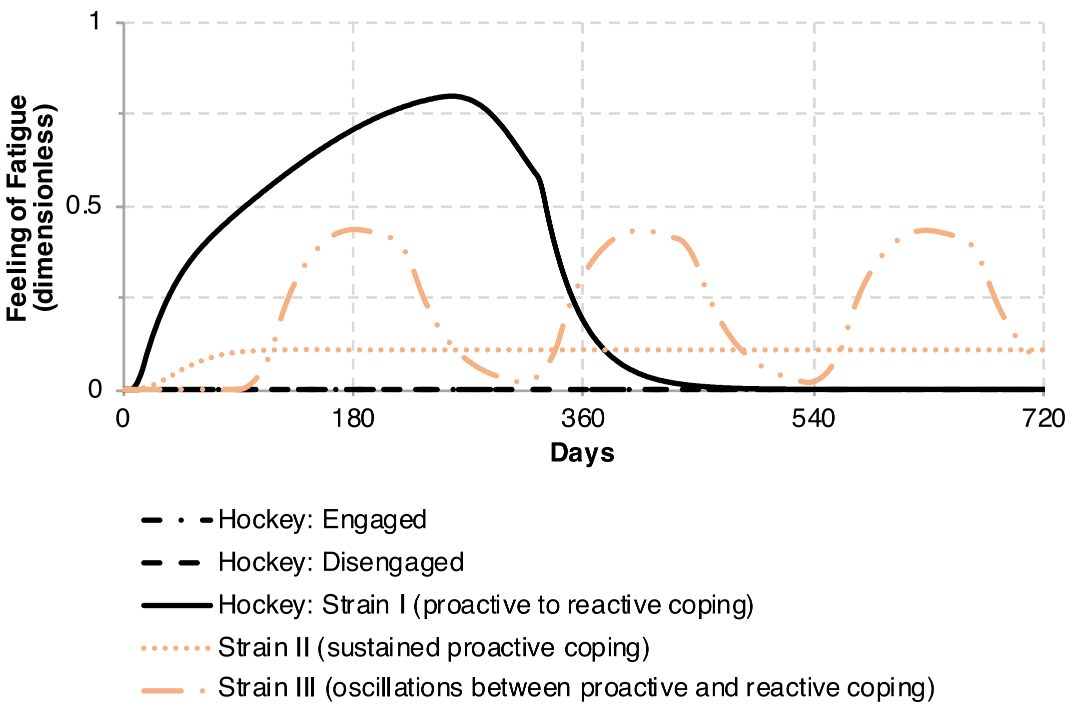


Figure DB.5. Dynamics of the Feeling of Fatigue for five work management modes

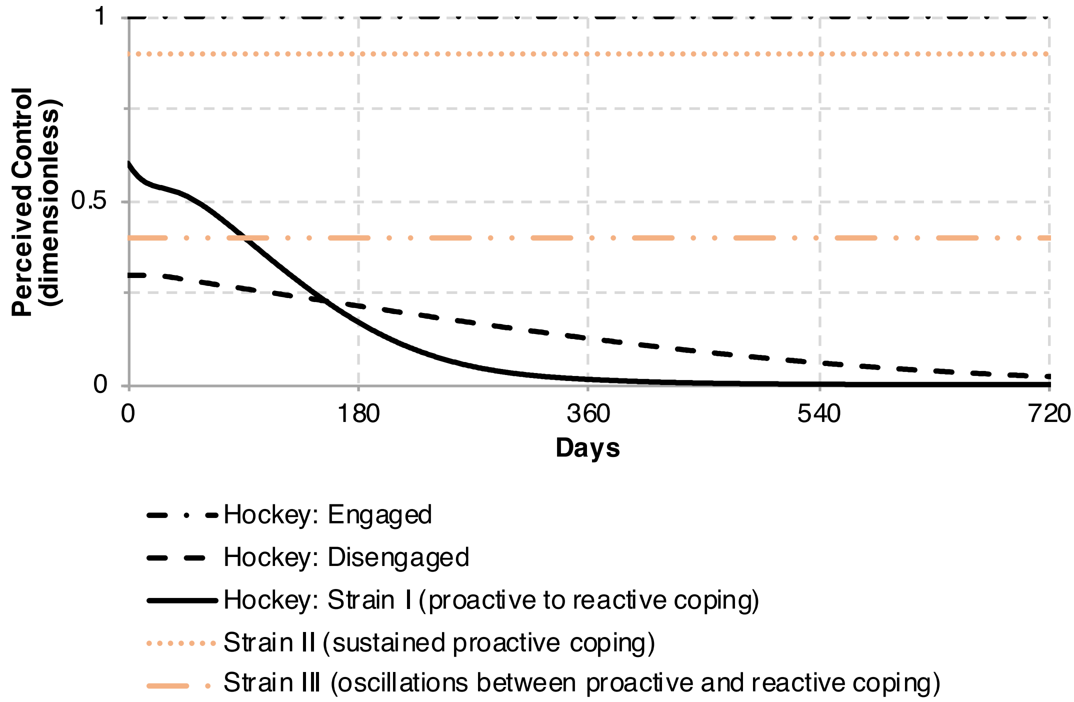


Figure DB.6. Dynamics of Perceived Control for five work management modes

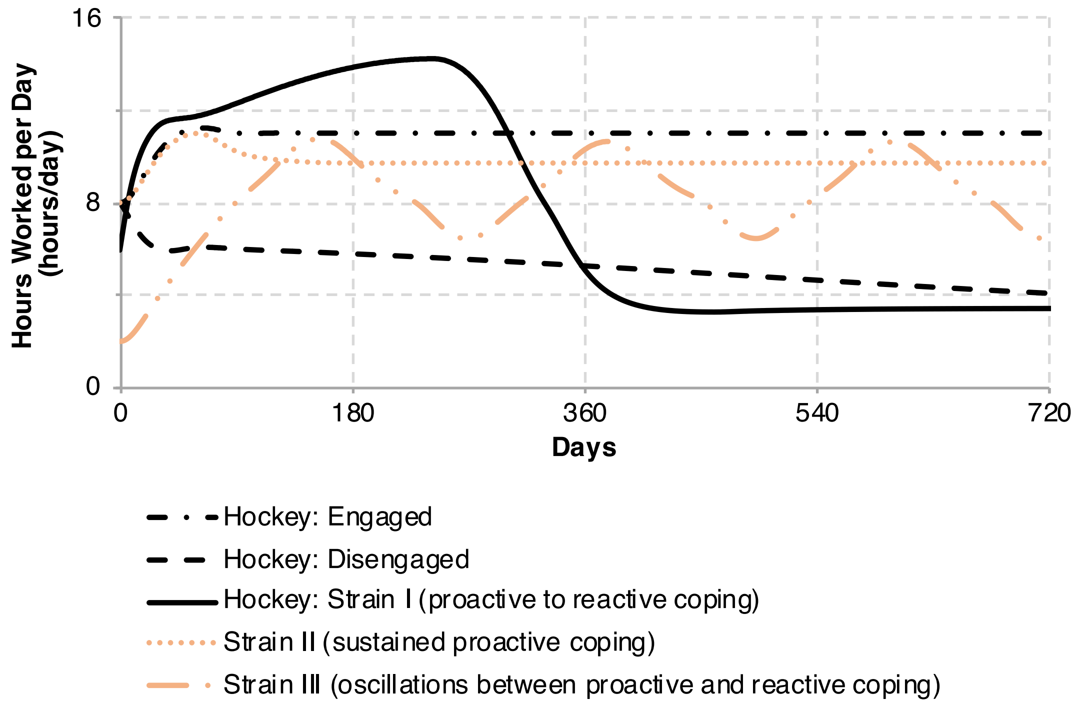


Figure DB.7. Dynamics of Hours Worked per Day on Current Activity for five work management modes

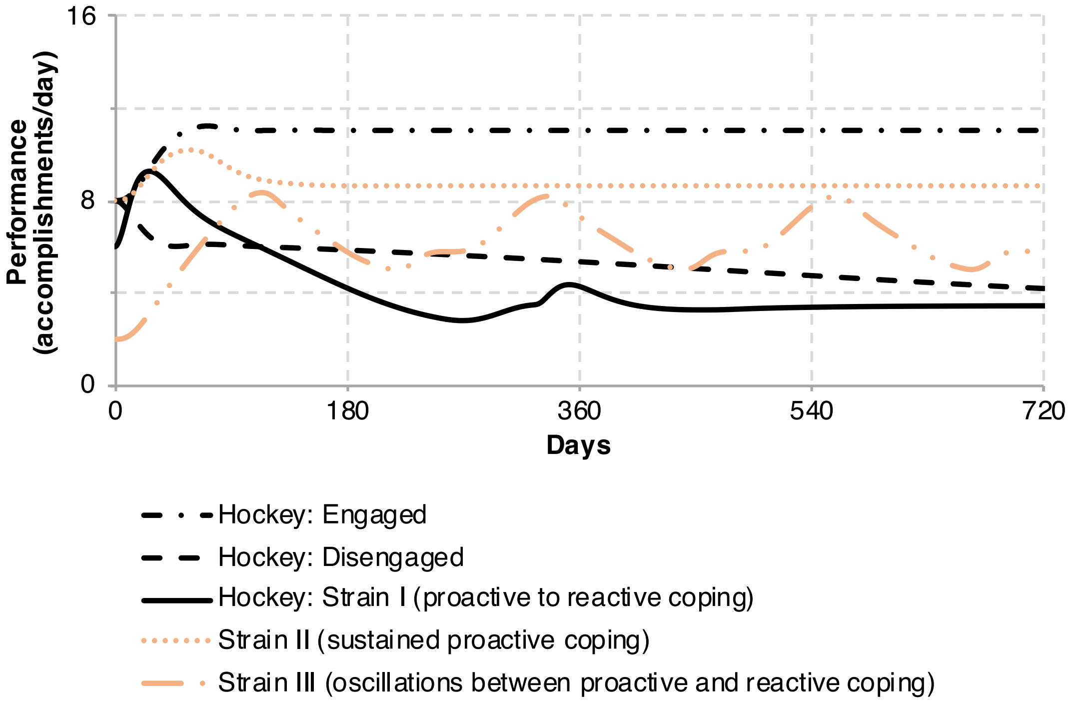


Figure DB.8. Dynamics of Performance per Day for five work management modes

Appendix DC
Empirical cases simulation

This appendix provides the data used to parameterise the generic model to the seven empirical cases carried out as part of the project. First, answers for closed-ended 7-point Likert scale questions are given for each case. Second, the appendix provides input parameters for each case that differ from the default values. Appendix consists of two sections:

DC.1. QUESTIONNAIRE ANSWERS

During the second set of interviews the participants were asked open- and closed-ended questions, the answers for which were used to parameterise generic SD model for each case. Closed-ended questions used 7-point Likert scale. Participants answers to the 7-point Likert scale questions for each case are presented in Table DC.1. Only a short title of each question is given in this appendix. Full text of each question can be found in the interview guide BD(II) in *Appendix BD. Interview guides.*

Table DC.1. Participants answers to 7-point Likert scale questions

Case A	Case B	Case C	Case D	Case E	Case G	Case H
[Question 1. State of the house before retrofit]						
Ability to support household's needs and everyday activities						
3 D* *Non-sustainable*	2 D* *Inadequate*	1 D* *Unsafe*	5 LC* *Comfortable*	2 D* *Inadequate*	2 D* *Inadequate*	1 D* *Unsafe*
A match between the household's taste and the style/ decoration of the house						
6 *Good*	2 *Inadequate*	3 *Few*	3 *Few*	1 *None*	2 *Inadequate*	4 *Neutral*
* D refers to 'state of disrepair', LC refers to 'liveable conditions'						
[Question 2. State of the house after retrofit]						
Ability to support household's needs and everyday activities						
7 LC* *Almost ideal*	7 LC* *Almost ideal*	6 LC* *Pleasant*	7 LC* *Almost ideal*	7 LC* *Almost ideal*	6 LC* *Pleasant*	7 LC* *Almost ideal*
A match between the household's taste and the style/ decoration of the house						
7 *Perfect*	7 *Perfect*	6 *Good*	7 *Perfect*	6 *Good*	6 *Good*	6 *Good*
* D refers to 'state of disrepair', LC refers to 'liveable conditions'						
[Question 3. Motivation]						
7 *Highly important*	7 *Highly important*	7 *Highly important*	7 *Highly important*	7 *Highly important*	7 *Highly important*	7 *Highly important*
[Question 4. Intrinsic satisfaction from the process]						
7 *Highly enjoyed*	7 *Highly enjoyed*	6 *Enjoyed many aspects*	5 *Rather enjoyed*	6 *Enjoyed many aspects*	6 *Enjoyed many aspects*	6 *Enjoyed many aspects*
[Question 5. Satisfaction from the job well done]						
7 *Very satisfied*	7 *Very satisfied*	7 *Very satisfied*	6 *Satisfied*	6 *Satisfied*	7 *Very satisfied*	7 *Very satisfied*
[Question 6. Theoretical knowledge before retrofit]						
4 *No specific knowledge*	7 *Expert knowledge*	7 *Expert knowledge*	7 *Expert knowledge*	6 *Good knowledge*	5 *Some useful knowledge*	3 *Somewhat incorrect knowledge*

(continued)

Table DC.1. Participants answers to 7-point Likert scale questions *(continued)*

Case A	Case B	Case C	Case D	Case E	Case G	Case H
[Question 7. Practical knowledge before retrofit]						
4 *No specific experience*	7 *Expert experience*	4 *No specific experience*	5 *Some useful experience*	5 *Some useful experience*	2 *Majorly misleading experience*	2 *Majorly misleading experience*
[Question 8. Control of what when and how to do]						
5 *Good*	7 *Absolute*	5 *Good*	2 OR 6 *Inadequate OR Very good*	5 OR 6 *Good OR Very good*	5 *Good*	6 *Very good*
[Question 9. Maximum feeling of fatigue from the project]						
3 *It was a bit easier than I thought*	5 *A bit tired*	5 *A bit tired*	5 *A bit tired*	4 *Neutral*	7 *Completely unbearable*	4 *Neutral*

DC.2. EMPIRICAL CASES BEHAVIOUR REPRODUCTION TESTS

Behavioural reproduction tests have been also conducted for the empirical cases, carried out as part of the research. They are described in *Chapter 6*, section 6.5d. Below are input parameter values for Figures 6.27–6.37, which differ from the default values (Table DC.2). For definitions and default values see *Appendix DA. Model documentation*.

Table DC.2. Input parameters for empirical cases behavior reproduction tests

Case	**A**	**B**	**C**	**D**	**E**	**G**	**H**
	Figure						
Variable name	**6.27**	**6.28 6.29**	**6.30 6.31**	**6.32 6.33**	**6.34**	**6.35 6.36**	**6.37**
ACTUAL CONTROL	0.8, then 0.9	1	0.6, then 0.85	0.7, then 0.85	0.8, then 0.9	0.6, then 0.8	0.6, then 0.8
INITIAL INTRINSIC MOTIVATION	1	1	1	1	0.8	Main works 1, between 0.3	1
EXTRINSIC MOTIVATION	0.3	0.6	0.6	0.3	0.3	Main works 0.8, between 0.3	0.3
PERCEIVED BENEFITS OF OTHER ACTIVITIES	0.375	0	0	0.375	0.375	0	0.375
MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE	1	1, then 8, then 1	0.5, then 8, then 0.5	1	2	Main works 10 and 6, between 0.1	2
HOURS IN A DAYTIME JOB	0	8	8	7	5	Main works 8, between 0	0
INITIAL HOURS WORKED PER DAY	1	1	0.5	1	2	0.1	2
Simulation time	360	1080	900	240	180	1800	14

Appendix DD

Scenario exploration

This appendix presents input parameters of the model as well as results of the various scenario exploration runs. Several scenarios have been explored. Seven main ones are described in *Chapter 6*, section 6.6. This appendix reproduces the seven runs described, as well as includes another five runs, amounting to 12 runs altogether. Table DD.1 shows, which figures in the section 6.6 corresponds to which figures in this appendix

Table DD.1. Corresponding figures between Chapter 6, section 6.6 and appendix DD

Figure in Chapter 6	Corresponding figure in appendix DD
6.38	DD.5
6.39	DD.6
6.40	DD.9
6.41	DD.10
6.42	DD.1
6.43	DD.2
6.44	DD.4

The figures in the rest of the appendix capture a comparison of different stop-and-go patterns for three strain work management modes:

(i) Strain work management mode I (proactive to reactive coping).
(ii) Strain work management mode II (sustained proactive coping).
(iii) Strain work management mode III (oscillations between proactive and reactive coping).

For each work management mode four graphs are presented:

(i) Continuous work without breaks. These graphs present the base run of the model.

(ii) Work with regular small breaks. These graphs capture a work pattern similar to the one of a full-time job with breaks for weekends.

(iii) Work with occasional big breaks. These graphs capture a work pattern similar to the one of a full-time job without breaks for weekends, but with seasonal holiday breaks.

(iv) Work with regular small and occasional big breaks. These graphs capture a work pattern similar to the one of a full-time job with regular breaks for weekends as well as seasonal holiday breaks.

The input parameters for the graphs, which differ from the default values, are given in Table DD.2. For definitions and default values see *Appendix DA. Model documentation*.

Table DD.2. Input parameters for comparison graphs for stop-and-go patterns of three strain work management modes

<table>
<tr><th rowspan="2">Variable name</th><th colspan="3">Work management modes</th></tr>
<tr><th>Hockey: Strain I
Figures DD.1 (6.42), DD.2 (6.43); DD.3 and DD.4 (6.44)</th><th>Strain II
Figures DD.5 (6.38), DD.6 (6.39); DD.7 and DD.8</th><th>Strain II
Figures DD.9 (6.40), DD.10 (6.41); DD.11 and DD.12</th></tr>
<tr><td>ACTUAL CONTROL</td><td>0.9</td><td>0.9</td><td>0.6</td></tr>
<tr><td>EXTRINSIC MOTIVATION</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>INITIAL INTRINSIC MOTIVATION</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE</td><td>10</td><td>1</td><td>1</td></tr>
<tr><td>INITIAL HOURS WORKED</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="4">SCENARIO EXPLORATION</td></tr>
<tr><td rowspan="2">Work with regular small breaks (weekends)</td><td>Figure DD.2 (6.43) only</td><td>Figure DD.6 (6.39) only</td><td>Figure DD.10 (6.41) only</td></tr>
<tr><td colspan="3">For the period of a break EXTRINSIC MOTIVATION, INITIAL INTRINSIC MOTIVATION and MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE drop to zero. PERCEIVED BENEFITS OF OTHER ACTIVITIES rise to 1.
Breaks are determined by PULSE TRAIN (0 ,6 ,7, 720)</td></tr>
<tr><td rowspan="2">Work with occasional big breaks (holidays)</td><td>Figure DD.3 only</td><td>Figure DD.7 only</td><td>Figure DD.11 only</td></tr>
<tr><td colspan="3">For the period of a break EXTRINSIC MOTIVATION, INITIAL INTRINSIC MOTIVATION and MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE drop to zero. PERCEIVED BENEFITS OF OTHER ACTIVITIES rise to 1.
Breaks are determined by PULSE TRAIN (0, 170, 185, 720)</td></tr>
<tr><td rowspan="2">Work with regular small and occasional big breaks (weekends and holidays)</td><td>Figure DD.4 (6.44) only</td><td>Figure DD.8 only</td><td>Figure DD.12 only</td></tr>
<tr><td colspan="3">For the period of a break EXTRINSIC MOTIVATION, INITIAL INTRINSIC MOTIVATION and MINIMAL OR EXTERNALLY REQUIRED TASK PERFORMANCE drop to zero. PERCEIVED BENEFITS OF OTHER ACTIVITIES rise to 1.
Breaks are determined by a multiplication of
PULSE TRAIN (0, 6, 7, 720) and PULSE TRAIN (0, 170, 185, 720)</td></tr>
</table>

STRAIN WORK MANAGEMENT MODE I (PROACTIVE TO REACTIVE COPING)

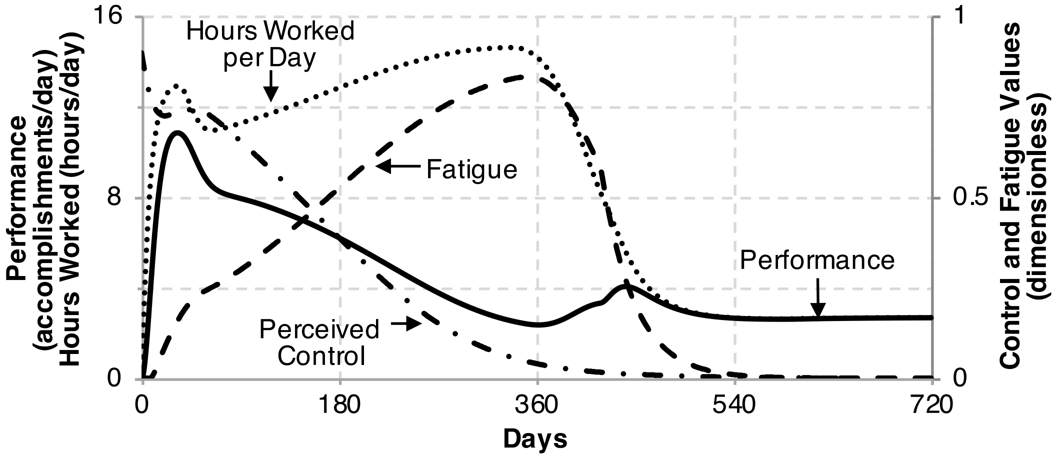


Figure DD.1. Strain work management mode I (proactive to reactive coping). Continuous work without breaks

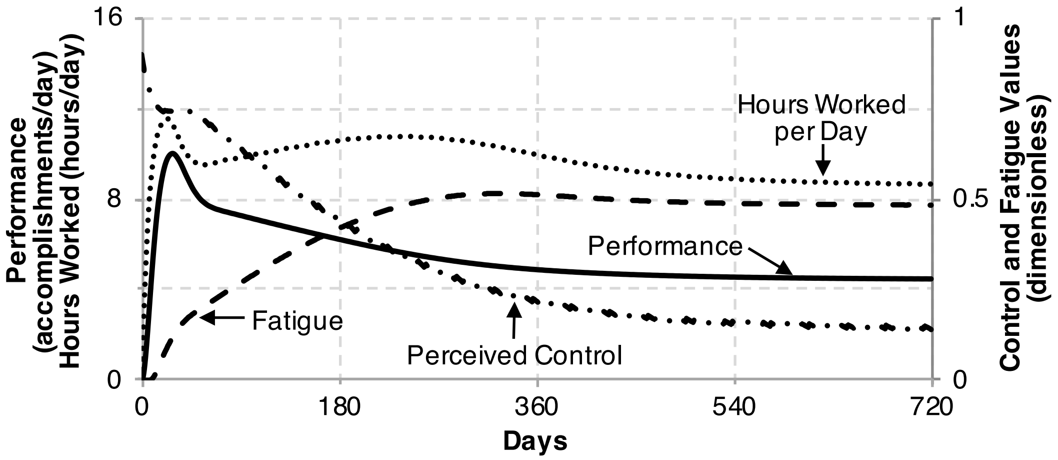


Figure DD.2. Strain work management mode I (proactive to reactive coping). Work with regular small breaks (weekends)

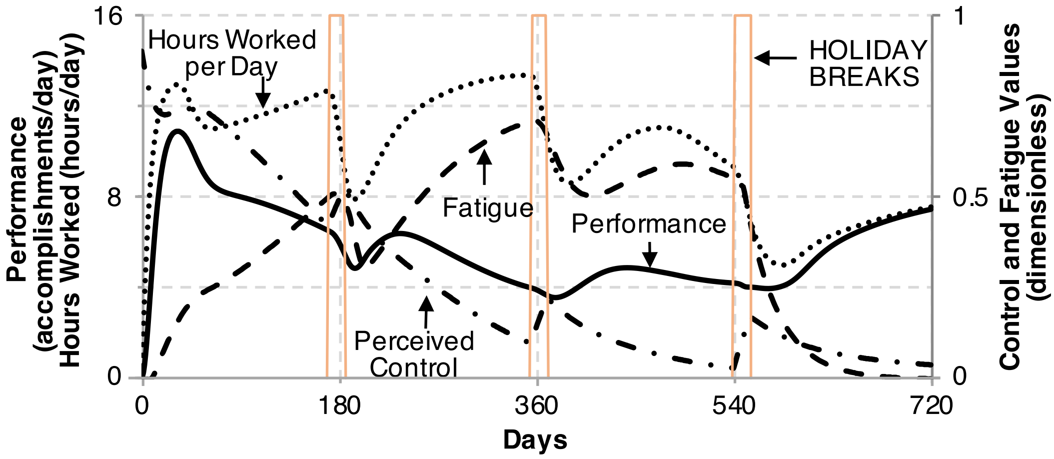


Figure DD.3. Strain work management mode I (proactive to reactive coping). Work with occasional big breaks (holidays)

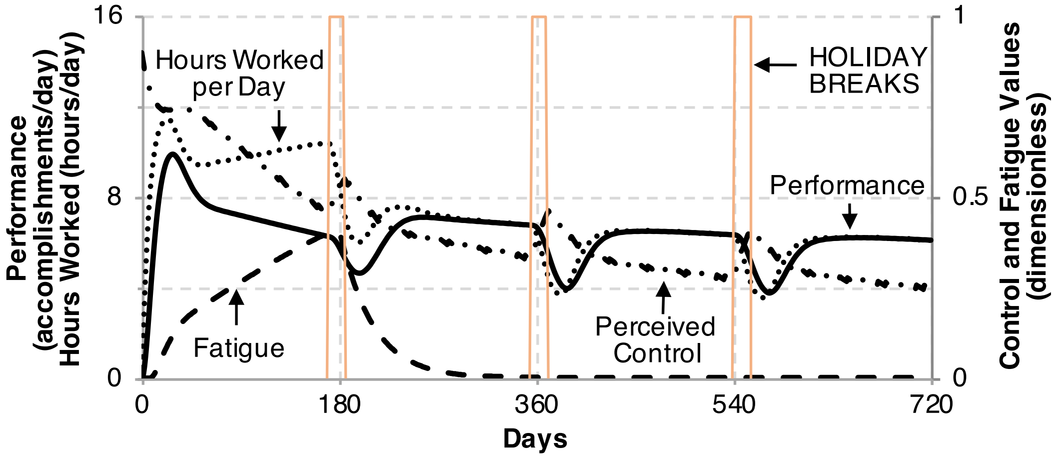


Figure DD.4. Strain work management mode I (proactive to reactive coping). Work with regular small breaks (weekends) as well as occasional big breaks (holidays)

STRAIN WORK MANAGEMENT MODE II (SUSTAINED PROACTIVE COPING)

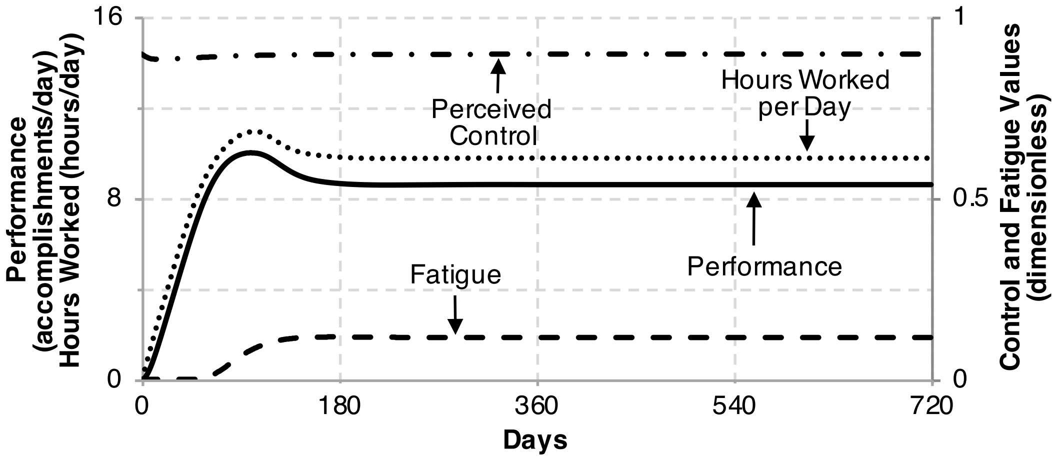


Figure DD.5. Strain work management mode II (sustained proactive coping). Continuous work without breaks

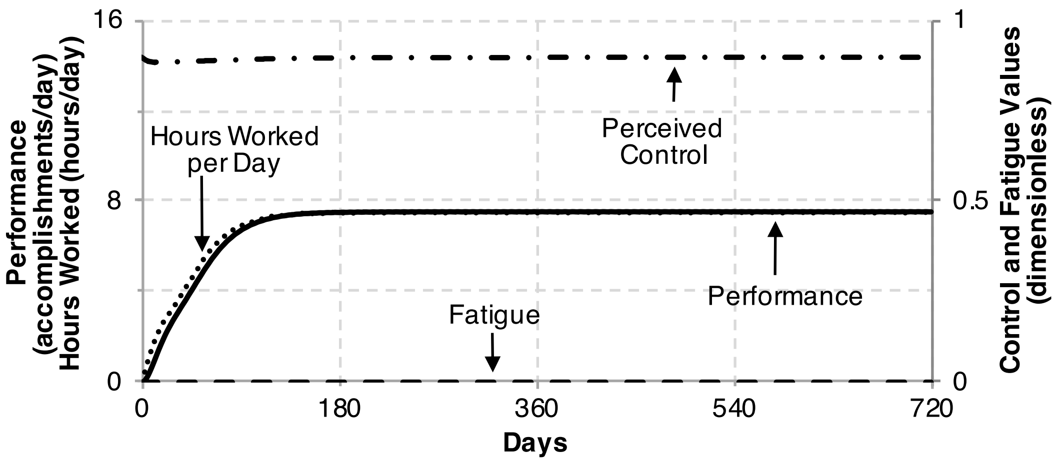


Figure DD.6. Strain work management mode II (sustained proactive coping). Work with regular small breaks (weekends)

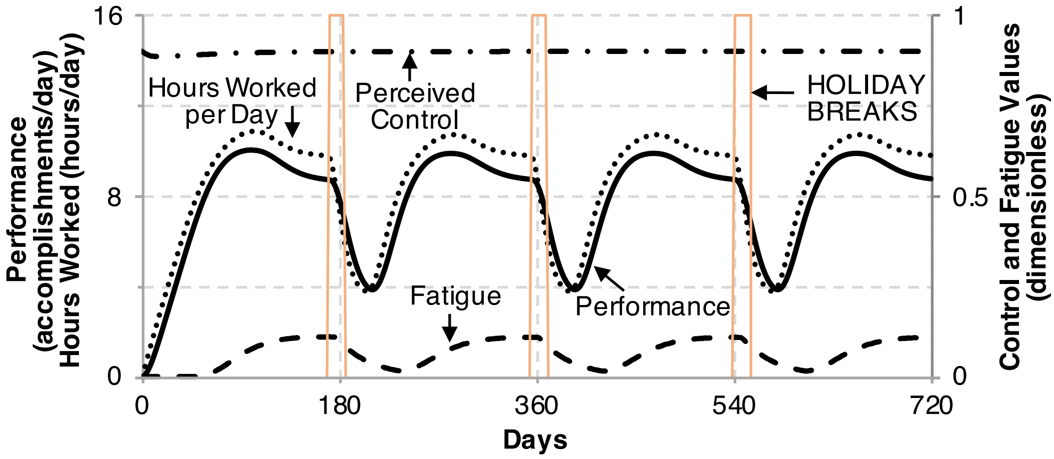


Figure DD.7. Strain work management mode II (sustained proactive coping). Work with occasional big breaks (holidays)

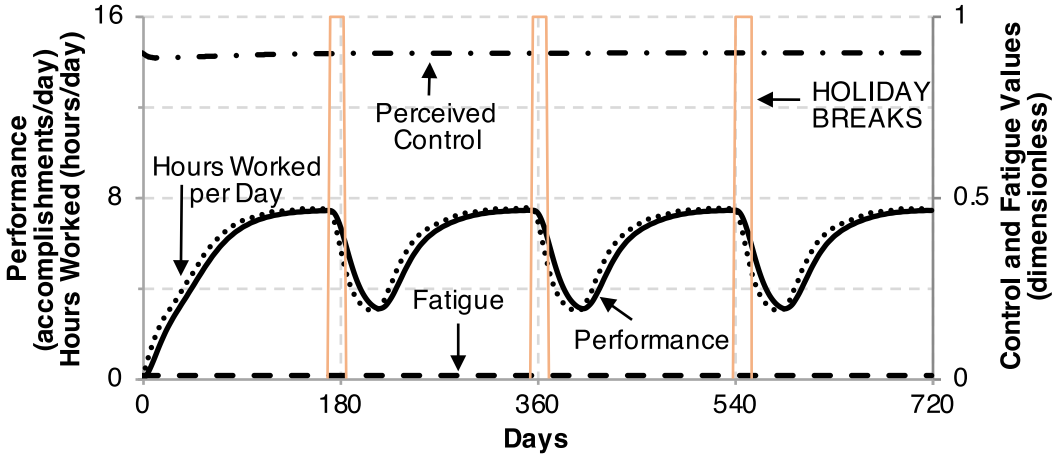


Figure DD.8. Strain work management mode II (sustained proactive coping). Work with regular small breaks (weekends) as well as occasional big breaks (holidays)

STRAIN WORK MANAGEMENT MODE III (OSCILLATION BETWEEN PROACTIVE AND REACTIVE COPING)

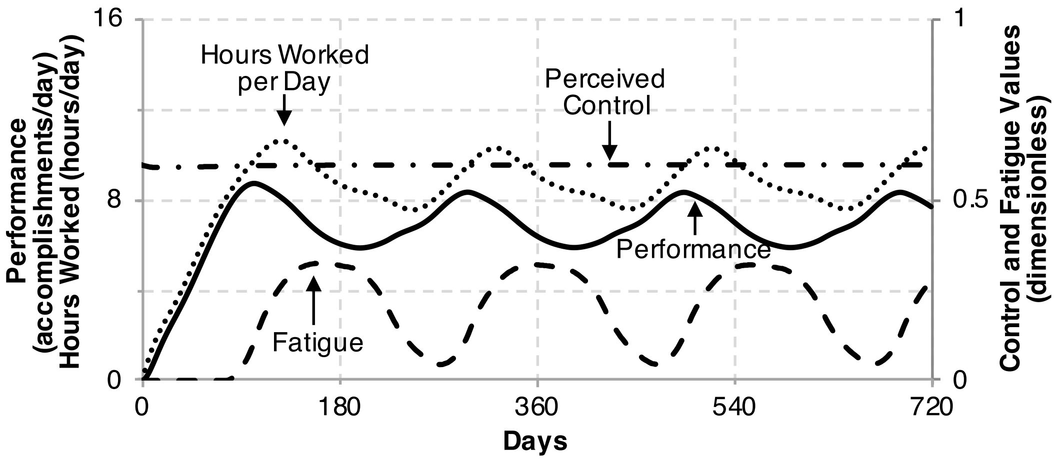


Figure DD.9. Strain work management mode III (oscillations between proactive and reactive coping). Continuous work without breaks

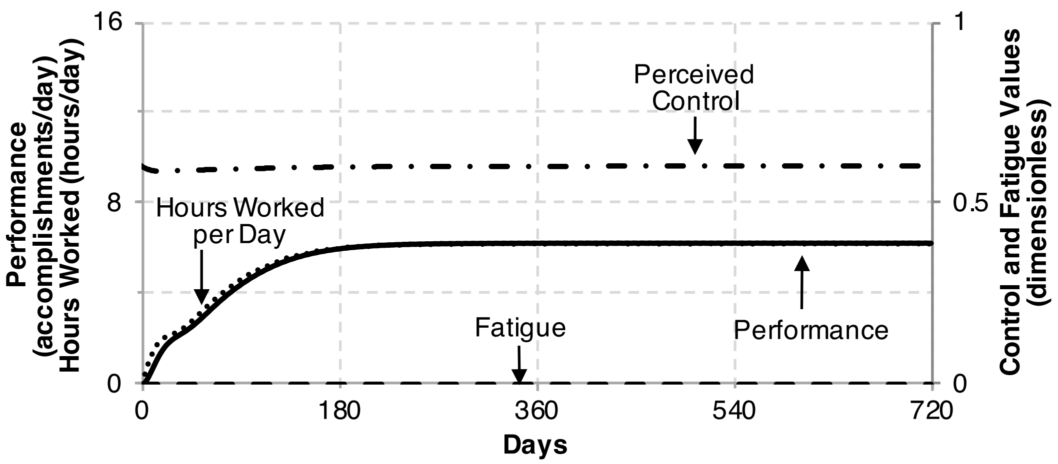


Figure DD.10. Strain work management mode III (oscillations between proactive and reactive coping). Work with regular small breaks (weekends)

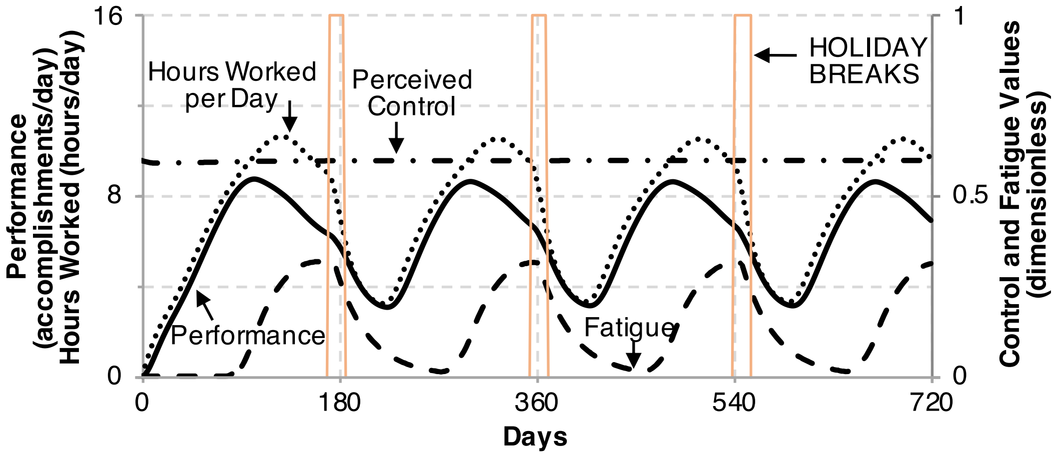


Figure DD.11. Strain work management mode III (oscillations between proactive and reactive coping). Work with occasional big breaks (holidays)

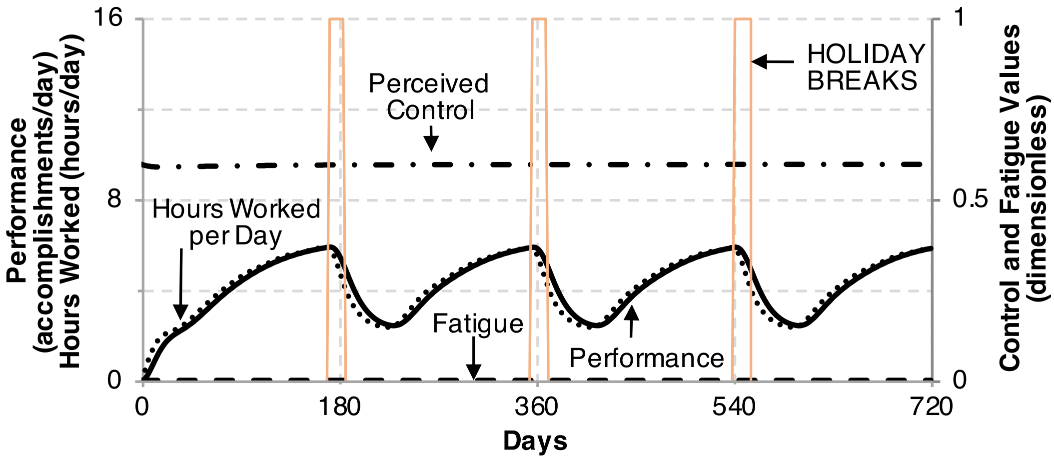


Figure DD.12. Strain work management mode III (oscillations between proactive and reactive coping). Work with regular small breaks (weekends) as well as occasional big breaks (holidays)

Appendix E

Materials on the supporting website

The system dynamics simulation model of Hockey's *motivation control theory of fatigue* is available in Vensim format and can be accessed at https://rdr.ucl.ac.uk/articles/A_system_dynamics_model_of_Hockey_s_motivation_control_theory_of_fatigue/12121089.