RISKS OF OVERHEATING

IN HIGHLY INSULATED ENGLISH HOUSES:

AN INVESTIGATION INTO THE DESIGN PROCESS, COMFORT PERFORMANCE AND OCCUPANT BEHAVIOUR

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ABSTRACT

When exploring the topic of overheating in buildings, the notion is commonly applied to *future* overheating, as a consequence of climate change. By contrast, this thesis is concerned with present-day overheating, as it is experienced in highly insulated houses. This can be claimed to be an unintended consequence of decarbonising the built environment, which has led to high levels of insulation and airtightness in the design of new homes in the UK.

However, evidence of overheating in such homes point at possible inadequacies in the design and regulatory processes leading to highly insulated homes. Such design and processes have tended to focus only on winter comfort and carbon reduction from space heating demand.

With a view of addressing the design problems leading to uncomfortably warm homes, this project is devoted to finding evidence of present-day overheating in highly insulated houses. This is pursued by an in-depth, multi case study, in which a mixed method approach to research is carried out in four (different typologies of) English houses -one of which is retrofitted while the other three were built as new. In this research, these houses have undergone longitudinal environmental monitoring and user perspective data gathering, across the four seasons of the year. In addition, in-depth semi-structured interviews with architects and designers of such houses were also carried out.

A number of design factors have been found to lead to overheating, mostly resulting from a design process in which the main (physical) factors, such as control of solar gain and provision of adequate ventilation, are largely overlooked. This overlooking has, in turn, originated a potential demand for cooling, especially when no other forms of adaption are provided within the houses.

Monitoring has shown that HIHs can be warmer environments: overheating was found in some instances and with different degrees of severity. However, it was also found that assessments may underestimate overheating (no consideration of vulnerable occupants throughout building lifespan). In some cases, it was found that occupants were adopting adaptive behaviour.

The interview with designers revealed a generalised limitation in knowledge, where the fabric first approach adopted in low-carbon design focused on winter comfort mostly. For, the role of thermal comfort (the means to deliver it through design, as well as to achieve it by the occupants) was found to be central in HIHs, as comfort is (ought to be) delivered entirely by design.

In summary, then, the research findings presented in this thesis indicate that today overheating in HIHs is the result of innovation in architecture, which requires immediate feedback from real-world research to guide regulatory bodies and designers.

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I want to dedicate this work to my father, Julio Cesar Enrique Toledo-Estremadoyro, for being my dream facilitator, again.

Quiero dedicar esta tesis doctoral a mi padre, Julio Cesar Enrique Toledo Estremadoyro, por ser el facilitador de mis sueños, una vez más.

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LIST OF ABBREVIATIONS

ACH	air changes per hour
AECB	Association for Environment Conscious Building
AMV	actual mean vote
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BRE	Building Research Establishment
DCLG	Department for Communities Local Government
DER	dwelling emissions rate
DTM	Dynamic thermal modelling
HCA	Homes and Communities Agency
HIH	highly insulated house
IAQ	indoor air quality
IEQ	indoor environmental quality
IPCC	Intergovernmental Panel on Climate Change
MHCLG	Ministry of Housing, Communities & Local Government
MVHR	mechanical ventilation with heat recovery
non-HIH	non highly insulated house
PHPP	Passivhaus planning package
PMV	predicted mean vote
POE	post-occupancy evaluation
ROSPA	Royal Society for the Prevention of Accidents
SAP	standard assessment procedure
TER	target emissions rate
UHI	urban heat island

CHAPTER 1: INTRODUCTION

1.1 THE NEED OF THIS RESEARCH

Today's concern about climate change and its consequent humanitarian impact has led to government strategies aimed at reducing greenhouse gases emissions - the so-called mitigation agenda [Crown, 2008; HM Government, 2011]. In an attempt to reduce energy consumption and associated carbon emissions from the residential sector, substantial changes have recently been made to UK building regulations. Those regulations are conducive to building houses with significantly improved standards of thermal insulation and much higher levels of 'airtightness' [Killip, 2005; HM Government, 2006, 2013c].

However, there is growing evidence of uncomfortably warm temperatures in such highly insulated houses (which will henceforth be referred to as HIHs) [DCLG, 2012; Dengel and Swainson, 2012; NHBC, 2012b]. These cases of overheating may be a symptom of a gap between the intention to design HIHs and their real-world thermal performance. In other words, there seems to be a growing problem of overheating HIHs, and this problem may be understood as an unintended consequence of the UK CO_2 mitigation agenda [Davies and Oreszczyn, 2012; Dengel and Swainson, 2012; Shrubsole *et al.*, 2014]. In fact, one might even contend that the low-carbon agenda is working against thermal comfort, since it has become increasingly evident that the delivery of sustainability (in this case, in the form of designing HIHs) has become characterised by a dichotomy between thermally efficient houses and summer thermal comfort.

The primary purpose of all domestic buildings is to provide their occupants with a stable indoor environment. However, cumulative effects of heat gain and insufficient ventilation have often resulted in an increased risk of overheating in HIHs. It is important, therefore, to ensure that in practice houses designed to comply with improved standards of energy efficiency are not subject to overheating so that they are able to provide appropriate levels of indoor air quality, and that the anticipated energy reductions are achieved. While it is difficult to identify a single, main reason for the gap between HIHs and thermally comfortable houses [NHBC, 2012a, 2012b], design practice needs to respond quickly to the growing evidence of overheating [DCLG, 2012; Garrett, 2014; Mavrogianni *et al.*, 2014; Sharpe *et al.*, 2016; McGill *et al.*, 2017] without sacrificing the objective of reducing carbon emissions associated with the residential sector.

This research is intended to contribute to a better understanding of the overheating risk in HIHs and so to increase our wealth of knowledge about how HIHs function in practice, especially when external temperatures raise.

1.2 ORIGINALITY

In order to improve the design of HIHs and to reduce their risks of overheating, it is essential to study how the conflicting requirements for thermal comfort, indoor air quality and energy efficiency are reconciled in current architectural practice, which is here understood as a form of practical, vis-à-vis purely theoretical, knowledge.

This research project aims to link the thermal performance of HIHs with the design thinking and the design process behind those houses. Likewise, this project is intended to identify and highlight the most significant factors that could contribute to an increase in the risk of overheating in HIHs at the design stage.

These objectives will be pursued by linking the practice of HIHs design to their actual performance. The methodology used to do so is based on a comprehensive mixed methods approach combining data collection (physical assessments, interviews, opinions, and observations) with appropriate tools for mapping the process in which overheating may occur. Accordingly, this work can be expected to contribute to filling the current gap in the knowledge of comfortable HIHs design by integrating information about the physical reality with the design intentions (or strategy) behind HIHs. In sum, this work is intended to nuance the processes leading to uncomfortably warm temperatures (which henceforth will be referred to as *production of overheating)* in HIHs and thus to aid architects and designers in their low-carbon designs.

The nomenclature '*production of overheating*' was chosen to carry the specific idea of overheating as it been manufactured by design of HIHs, and by so, conveying the idea to amend or rectify design in order to avoid it. This provides a marked distinction from overheating as a consequence of ('as produced by") climate change. In fact, the word 'production' refers to something that it is manufactured, and it is the result and/or output of a process. Ergo, overheating is here considered as the output of the process of designing HIHs. In addition, the word 'production' (and with it the word 'manufacture') convey the idea of 'mass-production' (like production of car, or production of housing). This is relevant to the case of HIHs and low-carbon design in general, where overheating has the potential to be a mass-produced widespread problem.

1.3 RESEARCH QUESTIONS AND OBJECTIVES

This research will examine HIHs and thus attempt to establish if the design process is actually delivering comfortable HIHs. Its specific focus will be on investigating the design issues that can lead to overheating in England. As a result, this study is instrumental to gaining an understanding of the actual performance of HIHs and to indicate the factors contributing to the heat excess within such innovative designs. These results will be specifically pursued by addressing two research questions, namely:

I. ***Do HIHs provide an uncomfortable indoor environment for their occupants?***
II. ***If so, how can the process of designing HIHs be improved to reduce the risks of overheating?***

The above questions are listed in the order in which they will be addressed in this research work, following a progression from (a) houses' performance, predominantly linked to the *in-use* stage of the building process (b) house design, predominantly linked to the *design* stage of the building process. The findings will be integrated by (c) mapping them in the context of the building process (fig. 1.1). While the focus of the research questions lies in the *design* and *in-use* stages, due to the variegated nature of the data collected, the results will include data from all the stages (including *brief* and *construction*).[1]

[1] The reader is directed to the 'overheating maps' in Chapter 7, sections 7.1 and 7.2 to appreciate such interconnectivity.

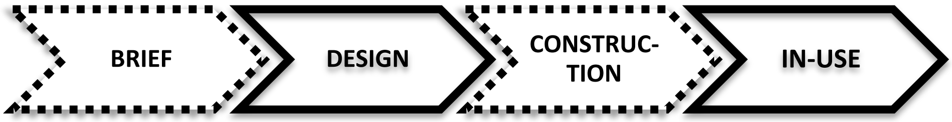


Fig. 1.1 Research questions framed within - a schematic view of - the building process. Such framework will be developed in the context of the RIBA Plan of Work, for which the reader is directed to Chapter 7, section 7.1.1.2

The more specific objectives underpinning the two fundamental research questions are listed below:

Obj. 1. To determine if HIHs currently experience **overheating** and to evaluate the thermal experience of their occupants. This issue will be dealt with, in particular, in Chapter 5, where data from the longitudinal study (post-occupancy evaluation) will be introduced and discussed.

Obj. 2. To examine the **design processes** currently employed by architects and designers and to evaluate the current knowledge that architects and designers have of how design affects thermal comfort. This objective will be pursued in Chapter 6 by means of a critical analysis of the interviews conducted with architects and designers.

Obj. 3. To evaluate the **tools** and verification techniques used by designers to assess the ability of energy efficient designs to provide thermal comfort. This objective will be pursued in Chapter 5 and Chapter 6.

Obj. 4. To examine the role that the **occupants** of HIHs play in relation to overheating risks and to evaluate their level of understanding of how to achieve and control thermal comfort. This objective will be pursued in Chapter 5 by means of a discussion of post-occupancy evaluation.

Obj. 5. To **map** findings from the data presented in Chapters 5 and 6, and to integrate these findings in a process map. This objective will be pursued in Chapter 7, where a specific process-mapping methodology will be introduced and subsequently validated by means of a **focus group**.

1.4 SCOPE OF THE RESEARCH

This work will adopt a multiple case study approach, which is considered most appropriate to the in-depth exploration of the research questions introduced above. More specifically, four HIHs whose builds were completed between 2011 and 2013 were selected.[2] These particular houses present substantial differences regarding their layouts, materials, and orientation with respect to each other (fig. 1.2). For these reasons, they are expected to provide a sufficiently variegated sample of HIHs and so a reliable base for arriving at an enriched map of the risk of overheating in HIHs.

The research will also adopt a mixed methods approach, which will combine longitudinal monitoring of environmental parameters, longitudinal post-occupancy questionnaires, photographs and notes taken during walkthroughs with occupants in their houses, interviews with designers and the focus group with a specialised audience. The rationale for the chosen methods will be discussed in Chapter 4, section 4.2.

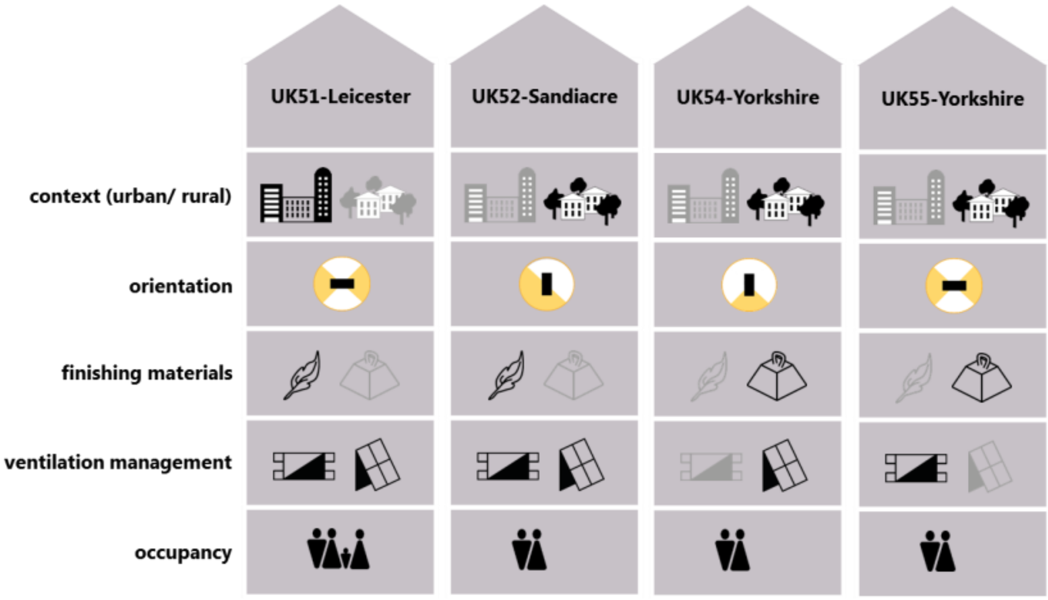


Fig. 1.2 Infographic depicting the four case studies central to this research work.
It is shown some of the main of the characteristics of each house and highlighting (a) the different contexts (urban or rural) and by so, any influence of the urban heat island effect; (b) in solar gains exposure from different façades (East, West and South); (c) thermal mass exposure in terms of finishing materials (lightweight or heavyweight), (d) the prevailing ventilation management (via MVHR, or via natural ventilation, or both concurrently); (e) number and type of permanent occupants.

[2] The case studies are introduced in some detail in Chapter 5

1.5 OUTLINE OF THE THESIS

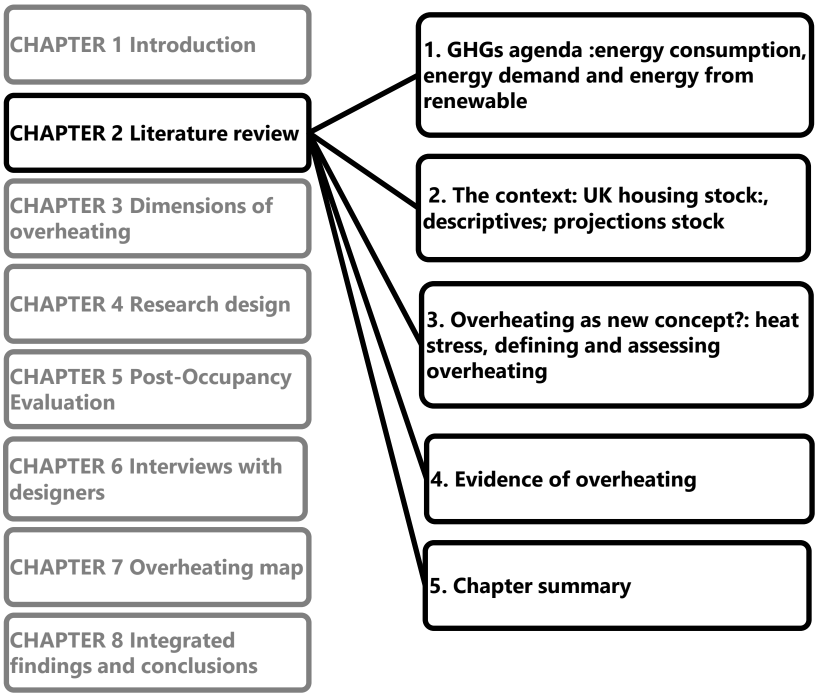
This thesis is organised into the chapters detailed below.

- Chapter 1 introduces the aims of the research and outlines the structure of this thesis.
- Chapters 2 and 3 review the existing literature in order to gain an understanding of the nature of overheating as it occurs in English HIHs today. In these chapters, the justification for the research will also be outlined by means of a review of today's concepts of overheating, particularly in relation to thermal comfort.
- Chapter 4 outlines the paradigms used in this research and the epistemological associations pursued in this work. The fundamental research strategies, their value and their limitations, will also be explored. In this context, the protocols of data collection will not be presented, since they will be introduced in the analysis chapters (namely Chapters 5, 6 and 7).
- Chapter 5 introduces the results of the data collected from the HIHs longitudinal monitoring (post-occupancy evaluation and thermal comfort survey). In one respect, this chapter could be qualified as being quantitative in nature. However, it also contains responses from the open questions included in the questionnaires. From a build process perspective, this chapter will focus on the *IN-USE* (performance) of HIHs (fig. 1.1).
- Chapter 6 presents the results of the data collected via interviews to architects and designers of the case study HIHs. Interviews will be coded, and the main themes will be developed and discussed. From a build process perspective, this chapter will focus on the *DESIGN* (prediction) of HIHs (fig. 1.1).
- Chapter 7 elaborates the results presented in chapter 5 and 6 in order to map the process leading to the overheating map of HIHs. In this manner, by means of a triangulation exercise. The triangulation critically approaches the findings relative to each case study and evidences the most significant issues in the *IN-USE* and *DESIGN* stages. This is achieved by means of a process mapping where different sources of data are linked, and focusing on the interconnectivity of the problem of overheating within the build process.

- Chapter 8 will present the integrated findings of the research. Those findings will be elaborated by means of an interrelated, critical reflection on the results presented in the previous chapters and on the experience of the methods used. Finally, this chapter makes recommendations to designers, and provide suggestions as to the directions future research might take.

CHAPTER 2: LITERATURE REVIEW

"Our destiny is frequently met in the very paths we take to avoid it"
Jean de La Fontaine, 1678



Synopsis

This chapter is concerned with providing some background information about the problem of overheating in HIHs. After presenting a panoramic of the GHGs agenda, a description of the residential stock is offered with a view of highlight some central issues of overheating in HIHs.

Then the phenomenon of overheating, as it occurs in UK, is described and subsequently a large body of studies depicting the complexity of overheating, as it occurs in the residential sector, are reviewed.

2.1 GHGS AGENDA

Climate change is widely recognised as one of the greatest emerging humanitarian challenges of our time. It is also demonstrated that urban environments amplify the impact of climate change [Henderson, 2010; HM Government, 2011]. The UK Climate Projections [Murphy *et al.*, 2009] predict an increase in temperatures that it is likely to both generate an alarming enhanced health-related risk for vulnerable groups of people [DCLG, 2012; NHBC, 2012a]. This occurrence has the potential to frustrate governmental efforts to improve the energy efficiency of the UK building stock as well as to increase GHG emissions (this is especially due to the associated risk of increasing the use of cooling demand) [Shove, 2012; Loveday *et al.*, 2016]. In fact, the UK climate has warmed of 1˚C over the last century in central England [Murphy *et al.*, 2009].

As a response to climate change and an attempt to reduce its consequences to the built environment, a large number of States worldwide have subscribed the Kyoto Protocol, which sets ambitious carbon dioxide emissions targets [Crown, 2008; HM Government, 2011] (those targets are summarised in the table 2.1). The UK government too set up emissions reduction binding targets through the Climate Change Act and the so-called mitigation agenda [Crown, 2008]. The framework created within the Climate Change Act imposes the 2050 Target for buildings, which consists in "*reducing emissions by at least 80% in 2050 from 1990 levels*".

Table 2.1: long-term climate change targets by European countries beyond the EU collective target of -8%, adapted from [Boardman et al. 2005; Crown 2008; UNFCCC 2014]

France	(limit per capita emissions) to 0.5 tons carbon by 2050
Germany	(reduce national CO_2 emissions) by 45-60% compared with 1990 levels by 2050
Sweden	(reduce per capita emissions) to below 1.2 tons carbon by 2050
UK	(reduce national CO_2 emissions) by 80% compared with 1990 levels by 2050

In the UK, this attempt to reduce energy consumption and associated carbon emissions from the buildings sector has led the UK government to develop strategies to reduce greenhouse gases emissions (the so-called mitigation agenda) [Crown, 2008; HM Government, 2011]. As a consequence, substantial changes have recently been made to UK building regulations, resulting in houses with significantly improved standards of thermal insulation and much higher levels of airtightness [Killip, 2005; HM Government, 2006, 2013c]. These progressive and rapid changes are explored in detail in Chapter 3, section 3.2).

There is however an intrinsic link between reducing GHG emissions (mitigation) and coping with the consequences of climate change (adaptation). While mitigation actions are intended to tackle the causes of climate change by decreasing greenhouse gases in the atmosphere or enhancing the sinks of greenhouse gases, adaptation addresses the impacts of climate change through an adjustment in natural or human systems in response to (actual or expected) climatic stimuli or their effects, which moderate harm or exploit beneficial opportunities' [IPCC, 2001].

In the context of the built environment, where *adaptation* refers to "adjusting to moderate harm" [UKCIP, no date], the UK government foresees that adaptation will be needed to cope with the inevitable climate change consequences such as flooding and rise of temperatures [Shaw, 2007; HM Government, 2013d]. Cities are not currently designed for climate change, since the majority of houses existing today were designed for climatic conditions prevalent at the time they were built [ARUP, 2008] and these conditions have changed since (and are expected to continue to change). Accordingly, adaptation is considered necessary to provide a more resilient housing stock [ARUP, 2008], and analysis has to be informed by susceptibility and/or resilience at a local level [Dear and Wang, 2015] .

2.1.1 UK ENERGY CONSUMPTION

According to the Office for National Statistics [ONS Digital, 2016] the UK is consuming less energy[3] than it did in 1998. There was a 17% fall of energy used by the UK between 1998 and 2015 (see fig. 2.1) There is also an increased use of energy generated by renewables.. Some of the plausible reasons for those variations lie in an increased use of energy efficient technologies by both households and firms and a decline in energy intensive manufacturing [ONS Digital, 2016]. An updated released in July 2017 states that "*the primary energy consumption (primary supply less non-energy use) was down by 1.4 per cent in 2016. On a temperature corrected basis, primary energy consumption was estimated to have fallen by 2.3 per cent*" [Office of National Statistics, 2017a].

[3] Energy consumption is measured in a million tonnes of oil equivalent (Mtoe) – this is a unit of energy defined as the amount of energy released by burning one million tonnes of crude oil [ONS Digital, 2016].

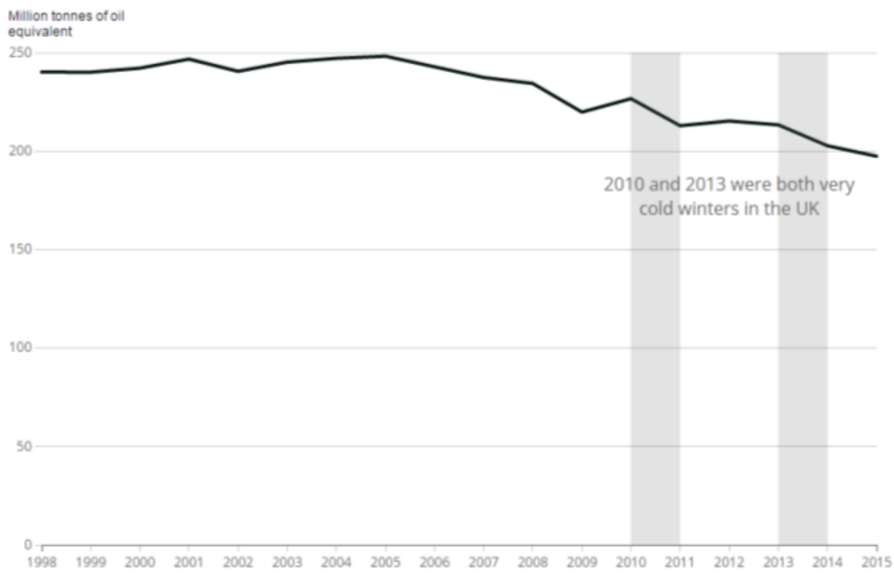


Fig. 2.1 Total energy consumed by the UK, 1998 to 2015 [ONS Digital, 2016]

The effects of household strategies for energy efficiency are deemed to be of great impact because of the substantial energy consumption linked to residential (this point is addressed in more detail in the next section). Figure 2.2, which shows consumption by category, indicates that transport and domestic use account for nearly two thirds of the total consumption.

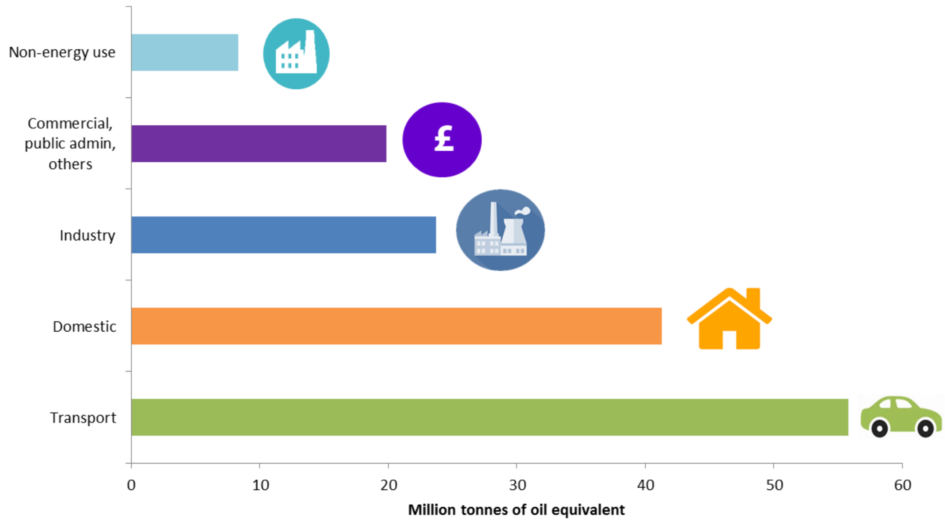


Fig. 2.2 Final energy consumption 2016 by category [Office of National Statistics, 2017a]

Not only has there been a decrease in energy demand, but also there has been an increase of production of renewable energy. The percentage of energy consumed from renewable sources has risen from 1% of total UK energy consumption to 9% [ONS Digital, 2016] (see fig. 2.3). In 2016, 8.9 per cent of total energy consumption came from renewable sources; this is up from 8.2% in 2015 [Office of National Statistics, 2017b]. While renewable electricity represented 24% of total generation, the renewable heat accounted for 6.2% of overall heat.

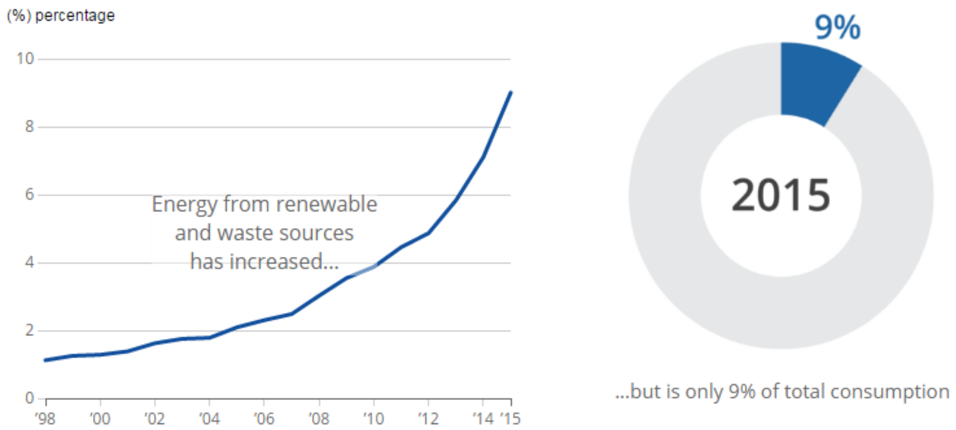


Fig. 2.3 Percentage of total energy consumed in the UK that comes from renewable or waste sources, 1998 to 2015 [ONS Digital, 2016]

Also, of all the energy consumed, a part of it has increasingly been imported. The decline in North Sea oil and gas production has meant that the UK has become more and more dependent on imports of energy, though with a downward trend since 2013 (see fig 2.4). This need to import energy places the UK in line with the neighbourhood European countries [ONS Digital, 2016; Office of National Statistics, 2017a]. Nonetheless the UK government aims at reducing the energy imports from other countries.

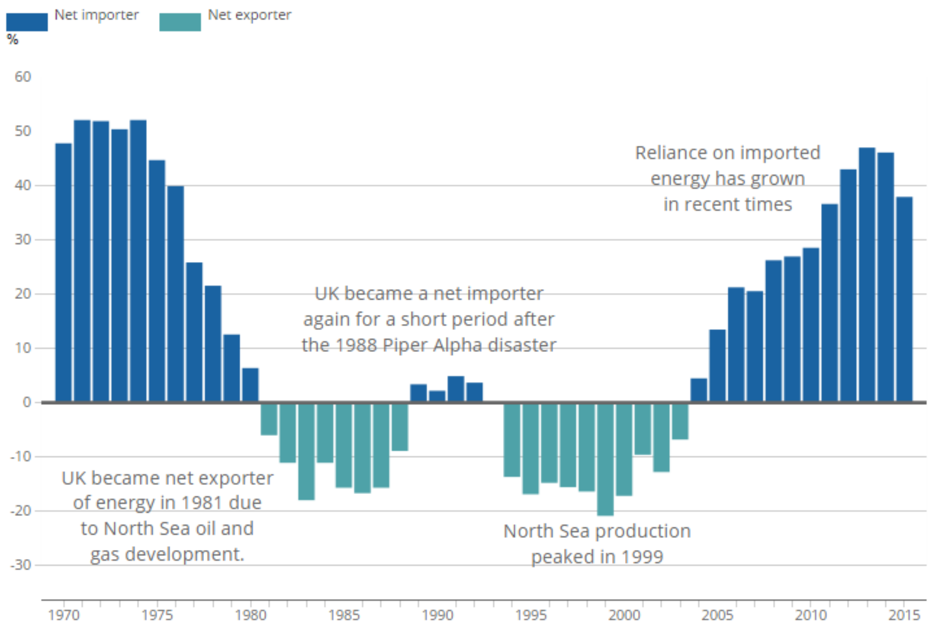


Fig. 2.4 UK energy import dependency: the percentage of UK energy supply made up of net imports, 1970 to 2015 [ONS Digital, 2016]

2.1.2 UK GREENHOUSE GAS EMISSIONS FROM THE RESIDENTIAL SECTOR

In the latest estimates of 1990-2016 UK greenhouse gas emissions[4], the residential sector accounted for **18% of all carbon dioxide emissions**. In 2016, emissions from residential were 15% lower than in 1990. It should be noted that emissions from this sector do not include those related to domestic electricity consumption [Department for Business Energy and Industrial Strategy (BEIS), 2017].

In the residential sector, the main source of emissions is the use of **natural gas** for both heating and cooking. Since 2004 there has been a general downward trend in emissions, although 2010 and 2012 were exceptions to this trend due to the particularly cold weather experienced in 2010 and the particularly warm weather experienced in 2011 [Department for Business Energy and Industrial Strategy (BEIS), 2017].

The energy demand from the residential sector is reliant on gas, and gas import has increased in the recent years. While carbon dioxide emissions from the residential sector have decreased since 2004, the residential sector demand remains high. Therefore, reducing carbon emissions from the residential sector by reducing the demand for energy as a strategy is still considered a priority.

Importantly, in the study of energy demand from residential, one should acknowledge all the sources of carbon emissions linked to the primary social practice of *inhabiting*, such as transport, and limited resources use, such as land. This clarification is necessary if one is to look at low-carbon design in a more comprehensive and interconnected way, to ultimately avoid generating new sources of energy demand that may result as a boomerang effect from energy demand reduction implementation strategies. For instance, energy demand for transport is linked to residential; therefore the location of new developments has the potential to impact on the energy demand for both residential and transport.

2.1.3 RISK OF INCREASED DEMAND FOR COOLING

As just stated, efforts put in place to reduce energy demand for heating from dwellings might, in the near future, experience a boomerang effect due to an increase in energy demand.

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[4] UK greenhouse gas emissions are presented in carbon dioxide equivalent units [Department for Business Energy and Industrial Strategy (BEIS), 2017].

In social psychology, the boomerang effect refers to the unforeseen consequences of an attempt to persuade resulting from purposive action. These unforeseen consequences are not necessarily undesirable, though this un-anticipation is mostly obviated by limitations in knowledge (inadequate knowledge or lack of knowledge) or by error [Merton, 1936].

Even though this concept was developed in social psychology, it can be applied to the implementation of sustainability in the built environment, as it concerns the dynamic of social and cultural change [Davies and Oreszczyn, 2012]. This is due to complex interactions in society and the ramifications that actions have in an interrelated system [Merton, 1936].

Overheating in HIHs may result in an increased demand from cooling to accommodate temperature change. Wright et al. claim that heat waves and internal temperatures could lead to a significant market for short-term cooling (such as portable cooling) or that comfort cooling and air conditioning could spread in housing, especially in the South of England [Wright, Young and Natarajan, 2005]. This has already started to be the case in London apartments [Young, 2014].

In addition, Peacock et al. used dynamic thermal simulation to investigate internal temperatures in the domestic sector and estimated that 18% of householders in the south of England would install air conditioning by 2030 if they responded to warm temperatures in the same way as US householders. This would equate to 550,000 homes equipped with air conditioning in London alone [Peacock, Jenkins and Kane, 2010].

Another significant driver for cooling demand seems to derive from poorly applied energy efficiency measures [Shrubsole *et al.*, 2014]. While efficiency measures are a fundamental way to deliver CO_2 reductions, they also risk producing uncomfortably warm temperatures, as current design has not yet transformed into mature low-carbon design. So, despite the efforts put in place to reduce energy demand and associated CO_2 emissions, there is still room for improvement in order to (a) not depend on energy import and also (b) to prevent an unaware rise of demand for cooling [ZCH, 2015b].

This section has reviewed the context in which overheating in HIHs may develop as a result of a contemporary carbon reduction agenda. In the next section, housing stock and projections of future housing development will provide a projected breadth of impact.

2.2 CONTEXT: THE UK HOUSING STOCK AND TRENDS

The Department for Communities and Local Government (DCLG) publish yearly reports representing changes in the UK housing stock based on a questionnaire sample of 13300 houses. In addition for a subsample of 6200 houses per year a physical survey is performed [GOV.UK, 2016]. For the purpose of understanding the characteristics of the UK building stock and within it, the proportion of HIHs, datasets from the English Housing Survey (managed by the Department for Communities and Local Government) are deployed here[5]. In this context, the reader should be aware of the fact that in this dataset the sample of HIHs should be expected to be small.

2.2.1 THE ENGLISH HOUSING STOCK

In 2014 there were about 23.4 million homes in England. In terms of tenure, 63% of these homes were owner occupied, 20% were privately rented, 10% were from the housing association stock and 7% were owned by local authorities [DCLG, 2016c] (fig. 2.5).

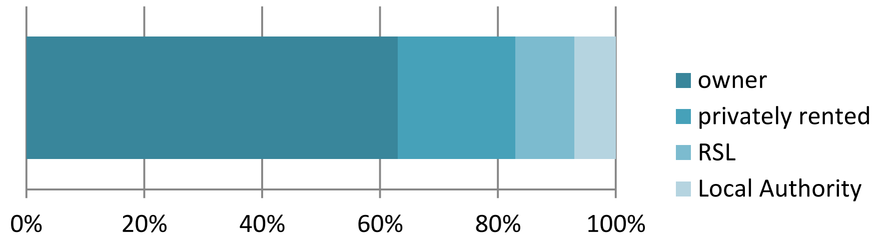

Fig. 2.5 Adapted from the English housing stock descriptive: by tenure [DCLG, 2016c]

In terms of typology, 42% were semi-detached or detached houses, 29% were terraced houses, 16% were purpose built flats, 9% were bungalows, and 4% were converted flats [DCLG, 2016c] (fig. 2.6). The present research is based on four case studies, one of which come from the first group typology (detached), two from the second group typology (terrace) and one bungalow, see Chapter 5 for details.

[5] It seems worth underlying that Census (ONS) will not be used. The main difference between Census and the English Housing Survey is in the sampling techniques of these two sources of data sets: census and survey. Census collects information about every member of the population, and a survey is a data collection activity that selects a sample of the population. For this reason, the latter is less onerous and less expensive and can be updated more frequently and focusing on a variety of information different than that collected by a census. It is also possible to say that a census is a 100% sample survey and Census statistics helps organisations such as DCLG to decide how, when and where capturing representative samples [ONS, no date].

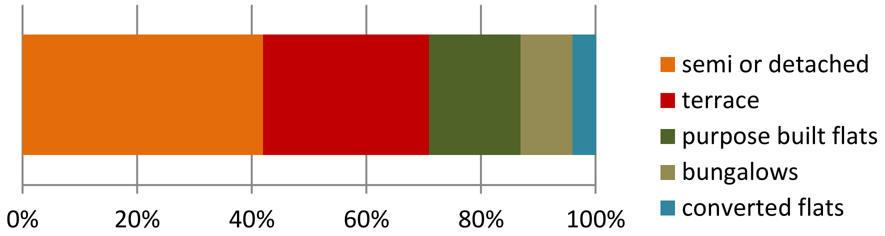

Fig. 2.6 Adapted from the English housing stock descriptive: by typology [DCLG, 2016c]

In terms of context, in England the majority of houses are located in suburban areas (61%), whereas 22% of homes are in cities or urban centers and 18% are in rural areas [DCLG, 2016c]. From the case studies included in this research, three out of four are from suburban areas.

2.2.2 NEW HOMES

Every year more than 100,000 new houses are built in the UK, of which about 80% in England, around 10% in Scotland and around 5% in both Wales and Northern Ireland [Beckett, 2014]. This figure varies greatly, as fig. 2.7 shows (for instance the number of dwellings built in England has halved compared to the 1980s decade). However the proportion in UK remains similar, with a great proportion of dwellings being built in England compared to the other UK nations.

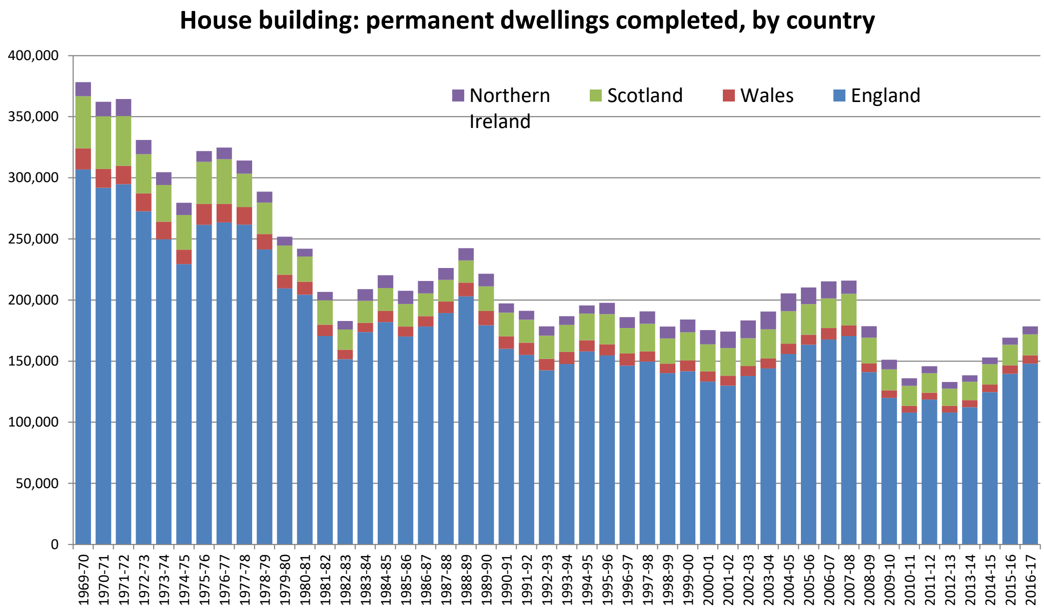

Fig. 2.7 UK house building, adapted from DCLG live table 209 [Beckett, 2014]

Within the existing stock in the UK, the largest proportion of dwellings is located in England (fig. 2.8). Of this large stock of over 23 million of English houses, the 0.5% is made of 'new dwellings' (fig. 2.9).

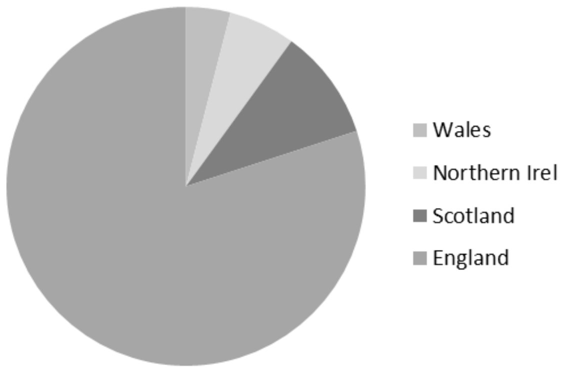

Fig. 2.8 UK dwellings stock (2014), adapted from [DCLG, 2016c]

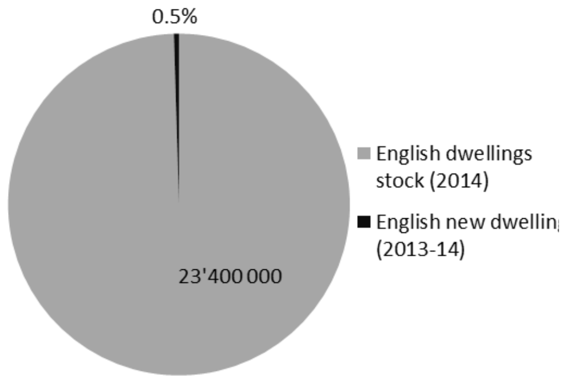

Fig. 2.9 English new dwellings (2013-14), adapted from [GOV.UK, 2016]

It is important to note that in the English housing survey, '*new homes*' are defined as houses built no more than ten years before the year of the survey (in this case 2015); that is, houses built in or after 2005 are qualified as new homes [DCLG, 2016c]. HIHs are characterized by their ' *super-insulation*', which is referred as a strategy of insulation to the extent that no heating systems are required [Nicholls, 2008]. Super-insulation is not a compulsory requirement in the Building regulations. As a consequence, HIHs are a subgroup of 'new homes' in the English housing survey.

Of the above mentioned figures, it is not possible to establish how many new homes are effectively HIHs, since the year of construction does not necessarily reflect the version of buildings regulations applied for approval. In fact, the applicable building regulations are set by the year in which the planning application permission is granted [DCLG, 2016b].

Even though semi-detached or detached houses are still the most built typology - between 1996 and 2014, around 1.3 million (out of 3 million) homes added to the English housing stock were either semi-detached or detached houses [DCLG, 2016c] – flats are growing in number, as shown in fig. 2.10.

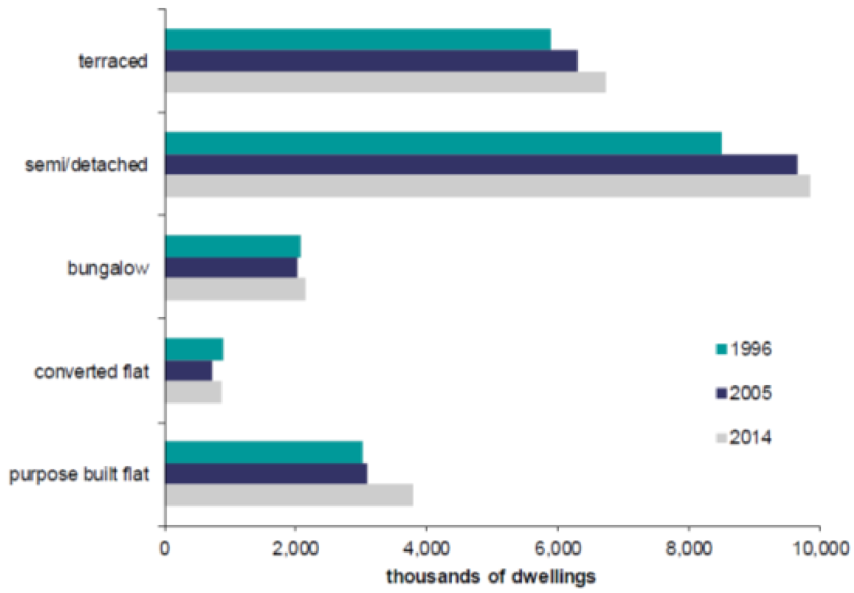

Fig. 2.10 Number of house builds completed England by typology across the years [DCLG, 2016b]

In England alone, about 110,000 new homes were built between 2013-14 [Beckett, 2014]. Of these new homes a large proportion were flats (44%) [DCLG, 2016c]. Between 2005 and 2014, around 1.3 million new homes were built in England with a higher prevalence of flats in all tenure types [DCLG, 2016c]. When looking at it in the perspective of overheating, this high density may aggravate the risks of overheating because of their reduced external wall area to volume ration [Beizaee, Lomas and Firth, 2013], and also in consideration of the fact that in most purpose-built flats are single aspects and so cross ventilation is not an option available there [Swainson M, 2014; ZCH, 2015b].

In 2014, dwellings had an average usable floor space of 94m^2, whereas the average sized flat was 61m^2, which is slightly lower than the average for small terraced houses [DCLG, 2016c]. The changing characteristics of new homes depict a built environment increasingly fragile to high internal temperatures. This is further exacerbated in the case of increasingly overcrowded social housing homes. So, it can be said that as development advances, the risk of overheating tends to increase. This is summarised in fig. 2.11.

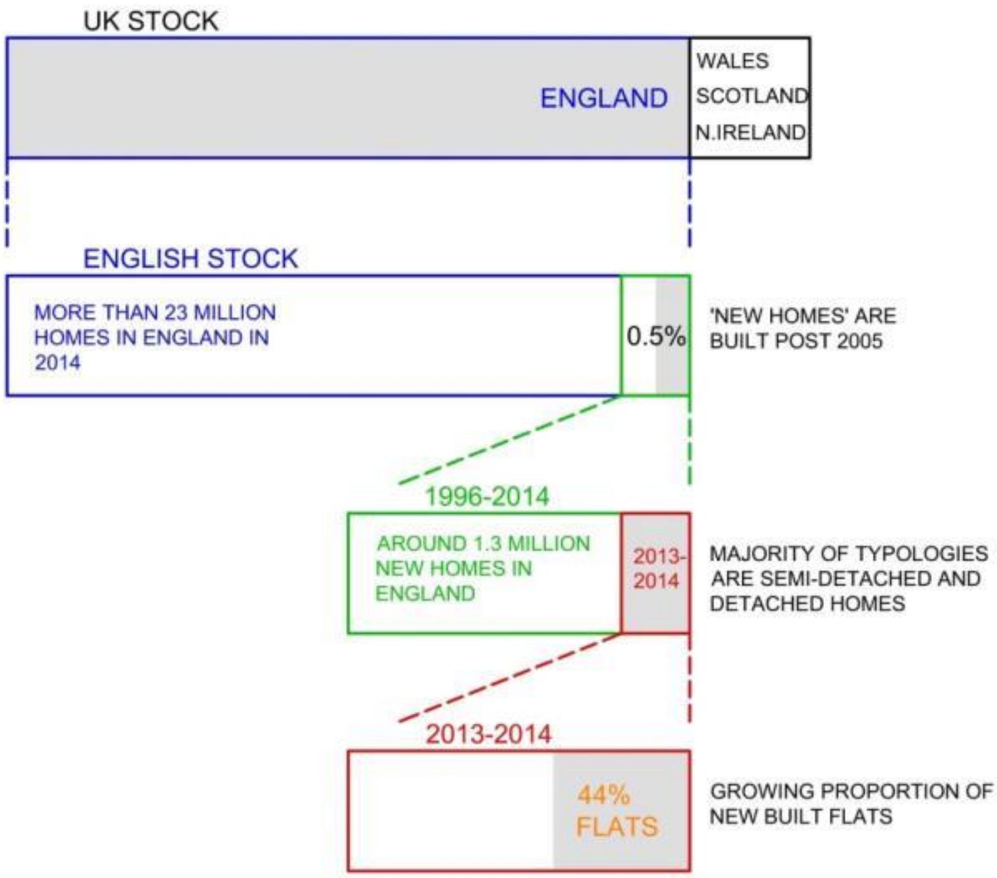

Fig. 2.11 The UK housing stock.
This figure shows the proportion of English homes over the UK stock, and the proportion of 'new homes' out of the English stock. Followed by the proportion of flats built during 2013-14. Diagram based on Beckett and DCLG [Beckett, 2014; DCLG, 2016c]

This section has reviewed the statistical data released by the government to locate the weight of overheating in the current stock and the trend might take in future developments, and this information has been summarised in fig. 2.11. Focused the scope of overheating risk within the housing stock, the next section review will elaborate the concept of overheating and why is an issue in the HIHs stock.

2.3 OVERHEATING AS A NEW CONCEPT?

Overheating in buildings in the UK can be perceived as an issue emerging from HIHs. In the growing body of literature devoted to overheating one cannot find a unitary definition of the phenomenon, as it is attested by the following quotation:

> *"Overheating is generally understood to be the accumulation of warmth within a building to an extent where it causes discomfort to the occupants. There is no clear definition of the term 'overheating' or the specific conditions under which this can be said to occur. Nor is there any statutory maximum internal temperature in UK Building Regulations or current health and safety guidance"* [NHBC, 2012b].

Still in the literature a clear connection is established between overheating, climate change, and, as a sort of paradox, HIHs design efforts to reduce energy demand [Energy Saving Trust, 2005].

The problem of overheating in buildings can be considered – at least in countries with mild climate like the UK - as a relatively modern problem, which has been discussed in the literature only from the second part of the 20th century. Those researching in the field of architecture actually mentioned cases of overheating in buildings also in the 1960s, when overheating was related to excessive heat gains due to the use of large glass areas in modern buildings [Loudon and Danter, 1965; Burberry, 1966]. In fact, in those buildings, when overheating was a problem, it was mainly due to excessive heat gains from the sun (radiation on the roof and sunshine through unshaded, single glazed windows) penetrating the building [Energy Saving Trust, 2005].

Likewise, the problems related to excessive heat have also been of concern to those researching in engineering. In the UK, studies conducted at the Building Research Establishment (BRE) in the 1960's look at the effect of excess-solar-gains through over-glazed modern buildings in summertime [Loudon and Danter, 1965; Loudon, 1968]. In these studies, overheating in buildings was already considered a problem especially for modern post-war schools and buildings. This means that already then design procedures for the new architecture were acknowledged to have the tendency to overlook non-apparent problems emerging in designs that move away from the traditional massive walls and small windows, to large proportion of window to surface area derived from the introduction of steel and structural engineering, replacing solid walls.

In addition, when high levels of insulation started to be applied, the length of the heating season was reduced, and internal temperatures were more easily maintained, however, the increasing insulation had the implication that internal temperatures were more sensitive to changes in heat input. In other words, the same heat gains put into a HIH is recognised to cause a much greater change in temperature than in an uninsulated house, to the extent that "*if heat gains are significantly greater than the losses then overheating can occur*" [Energy Saving Trust, 2005].

In this context, design procedures not only have to take into account the use of high levels of insulation but also the additional extensive use of lightweight cladding and, more recently, the increasing tendency to airtightness [NHBC Foundation, 2009]. The use of an airtight fabric was first recorded in the literature only in the 1980's in Sweden, whilst academic contributions in the UK appeared only in the late 1990's.

2.3.1 HIGH TEMPERATURES AND HEALTH: THERMAL COMFORT VS. HEAT STRESS

As temperatures rise, thermal stress increases. Whilst for most of the population overheating is just a matter of thermal comfort — a condition of satisfaction with the thermal environment—excess heat can have significant health implications. In fact, the actual implications of overheating on human health may take different forms, which range from loss of concentration and reduction of productivity to more severe consequences, such as heat strokes. Importantly, these consequences can be suffered not only by vulnerable groups (such as elderly, obese, and urban dwellers) but can also affect anyone whose body thermoregulation (i.e. sweating) is inhibited by diverse factors, such as the use of medication, or living in a humid environment [DCLG, 2012; Dengel and Swainson, 2012; NHBC, 2012b].

The UK Government introduced the Housing Health and Safety Rating System (HHSRS) as an approach for the evaluation of the potential risks to health and safety from any deficiencies in dwellings. Such assessments are based on an evaluation of both the likelihood of an occurrence that could cause harm and the probable severity of the outcomes of such an occurrence [Dengel and Swainson, 2012].

In the HHSRS, overheating in dwellings is expressed as 'excess heat', and it is included as one of the defined hazards from excessively high indoor air temperatures:

> "*As temperatures rise, thermal stress increases, initially triggering the body's defence mechanisms such as sweating. High temperatures can increase cardiovascular strain and trauma, and where temperatures exceed 25°C, mortality increases and there is an increase in strokes. Dehydration is a problem primarily for the elderly and the very young.*" [ODPM, 2006, p.64].

In addition the importance of night-time temperatures has been recognised, since the lack of nocturnal recovery may lead to high rates of mortality, especially in vulnerable groups of people. In fact the existing literature suggests that a change of as little as 1°C in skin temperature can affect the overall quality of sleep [Dengel and Swainson, 2012].

While HHSRS recognises that overheating in UK dwellings is unusual, it recognises the effect of heat waves[6] as an imminent treat: "*heat waves are forecast to become more common. It is possible, therefore, that there will be an increase in mortality and morbidity rates from excess heat associated with the inability to maintain a healthy temperature within dwellings*" [ODPM, 2006, p.64].

The HHSRS explicates the main factors that affect overheating in buildings and reduce them to the following three: (a) thermal insulation (but only in terms of inadequate or lack of provision, such as attic flats); (b) orientation of glazing (large areas of south facing glazing in inappropriately designed dwellings) an (c) ventilation provision (inadequate or inappropriate provision and inadequate means of controlling it) [ODPM, 2006, p.65]. Accordingly, there is no recognition of a likelihood of harm from HIHs. This is due to the fact that energy efficiency, or better the lack of it, has been linked to poor indoor environmental quality.

2.3.2 DEFINITION OF OVERHEATING

As indicated above, there is no universal definition of what constitute overheating. However, the Department for Communities and Local Government's (DCLG) *Investigation into overheating in homes* [DCLG, 2012] claims that overheating in buildings can be defined by its epidemiological evidence and by its physiological evidence[7].

[6] A definition of heat waves is provided in Chapter 5, section 5.2.3.
[7] *Epidemiological* relates to the occurrence of a disease, whereas *physiological*ly relates to normal, healthful functioning; not pathological [Collins, no date].

An **epidemiologically defined** heat threshold does not point out at which temperatures individuals begin to succumb to the heat. Instead, it uses evidence showing the link between temperatures and health-related effects (such as hospital admission, excess heat death, etc.). Therefore, this evidence can only make reasonable assumptions of, for instance, the effect of a heat wave on population. For London, epidemiological studies have shown that mortality begins to rise above a threshold of 24.7°C maximum daily temperature. However, the relationship between mortality/morbidity with outdoor temperature cannot accurately describe the causal connection to high indoor temperature [DCLG, 2012].

Overheating has also been defined on the basis of its **physiological evidence**, which provides indication of responses to specified temperatures. However, this alternative approach can be claimed to be too simplistic to define overheating by temperature alone, because the relationship between physiological response and adverse health is often unclear. For instance, it is not clear whether is the indoor or outdoor temperature exposure that carries the greatest health-related risk [DCLG, 2012]. Nonetheless, temperature has been recognised as the most important parameter in comfort, even though several respondents reported that humidity and ventilation may play as similarly significant role in the perception of overheating [DCLG, 2012].

An alternative definition of overheating can be found in CIBSE 2006, where overheating is defined as "*the temperature that limits the ability to carry out pre-specified levels of physical activity*" [CIBSE, 2006, p.323].

The Zero Carbon Hub has adopted a further definition of overheating in new homes. Such definition, which considers the effects on (a) thermal comfort, (b) health and (c) productivity reads as follows: overheating is "*the phenomenon of a person experiencing excessive or prolonged high temperatures within their homes, resulting from internal and/or external heat gains, and which leads to adverse effects on their comfort, health and productivity*" [ZCH, 2015a, p. 3].

2.3.3 DESIGN GUIDANCE

Design guidance aim at minimising heat discomfort in buildings set out temperatures thresholds according to building type. While there is no absolute temperature threshold for thermal comfort, there is documented evidence of internal temperatures harmful for occupant's health and wellbeing [Dengel and Swainson, 2012]. For this reason, overheating is also measured against a benchmark operative temperature[8] (related to the likelihood of discomfort) that should not be exceeded for a defined number of hours. As a result, a building is considered to 'overheat' whenever the benchmark operative temperature is exceeded for an established amount of time. The guidance available to overheating is listed below.

2.3.3.1 CIBSE GUIDE A - 2006

CIBSE Guide A [CIBSE, 2006a] sets design targets to define whether cooling is required in buildings. Guidance on operative temperatures threshold based on studies shows that sleep might be compromised above 24°C when all bedclothes except the sheet are removed and no further adaptation is possible. For this assessment, CIBSE recommended to use the CIBSE Design Summer Years (DSYs) in order to assess the overheating risk as these provide a more stringent test of overheating risk than do the CIBSE Test Reference Years (TRYs).

Table 2.2: CIBSE 2006 threshold of operative temperatures for overheating [CIBSE, 2006a]

Operative temperature for **indoor comfort** in summer	Living areas	25°C	
	bedrooms	23°C	
Benchmark (**threshold**) summer peak temperature	Living areas	28°C	1% annual occupied hours over operative temp. of 28°C
	bedrooms	26°C	1% annual occupied hours over operative temp. of 26°C

2.3.3.2 CIBSE TM52

CIBSE TM52 *The limits of thermal comfort: avoiding overheating in European buildings* claims that the advice on overheating in CIBSE Guide A 2006 is very limited and should

[8] Operative temperature is often referred as the 'temperature of a space': it is a theoretical measure (not an empirical measure) that combines the ait temperature and the mean radiant temperature into a single value to express their join effect. It is a weighted average of the two, the weights depending on the heat transfers coefficients by convection and radiation at the clothed surface of the occupant. In highly insulated homes and away from direct radiation from the sun or from temperatures (and hence between the air and operative temperatures) is small.
For indoor air speeds below 0.1 m/s, the equation for operative temperature is:

$$T_{op} = ½\ T_a + ½\ T_r$$

(where T_a is air temperature and T_r is the mean radiant temperature).

be changed from a fixed indoor temperature (regardless of outdoor conditions) to an adaptive approach, especially valid in free running buildings[9]. The rationale is that a fixed maximum temperature is not appropriate for all climates and, in order to achieve thermal comfort, people adapt[10] to the outdoor temperature at the time.

CIBSE TM52 does not provide any precise definition of overheating, as it indicates that "*all comfort standards have problems because they try to give precise definitions when the phenomenon they are describing is inherently imprecise*" [CIBSE, 2013]. On the other hand, it highlights the usefulness of adaptive comfort models as they are related to outdoor temperatures[11].

To some extent, CIBSE TM52 highlights the importance of buildings being designed to allow occupants to control their indoor conditions and hence to adapt to their environment. In this way a standard can act as a guide rather that a prescriptive restriction on indoor temperatures [CIBSE, 2013]. CIBSE TM52 also recommends that new buildings and major refurbishments should conform to Category II as set in BS EN 15251[12]. This category sets a maximum acceptable temperature of 3°C above the comfort temperature for buildings in free-running mode.

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[9] Also known as naturally ventilated buildings.

[10] There are three categories of thermal adaptation (a) behavioural, (b) physiological, and (c) psychological. Psychological adaptation refers to an altered thermal perception and reaction due to past experiences and expectations, and is an important factor in explaining the difference between field observations and PMV predictions (based on the static model) in naturally ventilated buildings [de Dear and Brager, 1998].

[11] The adaptive models of thermal comfort are implemented in some standards such as ANSI/ASHRAE Standard 55, European standard BS EN 15251 and ISO 7730 standard. Even though the exact derivation methods and results of the last two are slightly different from the ANSI/ASHRAE Standard 55, they are in substance the same. However, ANSI/ASHRAE Standard 55 only applies to buildings without mechanical cooling installed, while BS EN 15251 can be applied to mixed mode buildings provided the system is not turned off [BSI, 2007].

[12] The European Standard EN 15251 was developed in response to the Energy Performance of Buildings Directive (EPBD), and addresses considerations of the indoor thermal environment as well as indoor air quality, lighting and acoustics.

The EN 15251 follows the general building categorisation of ASHRAE, i.e. (a) mechanically cooled buildings assessed with PMV model and (b) free-running buildings assessed with the adaptive model. In addition, the EN 15251 uses a 'category description' for such buildings according to a level of expectation of comfort:

- Category I – For high level of expectation (fragile handicapped, sick, very young, elderly)
- Category II - For a normal level of expectation (for new buildings and renovation)
- Category III - For acceptable-moderate levels of expectation (existing buildings).

According to CIBSE TM52, overheating occurs when a room or a building fails any two of the three criteria below listed. The most recent version of CIBSE Guide A [CIBSE, 2015] embeds the CIBSE TM52.

Table 2.3: CIBSE TM52 conditions to overheating [CIBSE, 2013]

Criterion 1 – *Hours of exceedance (He)*	It sets a limit on the number of hours that the operative temperature can exceed the threshold comfort temperature (i.e. the upper limit of the range of comfort temperature) by 1 K or more during the occupied hours of a typical non-heating season (1 May to 30 September). The number of hours (He) during which ΔT is greater than or equal to one degree (K) during the period May to September inclusive should not be more than 3% of occupied hours[13].
Criterion 2 – *Daily weighted exceedance (We)*	It deals with the severity of overheating within any one day, the level of which is a function of both the rise of temperature and its duration. This criterion sets a daily limit of acceptability. To allow for the severity of overheating, the weighted exceedance (*We*) must be less than or equal to 6 on any one day where: *We* = (Σ he) × WF = (he0 × 0) + (he1 × 1) + (he2 × 2) + (he3 × 3) where the weighting factor WF = 0 if ΔT ≤ 0, otherwise WF = ΔT, and *he* is the time (h) when WF = y [14].
Criterion 3 – *Upper limit temperature (Tupp)*	It sets an absolute maximum daily temperature for a room, beyond which the level of overheating is deemed unacceptable. The recommended definitions for the criteria set that the absolute maximum value for an indoor operative temperature is set as follows: the value ΔT shall not exceed 4 K. This absolute maximum temperature is one in which adaptive actions are inadequate and cannot restore occupant comfort.

2.3.3.3 CIBSE TM59

CIBSE *Technical Memorandum 59: Design methodology for the assessment of overheating risk in homes* has been developed recently to address a new awareness of overheating risks in the residential sector. It consists of a standardised methodology to assess the risk of overheating in dwellings, care homes and student residences; further, it incorporates aspects of the "threshold" approach as well as the "adaptive" approach. The methodology is based on data from the UK domestic sector and has been tested on major risk projects, such as flats [CIBSE, 2017]. Its main purposes consisted in solving the tensions between winter comfort from building regulations requirements and summer

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[13] If data are not available for the whole period (or if occupancy is only for a part of the period) then 3 per cent of available hours should be used.

[14] "*Thus suppose we have a room where the temperature is simulated or monitored at half-hourly intervals over 8 occupied hours, so we have 16 readings, ten of them where ΔT is zero or negative (wf = 0), three readings where ΔT = 1 (wf = 1), two where ΔT = 2 (wf = 2) and one where ΔT = 3 (wf = 3) then: W_e = ½ [(10 × 0) + (3 × 1) + (2 × 2) + (1 × 3)] = 5 (i.e. the criterion is fulfilled)*" [CIBSE, 2013].

comfort, on the one hand, and in limiting the overheating risk, which is thus recognised to be a challenge in low-carbon housing on the other hand [CIBSE, 2017].

In accordance with the standard set by CIBSE TM59, houses that are (predominantly) naturally ventilated, including those with MVHR (mechanical ventilation with heat recovery), are required to pass two criteria:

Table 2.4: CIBSE TM59 conditions to overheating [CIBSE, 2017]

Criterion 1	Living areas Kitchens and bedrooms	CIBSE TM52 criterion 1 (hours of exceedance)	The number of hours (He) during which ΔT is greater than or equal to one degree (K) during the period May to September inclusive should not be more than 3% of occupied hours.
Criterion 2	Bedrooms from 22:00-07:00	26°C	No more than 1% of annual occupied hours shall exceed operative temperature of 26°C (1% of annual hour between 22:00 and 07:00 for bedrooms is 32 hours, so 33 or more hours above 26°C will be recorded as fail).

2.3.3.4 PASSIVHAUS

Another definition of overheating is provided by the **Passivhaus Standard**[15]. Due to the increasing number of homes been designed to this standard, the definition has become of wide use within the sector. In order to evaluate the risk of overheating in a building, the Passivhaus standard uses a fixed threshold temperature that remains the same irrespective of the external conditions and occupants' vulnerabilities. The standard established that it is not acceptable for living areas to exceed an operative temperature of 25°C for more than 10% of the total occupied hours. The standard also recommends that this threshold is not exceeded for 5% of the time. [BRE Trust, no date; Passivhaus Institut, 2015].

Unlike the other definitions, the Passivhaus calculation is tailored for an energy efficient building, and the overheating criteria check refers to the whole building. For this reason,

[15] For the definition of the Passivhaus Standard, please refer to Chapter 3, section 3.2.

in the process of designing a Passivhaus, the designer deals with calculations of the building as a whole; and this facilitates the process of judgement. Such judgement of the thermal performance is intended to constitute a starting point enabling one to design more resilient buildings to cope with overheating and climate change in general.

2.3.3.5 OTHER ASSESSMENTS AND DEFINITIONS

Another definition is provided by **ARUP** *Beating the heat: keeping UK buildings cool in a warming climate*, where it is advised not to exceed 28°C (living rooms) and 25°C (bedrooms) for more than 1% of the time. Also, this document reports a heat stress risk at 35°C (50% relative humidity) [Hacker, Belcher and Connell, 2005].

Other definitions are provided in table 2.5. In this context, it is worth noting that there are no statutory maximum internal temperatures in the Building Regulations [Young, 2014].

Table 2.5: Overheating and comfort thresholds for temperatures relevant to UK based on [CIBSE 2002; CIBSE 2006a; Armstrong et al. 2011; CIBSE 2013; CIBSE 2015; Office of the Deputy Prime 2006; Passivhaus Institut n.d.; JN Hacker et al. 2005]

Temperature	Description (assumes appropriate clothing)	Source
32˚C	• Threshold maximum outdoor daytime temperature defined by the Met Office for London	• Public health England (2013)
30˚C	• Threshold maximum outdoor daytime temperature defined by the Met Office for East Midlands	• Public health England (2013)
28˚C	• Overheating threshold for 1% annual occupied hours over operative temperature	• CIBSE A (2002 & 2006), ARUP (2005)
27˚C	• Maximum acceptable (cat II)*, sedentary	• CIBSE A (2015)
26˚C	• Maximum acceptable (cat III)*, sedentary (living rooms) • Upper 'desirable' limit without air movement (living rooms) • Overheating threshold for 1% annual occupied hours over operative temp. in bedrooms • Increased discomfort above this temperature in living rooms	• CIBSE A (2015) • CIBSE A (2015) • CIBSE A (2006), ARUP (2005) • CIBSE A (2015)
25˚C	• Comfort temp. in living rooms • Threshold Passivhaus standard for 10% annual • Threshold as a treat of health hazard	• CIBSE A (2006) • Passivhaus Institute • HHSRS (2006)
24.7˚C	• External temperature threshold London (mortality begins to rise)	• Armstrong et al. (2011)
24˚C	• Sleep may be impaired in bedrooms • Increased discomfort above this temperature in bedrooms	• CIBSE A (2006 & 2015)
23˚C	• Comfort temp. in bedrooms	• CIBSE A (2006)
20.9˚C	• External temperature threshold North East of England (mortality begins to rise)	• Armstrong et al. (2011)
18˚C	• Threshold maximum outdoor night time temperature defined by the Met Office for London	• Public health England (2013)
15˚C	• Threshold maximum outdoor night time temperature defined by the Met Office for East Midlands	• Public health England (2013)

2.3.4 ASSESSING OVERHEATING: STATIC OR ADAPTIVE CRITERIA?

As mentioned in the earlier paragraphs, the thermal comfort evaluation can be assessed through two alternative approaches: (a) static overheating criteria and (b) adaptive overheating criteria.

The static criteria, such as CIBSE 2006 or Passivhaus, have been used as a guide for thermal design [CIBSE, 2002, 2006a; Feist *et al.*, 2007] to assess or predict annual overheating risk related to a threshold temperature. The same threshold approach has been used to *evaluate indoor temperatures* during the 2003 heat wave [Wright, Young and Natarajan, 2005; Peacock, Jenkins and Kane, 2010; Porritt *et al.*, 2012].

As reported in a study conducted by Lomas, static criteria are helpful for rapidly comparing temperatures in different homes. However in real life, individuals adapt to the changing environment by changing clothes, by changing activity and by interacting with such environment (e.g. by opening/closing windows and shutters.) [Lomas and Kane, 2012]. For this reason, the adaptive approach of overheating seems to be more appropriate.

It should also be added, though, that there exists a discrepancy between both methods, especially when comparing the results of overheating assessment with both approaches. For many studies have reported different results depending on whether temperatures are analysed with one or the other approach [Beizaee, Lomas and Firth, 2013; Lomas and Kane, 2013; Mavrogianni *et al.*, 2016].

Between the two approaches, Lomas found that many houses in Leicester overheated despite the cold summer when temperatures were assessed with the static criteria, whereas the same homes were found to be generally cool when using an adaptive approach [Lomas and Kane, 2012]. Also, Beizaee et al. raise questions on the reliability of BS EN 15251, because it does not differentiate geographical regions [Beizaee, Lomas and Firth, 2013].

Moreover, on an assessment of overheating of 25 dwelling monitored homes during three summers (2011, 2012, 2013), Tabatabaei Sameni et al. found that criterion 2 of the CIBSE TM52 (daily limit for severity of overheating to 6 hours) does not reflect the actual occupancy (which could be more or less than 6 hours). As a result, this assessment may ultimately overestimate or underestimate overheating [Tabatabaei Sameni et al., 2015].

Recently, CIBSE TM59 combines aspects of the static and the adaptive assessment for overheating, but no studies have published up to date to establish the effectiveness of the suggested criteria in predicting overheating. This assessment will be performed in Chapter 5 of this thesis.

Overall, and for the reasons just exposed, rather than quantitatively determining overheating, this study will focus on the evaluation of the design performance, and what the sources of such failure in delivering comfort, if any.

This section has described overheating as a potential health issue, and the fine line that exists between comfort problem and heat stress problem. A review of temperatures thresholds as well as design guidance and assessment were presented, which created the preamble for evidence of overheating in the next section.

2.4 EVIDENCE OF OVERHEATING IN HOMES

The emerging problem of overheating has been substantiated by anecdotal and, recently, by scientific evidence. Among the academic evidence, a comprehensive review of the evidence of overheating in new UK houses conducted indicate that new HIHs (i.e. super-insulated, airtight dwellings) do indeed suffer from overheating and can result in adverse health effects for its occupants [Dengel and Swainson, 2012; Tabatabaei Sameni *et al.*, 2015]. Overheating in HIHs was also reported by a meta-study of 60 low-energy UK houses, with occurrence of overheating during February and April, indicating that the problem is not entirely due to external temperature and solar gains, but also an alarming and emerging problem of internal gains and insufficient ventilation [McGill *et al.*, 2017].

2.4.1 MONITORED STUDIES

Monitoring studies of dwellings with perceived overheating have often collected information about both the use and construction of the building.

When looking at **typologies**, in a national representative study of English homes, purpose built flats and end of terraces were found to have consistently high overheating compared to other built form types [Firth and Wright, 2008]. Interestingly, purpose built flats were found to be the best performing typology when it comes to Building Regulations' compliance calculation. Another finding in this study is that temporary dwellings (with low thermal mass) showed both very low and very high temperatures [Firth and Wright, 2008].

Lomas and Kane monitored 282 representative Leicester homes during summer 2009 and found that households with people over 70 years old are more likely to heat their homes during summer. Moreover, 30% of those households exhibited occurrences of extreme overheating (when assessed against static criteria and no occurrence of overheating when assessed with methods referring to the adaptive thermal comfort [Lomas and Kane, 2012].

During the same summer, in a study of 101 representative dwellings in London, Mavrogianni et al. found that:

- 42% of bedrooms fail CIBSE 2006 (especially purpose built flats), and sleep impairment might have occurred in 86% of bedrooms;

- An understanding of the causes and effects of indoor overheating was found to be a challenge, since it is not clear if the higher temperatures in these bedrooms led occupants to open windows or if the provision of ventilation effectively provided cooling benefits (in consideration of the fact that at the time external air temperatures were high;
- The building operation of the residents in urban dwellings might differ markedly from standard behaviour assumptions (often used in modelling studies) and best-practice public-health recommendations (for instance, occupants may not open windows for security reasons or external noise levels and windows are kept close during daytime) [Mavrogianni et al., 2016].

In a survey of 207 statistically representative samples of English homes that Beizaee et al. performed during one of the coldest summers (August 2007), overheating was regarded as constituting a risk for comfort and health [Beizaee, Lomas and Firth, 2013]. It was found that:

- Purpose built flats presented consistently high temperatures and detached homes recorded the lowest temperatures. This was considered to be the result of the fact that flats often have a reduced external wall area to volume ratio (whereas, for instance, in detached homes this ratio is high), and so cooling may be delayed;
- bedrooms tend to exceed static threshold;
- The instances of bedrooms that exceeded static threshold were more frequent in post-1990 buildings;
- Even though the survey was performed during a cold summer, a large proportion of bedrooms and living rooms had more than 5% of occupied hours above the CIBSE recommended temperature of 24˚C & 25˚C. This observation was more evident when considering post-1990 buildings and flats [Beizaee, Lomas and Firth, 2013].

In a monitored study of 36 London dwellings (not a representative sample), Mavrogianni et al. found that 42% of bedrooms fail CIBSE static criteria, especially in purpose built flats. In the same study, it is claimed that sleep impairment might have been caused in

86% of the bedrooms on a five-day hot spell of Summer 2009[16] [Mavrogianni et al., 2010].

In a study monitoring 25 Passivhaus flats during three summers (2011, 2012, 2013), Tabatabaei Sameni at al. compared averages of (external) environmental factors and internal averages above the overheating static threshold and found no direct relationship between such factors and indoor overheating. More specifically, in this study:

- a regression analysis demonstrated that occupant behaviour (window patterns, the use of curtains, and internal gains due to appliances) had a significant impact on temperature variation and overheating;
- Questions arose as to whether it is possible not to rely on occupants to open/close the curtains are valid, since developers seem reluctant to incorporate external shading in designs due to a substantial increase in construction costs [Tabatabaei Sameni et al., 2015].

In another study, two side-by-side Passivhaus dwellings were monitored for over two years. The dwellings have the same building specifications, similar building layout. The main difference consist in the window-to-wall ratio (WWR): in dwelling 1 the windows occupy 55% of the south elevation and in dwelling 2 the glazed area is 20% of the elevation. Whereas in dwelling 1 the design's intention was to maximise the potential for solar gains and the vision area, in dwelling 2 the intention was to reduce the constructions costs associated with large windows and blinds [Ridley *et al.*, 2014]. The most significant results of that study can be summarised as follows:

- Monitored temperatures of both homes failed the CIBSE static summer overheating criteria [CIBSE, 2006a] in the bedrooms. When using the BS EN 15251 adaptive criteria [BSI, 2007], dwelling 1 showed a high risk of overheating due to its solar gains through windows, whereas dwelling 2 was found to be at low risk, and anyway at a risk significantly lower than dwelling 1. To confirm that the risk of overheating is predominantly due to solar gains, the study carried a multiple regression analysis. Such analysis confirmed that while dwelling 2 is more dependent on external temperatures than dwelling 1, dwelling 1 had temperatures more dependent on solar gains;
- Interestingly, dwelling 1 was fitted with external blinds but the interviews with the occupants revealed that the occupants did not fully understand how to operate

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[16] Summer 2009 has been categorised as a cold summer.

them and that they were reluctant to open the windows during summer to prevent insects from entering the house [Ridley et al., 2014]. This fact highlights the contrasts between innovative design and occupants' behaviour [Ridley et al., 2014].

A study monitored two Passivhaus flats in Cardiff (one above the other) over two years. One of them has turned the MVHR off and hence was operated as a naturally ventilated dwelling. The management of the free-running apartment was conducted by maintaining the MVHR off, opening the windows to refresh the air and using an electrical panel heater mainly in the living room and bedroom. Internal temperatures were lower in the free running flat, with averages temperatures in the bedroom between 16-17°C and between 17-20°C in the living space. So, it seems that by allowing for natural ventilation, and hence adaptive behaviour, the range of comfort is widened and, therefore, the risk of overheating can be reduced [Sassi, 2013]. On the basis of these findings, Sassi questions whether naturally ventilated HIHs are more appropriate in mild maritime climates, such as the southern UK, by so avoiding the heat recovery when not needed. As this case suggests, a naturally ventilated HIH can perform well with no MVHR but, importantly, only in terms of energy consumption, because the indoor air quality was not assessed in this study.

In 60 low-energy homes across UK, differences in internal temperatures were evident from houses with and without MVHR. Interestingly, it was found that during winter, houses with MVHR reported greater temperature stability and better levels of ventilation compared to houses without MVHR. During summer however instances of overheating were reported in houses equipped with MVHR. This study recognises the importance to adequate summertime ventilation provision in airtight houses and the need to develop a know-how aimed at effective implementation of ventilation strategies to avoid overheating [McGill *et al.*, 2017].

A recent report presented by Innovate UK [Palmer *et al.*, 2016] and based on the largest building performance evaluation programme of energy efficient housing across UK - 76 homes were chosen from 59 monitoring projects that Innovate UK funded through its £8 million Building Performance Evaluation programme over the years 2010-2014 - present a number of findings, which are listed below:

- Developers and housing associations are often keen to reduce the energy demand of their buildings;

- During the first year of inhabiting low-carbon houses can sometimes increase quite considerably the energy demand and related CO_2 emissions. The report also highlights that these adjustment issues might not be spotted and fixed unless there is in place performance evaluation;
- Changes in the designs (such as changing a cladding or changes to account for fire regulation compliance) during the construction phase were shown to worsen the building fabric performance and in some cases causing overheating;
- The provision of air gaps at the bottom of doors was not always implemented' as a result cross ventilation was compromised;
- Heat recovery ventilation was installed with flexible ductwork with unnecessary bends. This caused the system's air flow to underperform and increase noise (an example of wrong installation of ductwork can be seen in figure 3.8 in Chapter 3);
- When low-carbon energy systems were installed (MVHR, biomass boilers, etc.), their operation were not fully understood, and/or controls were complex to use. Not only residents needed clear explanations, but also automatic controls were found to be problematic and by so they be avoided;
- The report also questions whether low-carbon technologies are appropriate due to their unclear benefits and unfamiliarity in design, installation, and use;
- There were found gaps in responsibilities and weak communication in the procurement contract, between designers and contractors;
- Loggers recorded temperatures above 28°C in half of the properties, but only for a short amount of time (less than 0.6% between May and August);
- One Passivhaus exceeded 28°C for 9% of the summer and exceeded 25°C for one-fifth of the summer. The report suggests that this may have been caused by the fact that the residents left the windows closed for much of the time. However, leaving the windows closed and letting the MVHR "do the job" is the instruction provided to the residents. So clarity is missing in the ventilation strategy;
- The report also suggests that window-opening routines might be a factor more important in influencing overheating than insulation and air tightness itself;
- Another main finding is that air tightness deteriorates over time. This issue could be of relevance to the study of overheating in rural contexts and an aggravator in UHI contexts.

OTHER INTERNATIONAL PROJECTS

Other international projects have instead shown the suitability of highly insulated houses. The European funded research project CEPHEUS project (1998-2001) provides findings from a number of monitored Passivhaus houses in Germany, Sweden, Austria, Switzerland, and France. This study comprises a total of 221 housing units in 14 building projects. Here, houses were monitored also from the point of view of the acceptability of Passivhaus dwellings by its inhabitants [Feist, Peper and Görg, 2001]. These surveys showed a generalised high level of acceptance (fig. 2.12):

- The substantial majority of occupants found the winter indoor climate as *good* to *very good*. In addition the higher surface temperatures and the even temperature distribution throughout the space was experienced as highly pleasant.
- During summer, occupants expressed to be *satisfied* or *very satisfied* with the indoor climate, especially thanks to the cooler environment when windows were closed (most households apply night time ventilation).

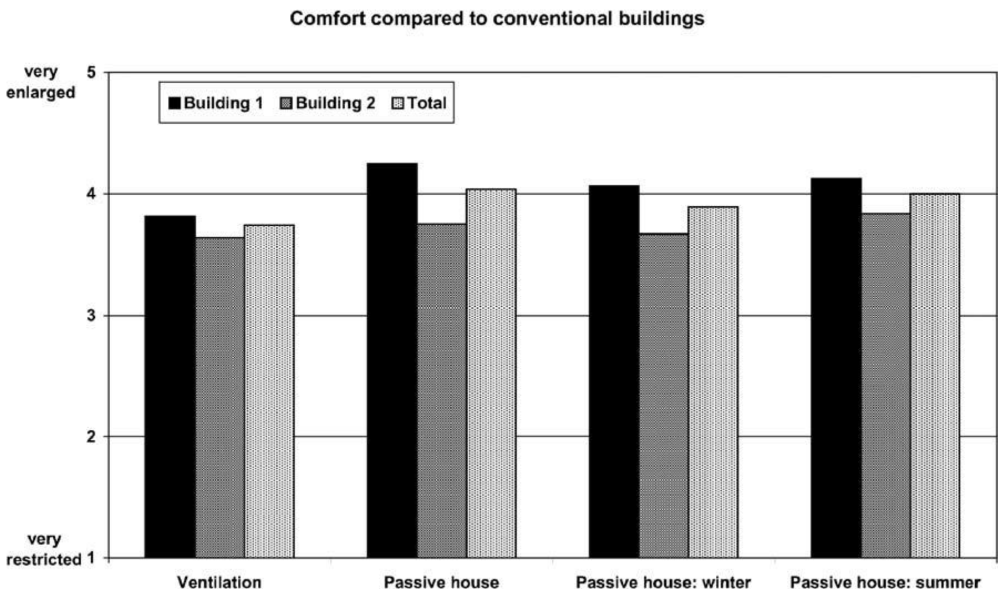


Fig. 2.12 Evaluation of comfort in the CEPHEUS project [Schnieders and Hermelink, 2006]

2.4.2 MODELLING STUDIES

Thermal modelling offers a powerful tool to predicting the possibility or probability of overheating and can be used to test the consequences of changes in specific parameters, such as orientation, house types, house layout, climate change, etc. under well-defined conditions.

Dynamic thermal modelling (DTM) offers a powerful tool to evaluate the design choices and to assess the different zone's temperatures by so informing the decision making of designers. As a result, valuable lessons can be learned from academic modelling studies. However modelling studies, like DTM, may be unreliable in assessing the overheating risks, because they are not able to reliably model human behaviour and their thermal interaction with their environment [Beizaee, Lomas and Firth, 2013].

A low energy steel frame house in Nottingham was modelled with a base case-current weather data and future climate scenarios. In this study, the current base case presented acceptable levels of overheating only when external solar shading was applied to the model. In the future weather scenarios, the house was found to be likely to overheat even with shading, ventilation and earth-to-air heat exchangers [Rodrigues, Gillott and Tetlow, 2013]. The study also recognises the implications of high temperatures in one room having an effect on other rooms' temperatures. In fact, the use of solar shading that has greatly reduced the percentage of high temperatures in the living room has had an effect on the temperatures of the adjacent areas, even though those areas are not directly affected by solar gain. Likewise – the high temperatures in the sunspace affected the overall temperatures in the house. The sunspace presented a particularly high risk of overheating as the incorporation of phase changing materials in the ceiling showed to be not sufficient at mitigating peak temperatures [Rodrigues, Gillott and Tetlow, 2013].

A larger modelling study was performed on a stock representative of London. Mavrogianni et al. performed a DTM of a combination of 3456 virtual dwelling types in order to test current and future weather scenarios over a warm continuous 5-day period of modelling [Mavrogianni *et al.*, 2012]. The results of this study can be summarised as follows:

- Flats and bungalows are at most risk, and in flats the overheating risk increases as floor level rise;
- A strong relationship was found to exist between insulation levels and internal temperatures. In general, insulation appears to reduce overheating, but in some cases, overheating increases (it was modelled as internally insulated). This shows an initial indication of the intrinsically different indoor environments resulting from the use of insulation;
- There was a greater variation of living rooms internal temperatures within housing types than within rooms of the same dwelling;

- Interestingly, this study acknowledges its limits by not having taken into account of location specific (microclimate) factors to correctly map overheating risks [Mavrogianni *et al.*, 2012].

A recent simulation study finds that buildings with thermal mass are at less risk of overheating and that thermal mass becomes more important as insulation levels increase [Mulville and Stravoravdis, 2016].

2.4.3 OTHER EVIDENCE

The non-academic evidence relates to the bulk of reports conducted by knowledge platforms, such and Good Homes Alliance (GHA) or Zero Carbon Hub (ZCH) – and at the time the present research was undergoing - in the attempt to feed information quickly to professional bodies.

GHA has conducted an exploratory study to call for evidence of overheating and to get a grasp of the extent of the problem of overheating in UK. GHA conducted a consultation with environmental health officers, housing providers, consultants, etc. and also two online surveys. Within this, 185 instances of overheating where found, shown in fig. 2.13. It should be noted that fig. 2.13 does is not a representative sample.

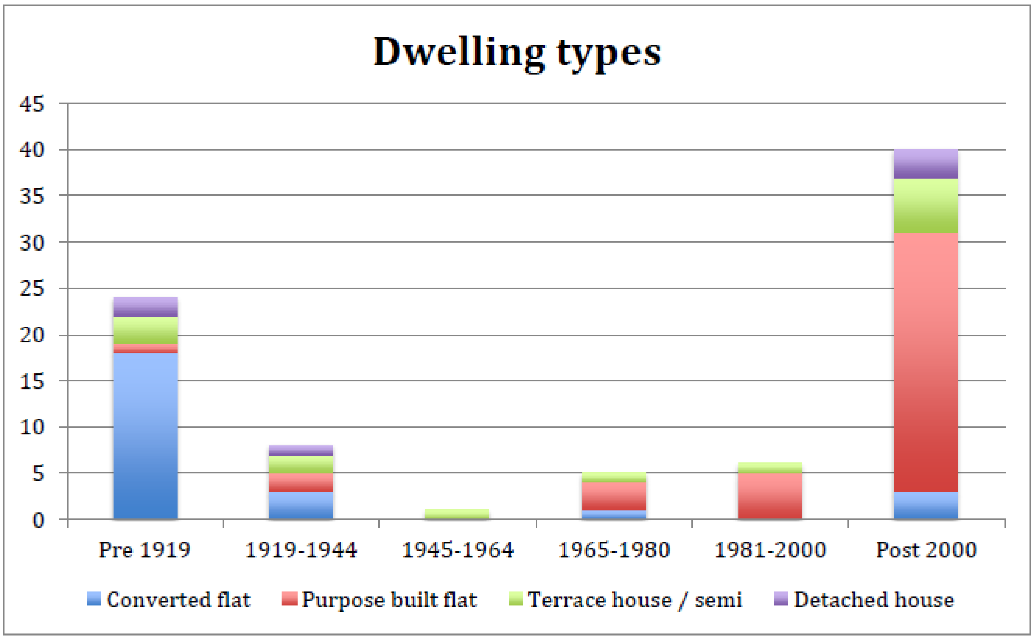


Fig. 2.13 Instances of overheating according to typology [Taylor, 2014]

In this investigation, most observed causes of overheating are related to large glazing areas to the south and insufficient or flawed ventilation [Taylor, 2014]. In this respect, purpose built flats are at major risk, because dwelling units layouts often do not incorporate the possibility of cross ventilation. In addition, the main internal corridor is generally not ventilated and so it builds up the heat (and pollutants), which is then distributed to the dwellings units [Taylor, 2014].

Purpose built flats, present a number of intrinsic 'defects' or 'risk' in terms of overheating due to a number of factors such as:

- are mostly built in already high-density locations, such as urban contexts and therefore exposed to UHI effect;
- are characterised by single-aspects layout, probably due to financial considerations;
- for marketing purposes purpose flats have floor-to-ceiling glazing (and no solar shading);
- the dwelling units are affected by heat gains from the corridors;
- windows have very limited opening (according to GHA often only the 10%).

All these factors could be summarised into no solar control, no proper ventilation and extra heat gain encountered (from UHI, corridors, inefficient appliances) [Taylor, 2014].

2.5 CHAPTER SUMMARY

It was found that there is no universal agreement on what constitutes overheating and that imposing a temperature limit would require many different thresholds (depending on age group, user-type, season, adaptability, type of house design). In addition, when assessing overheating, many studies agree that the static and the adaptive criteria analyses differ significantly in their assessment of overheating.

The review of literature shows that despite the effort of the UK government to reduce energy demand for heating from the buildings stock, there is an increased demand for cooling of poorly designed in HIHs.

Monitoring studies representative of the highly insulated building stock have shown that there is no direct relationship between averages of external temperatures and internal ones, as the occupants' behaviour is one of the most influential factors in determining the occurrence of overheating. In this context, the reliance on the occupants' behaviour for solar shading or ventilation constitutes one of the main causes of indoor thermal performance and might be at the origins of high indoor temperatures in some cases.

Evidence of overheating has been identified in the generic UK stock. Studies surveying the monitored temperatures of representative building stock indicate that bedrooms experience higher temperatures. Moreover, purpose built flats have been found to be the typology at most risk of overheating, probably due to their incapability to incorporate cross ventilation. This risk factor is aggravated by the fact that a significant proportion of new dwellings are flats.

Modelling studies of HIHs have shown that high temperatures in one room have an effect in the adjacent areas. So the problem of overheating is not limited to individual rooms. Also in addition, passive design implementations, such as sun spaces, can exacerbate internal temperatures. Dynamic simulation has also demonstrated that – even in the case of a perfectly balance MVHR system (well designed, installed and used) - MVHR systems are not able to mitigate excess temperatures in buildings with high thermal mass, because they are not able to remove sufficient heat to prevent overheating.

Large monitoring studies representing the highly insulated building stock collected by Innovate UK (prior known as Technology Strategy Board) have showed that **HIHs are**

particularly vulnerable to a number of issues. Those issues include communications during the built process, in-construction changes affecting the thermal performance and lack of knowledge in implementing and operating low-carbon technologies.

The studies introduced in this chapter indicate the main physical causes producing uncomfortably warm temperatures can be related to the following factors:

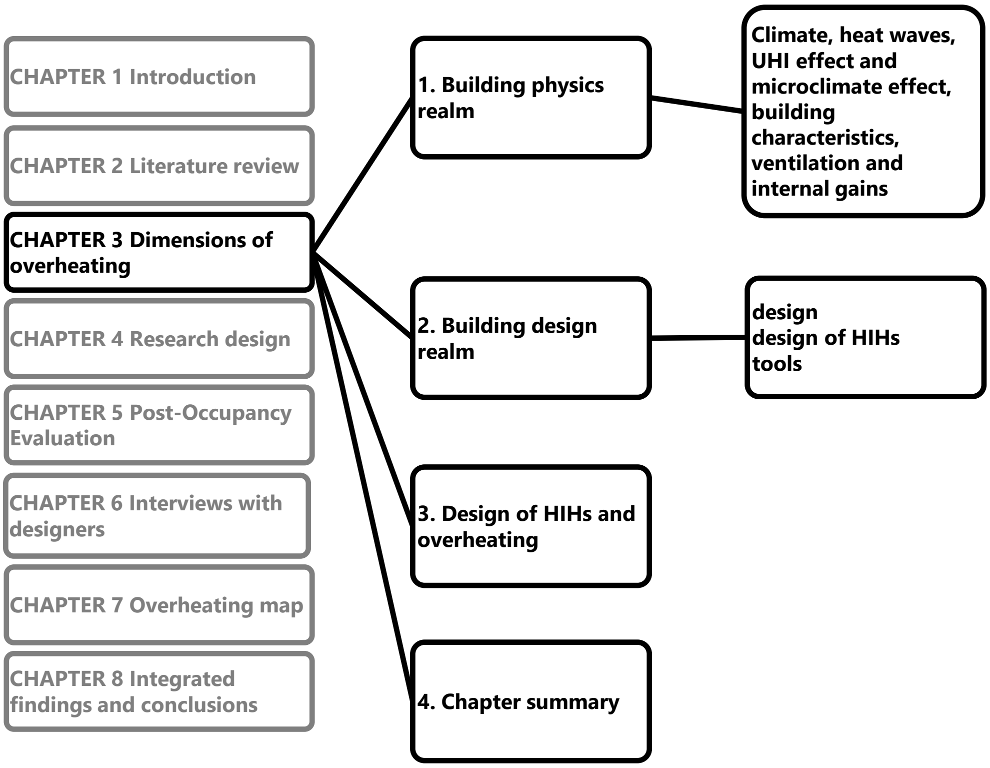
- occupant behaviour;
- house typology and type of rooms;
- ventilation strategy;
- lack of solar control strategy;
- absence of thermal mass;
- Insulation as a condition that can both attenuate as well as exacerbate overheating.

This provides an initial indication that innovation linked with HIHs may not have yet developed the necessary know-how in the construction industry. For instance, the advantages of mechanical ventilation may well not yet compensate the shortcomings associated with designing, installing, and operating it. For thermal efficiencies have been found to be lower than predicted, energy consumption slightly higher than predicted or calculated. Proper ventilation strategy for excess heat removal was also found to be almost inexistent.

In conclusion, the treatment offered in this chapter justifies the statement that the current understanding of overheating in HIHs in the UK is limited. The next chapter will hence explore the dimensions of overheating in HIHs in relation to both thermal factors and design.

CHAPTER 3: DIMENSIONS OF OVERHEATING

"*The whole is something else than the sum of its parts*"
Kurt Koffka, 1935



Synopsis

This chapter is concerned with providing background information to conceptualise the most important dimensions of the problem of overheating. The two dimensions specifically engaged in this chapter are the factors relating to the building physics and to the practice of design.

The recognition of those different dimensions of overheating is part of a broader methodological approach that is best characterised as a form of interpretivism (which will be introduced later in this thesis).

The first part of this chapter elaborates on the physical factors leading to overheating in dwellings and how they are informed by the factors influencing the thermal performance of HIHs. The second part revisits the meaning of design as a practice, its basic traits and moves to the specific traits of the design of HIHs.

3.1 THE REALM OF BUILDING PHYSICS

The thermal performance of a dwelling – and with it, the potential occurrence of overheating - is a complex phenomenon with multiple factors. Therefore, it is not possible to account for the phenomenon of overheating without reconstructing all the factors that influence the thermal performance of buildings. Literature has shown that in the UK overheating in homes is associated to three main compound factors, which are: (a) external heat gains (sun, UHI), (b) internal heat gains (occupancy, appliances) and (c) inadequate ventilation [Dengel and Swainson, 2012; NHBC, 2012b]. Further elements, such as climate, urbanization, dwelling characteristics and others, etc., can play an important role in more than one of those areas.

Careful attention to the implication of each element in the three core areas of overheating is required when designing HIHs, since studies presented in the previous chapter have reported that the role of such elements are exacerbated in the context of HIHs [Orme, Palmer and Irving, 2003].

The three core areas of overheating can be affected by different elements, which from the designers' point of view can be qualified as *unmodifiable* or *modifiable*. A tentative categorisation is provided in the illustrated figure 3.1[17], conceptualised after [Lewis, 1999; Dengel and Swainson, 2012; NHBC, 2012b]. Each element impacting on overheating will be described in the following pages, where its relationship to overheating in HIHs will also be explicated[18].

[17] The categorisation is considered as *tentative* because depends on the context and also on the actual scope for design that each specific project allows.

[18] According to The Energy Saving Trust, the factors concurring to overheating are these plus thermal mass [Energy Saving Trust, 2005].

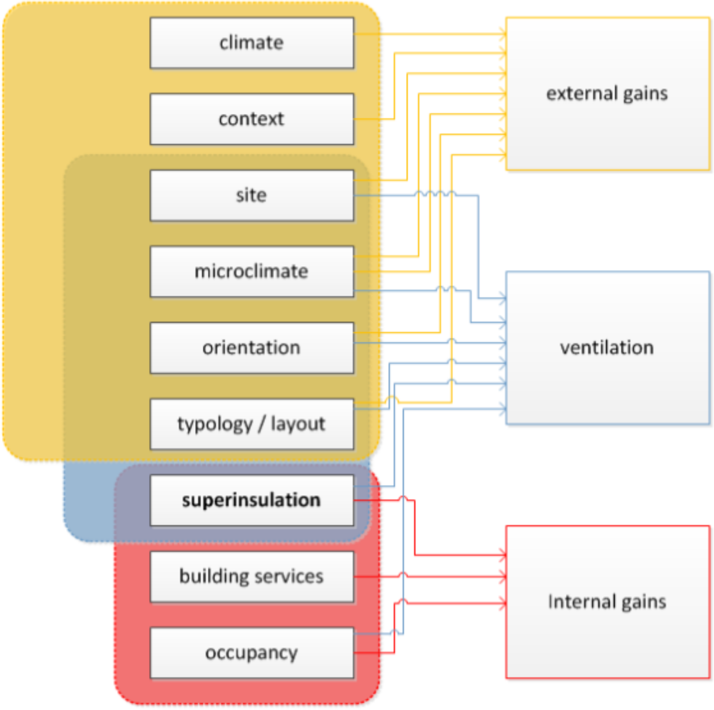


Fig. 3.1 Diagram of factors concurring in the thermal performance of buildings (left side) and their possible relationship with the main compound problems concurring in overheating (right side)

It should be noted that, in the setting of this research, HIHs (and, with it, super-insulation and airtightness) are considered the context where overheating develops, on the basis that, the compound factors leading to overheating (namely, external heat gains, internal heat gains, and inadequate ventilation) manifest differently than in a non-highly insulated (traditional housing stock)[19]. To restate this point, in this research, HIH is the *context* where gains and ventilation act differently than in a non-HIH, and therefore insulation is not considered a reason per se. This statement is supported also by the evidence provided by building simulation studies [Orme and Palmer, 2003].

In the following paragraphs, it will be developed the factors concurring in the thermal performance of buildings and their relationship to the occurrence of overheating in HIHs.

3.1.1 CLIMATE

As reported by the Met Office, under a global perspective, the climate of the Earth depends on how much of the sun's energy is retained by the land, sea, and air, and on how the climate system responds to changes [Met Office, 2013]. Under a regional scale, climate depends on several other factors, of which the latitude (or distance from the

[19] This contextual aspect will be developed in section 3.2, *the realm of building design*.

Equator) is one of the most important factors[20]. The actual weather in an area may vary considerably from what is typical of that region's climate [Met Office, 2013]. In fact, the very broad climate zones can be further refined at a local scale according to the (1) altitude, (2) prevailing wind, (3) distance from the sea, (4) ocean currents, (5) topography, (6) vegetation, and (7) urban/rural context of the location at stake [Met Office, 2014].

However reported climate observations of global and UK climate trends make evident that the climate is warming has risen by nearly 0.8°C since the late 19th century, and rising at about 0.2°C /decade over the past 25 years due to man-made GHG emissions (>90% probability) [Jenkins, G.J., Perry, M.C., and Prior, 2008], see figure 3.2.

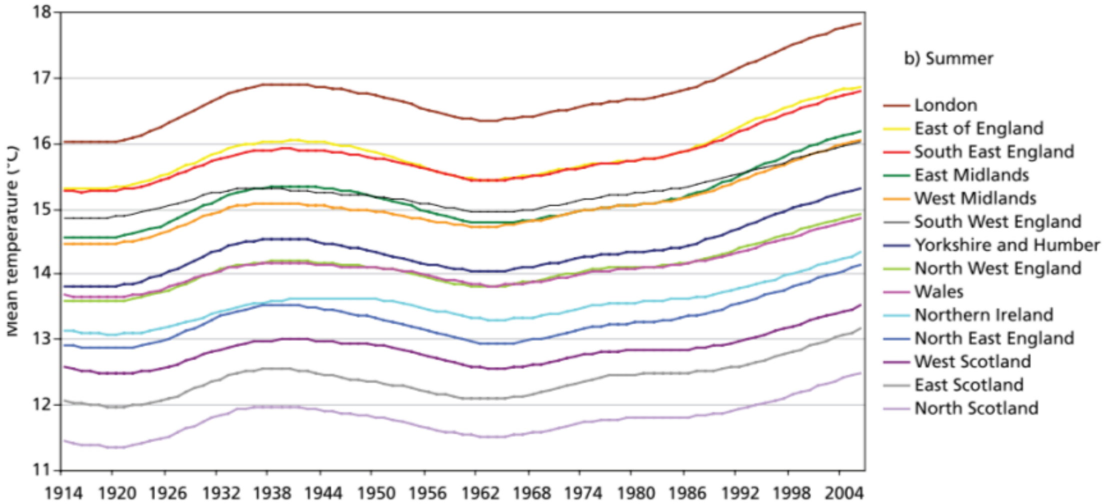


Fig. 3.2 Observations of summer mean temperature change [Jenkins, G.J., Perry, M.C., and Prior, 2008]

3.1.2 HEAT WAVES

Since 2003 when an excess of heat-related deaths was recorded across Europe, the heat wave status shifted from unperceived risk to an instance of dangerous climate. This idea was reinforced after the Intergovernmental Panel on Climate Change (IPCC) claimed that more frequent and severe heat waves are likely to occur. The peak temperatures experienced in England and Wales in August 2003 reached 38.5 ˚C, and they are believed to have caused a 16% excess in mortality during the relevant period. This means that

[20] The most used description of climate zones - the Köppen system – divides the world in six (macro) climate zones: *Equatorial*, *Arid*, *Mediterranean*, *Snow*, *Polar*, and *Temperate* [Met Office, 2015a]. Temperate climate covers a range of climates from near-Mediterranean and humid, sub-tropical zones to maritime climate (influenced by the oceans). The latter refers to the UK [Met Office, 2015a].

heat waves should be considered a major mortal risk and in fact the number one risk among the natural hazards of post-industrial societies [Poumadère *et al.*, 2005].

By investigating the relationship between heat and mortality in London in a 21 year period, Hajat et al. concluded that an increase of heat-related deaths in hot days starts being registered at an outdoor daily average temperature of 19˚C. The duration of exposure to high temperatures was also found to be an important factor in determining the increased rate of mortality [Hajat et al. 2002, as cited by Beizaee, Lomas and Firth, 2013].

Another study claims that mortality across population begins at a (93rd centile threshold) outdoor daily maximum temperature of (to name few):

- 24.7°C in London
- 23°C in the Midlands
- 22.2°C in Yorkshire and Humberside [21] [Armstrong *et al.*, 2011].

Naturally there is a link between internal and external temperatures (at least in the absence of mechanical cooling). However, this link is not well understood due to lack of data on internal temperatures [Dengel and Swainson, 2012]. One of the reasons may be because in buildings, internal conditions vary considerably with building type, layout and age but also between individuals and households in their behavioural and physiological responses to their temperatures. For example HIHs are meant for comfortable stable indoor conditions, but the effects of orientation and occupancy may alter completely comfort.

During heat waves, people directly experience both external and internal temperatures, but people are likely to spend most of their time indoors though (particularly if it is very hot outside). Furthermore, it is well documented that the majority of excess deaths during a heat wave occur amongst the elderly [Poumadère *et al.*, 2005], who are known to spend an even higher proportion of time at home indoors than the general population. As a result, indoor temperatures are particularly important in this context.

[21] Most of the analysis and projections available for heat waves about deaths uses only external temperatures, simply because this is readily available with a long historical record, and applies to the whole population in a given location. For details on this study see [Armstrong *et al.*, 2011].

Relationship to overheating

When looking at indoor temperatures during heat waves, alarming results were found. A study monitoring 9 dwellings between Manchester and London during the August 2003 heat wave, when the daily averages of external temperatures were exceptionally high for the UK (20°C), recorded the occurrence of remarkably high temperatures in the London dwellings, with several room averages exceeding 27°C, and room temperatures above 25°C for the entire 7 days of hot spell [Wright, Young and Natarajan, 2005].

In addition, careful considerations are to be taken when thermal insulation is installed. In a simulation-based study of a terrace house during the 2003 heat wave, Porritt et al. found that retrofitting via internal wall insulation produced an increase in overheating on an end of terrace for some future climate scenarios. However, if such internal wall insulation is fitted in combination with other solar control measures, overheating can be effectively be reduced, whilst also reducing annual space heating demand [Porritt *et al.*, 2012].

The above paragraphs suggest that there is a risk that HIHs can become uncomfortably warm, and especially at evenings when they are occupied. The lack of thermal mass and solar protection can exacerbate internal temperatures, and there is no guarantee that effective ventilation through the windows may be achieved. For MVHR is not designed to cover this role: MVHR systems are often being installed with no summer bypass[22] [Sharpe *et al.*, 2016], and even in the case summer bypass is available, summer bypass may leak some heat[23]). As a result, removal of excess heat is made slow, and night cooling (essential to lower indoor temperatures) would not be possible with the 1.5ACH offered by an MVHR (at least 10ACH are required to provide night ventilation) [Orme and Palmer, 2003].

3.1.3 URBAN HEAT ISLAND EFFECT AND MICROCLIMATE

The urban heat island (UHI) is a phenomenon known for about a century and has attracted much attention in the last 10 years (see figure 2.12 in Chapter 2). The urban

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[22] Summer bypass is a feature of MVHR systems to exclude heat gains when heat inputs are not required (such as summer). See Section 3.1.5.2 for an extensive treatment of the summer bypass.

[23] This is based on anecdotal evidence, from ‘corridor’ conversations with BRE-MVHR specialist in one of the attended overheating events (Workshop: Overheating and Indoor Air Quality in new homes - Peterborough - 23 June 2015, organised by Homes and Communities Agency).

heat island (UHI) refers to the different temperature between urban areas and their surroundings , and it is responsible for a summer temperature increase of at least 1-4.5°C and possibly 8-10°C in cities as well as for [Givoni, 1998; Santamouris, M., Asimakopoulos, 2013].

Suburban areas are characterised by a higher proportion of green space, mainly gardens. These green areas have a high solar absorptivity (around 80%) and through evapotranspiration of the plants, temperature is lowered. Also evaporation keeps surfaces and air in contact at moderate temperatures [Santamouris, M., Asimakopoulos, 2013]. By contrast, the artificial materials urban areas are made of (such as asphalt) have low solar reflectance (low albedo). Therefore, they absorb almost all the solar radiation falling on it, store it and radiate it back to their surroundings after late afternoon. Moreover, if the buildings have different heights, the higher buildings slower the radiative cooling rate of the lower buildings. Tall buildings can also reduce wind speed, which can be up to 25% lower than the wind speed recorded in open areas. Finally, in cities the air pollution blocks the night heat radiation to the sky dome [Givoni, 1998; Mumovic and Santamouris, 2013].

The UHI effect is more intense during the night. As a result occupied dwellings are characterised by reduced relative humidity due to high air temperatures and lack of sources of humidity [Santamouris, M., Asimakopoulos, 2013]. This has the potential to cause thermal stress to people.

The factors determining UHI have been categorised by Givoni as:

- meteorological (i.e. non subject to human interventions, such as cloudiness and regional wind speed;
- manageable, affected by the design of the buildings, such as the colour of buildings (which determines the fraction of solar radiation reflected away), the amount and distribution of urban vegetation, the energy use for building and air conditioning, the density of the built-up areas and types of buildings (which affects the amount of solar radiation reaching the ground levels and the nocturnal radiant loss), and the orientation of streets with respect to the predominant winds (affecting the wind speed near the ground) [Givoni, 1998].

In respect to the manageable component of UHI, and with the generic increase of urbanisation globally, inevitably, UHI is likely to be exacerbate overheating, and more dwellings will be interested. There is also a meteorological unavoidable risk, the occurrence of a heat wave, which can exacerbate the UHI intensity. In London 2003, the average night time UHI, around 3-4°C, escalated to 6-9°C thus increasing the vulnerability of London's population to heat-related health risks Hajat el al. 2007, cited by [Mavrogianni *et al.*, 2012]. So some strategies for mitigating its effects are expected to be a necessary component of any urban planning [GLA, 2016], while some new developments in London are opting to incorporate some form of active cooling despite the buildings' natural shading and ventilation [Swainson M, 2014].

Microclimate

The microclimate is intrinsically linked to the UHI effect. The microclimate refers to "*the condition of the solar and terrestrial radiation, wind, air temperature, humidity, and precipitation in a small outdoor space*" [Brown and Gillespie, 1995]. This definition indicates that the microclimate is a result of landscape elements as well as building features.

In fact, the urban space bounded by buildings is called the urban canopy layer. Santamouris [2001] sustains that the urban canopy layer includes an unlimited number of microclimates generated by different configurations of urban spaces or forms. Within these configurations there are varied micro conditions (such as vegetation, albedo or surface materials), which in their combination contribute to determine the microclimate of a city [Taylor et al., 2008]. Taylor claims that improving the comfort of unconditioned and external places can also reduce the overall energy consumption of cities. Microclimate design has then the capacity of minimising the amount of energy for heating and cooling in buildings [Brown and Gillespie, 1995].

Most of research focusing in the microclimate is aimed at attenuating the UHI effect and hence is intended for a city-wide strategy scale [Virk et al., 2014]. In the study of Virk et al. the effectiveness of green roofs and cool roofs in terms of reduction of overheating in a modelled building was assessed. The types of impact of the roofing strategies were split into direct and indirect effects. The effects of the roofs were modelled using microclimatic modelling software. The results showed that among the direct effects, a non-insulated green and cool roof were more effective than insulated roofs at reducing levels of overheating. The study also found that green and cool roofs are appropriate to mitigate the UHI effect, as they decrease the amount of heat absorbed into the fabric of the building and cool the surroundings [Virk et al., 2014].

Indirect effects of roofing were analysed by considering how the perturbed weather files impact on the indoor temperatures. On the one hand, the study found that green roofs temperature perturbations are greatest in the evening and cool roofs in the morning. On the other hand, it found that, when compared to direct effects, the indirect cooling has little impact on reducing overheating, mostly because – in current climates - the temperature and humidity perturbations have no significant effect on the internal temperatures. However, in 2050 the indirect effects are expected to have a slightly greater impact on the reduction of overheating [Virk et al., 2014].

Relationship to overheating

If UHI is not taken into consideration in the design of HIHs – where much attention is given from the exterior to the interior – HIHs may ultimately be affected by excessively high temperatures and so constitute a health risk. As a boomerang effect, these dwellings may necessitate air conditioning, which then increases the anthropogenic heat and the overall UHI effect. So HIHs could potentially be affected by overheating and at the same time cause overheating.

Mavrogianni et al. claim that UHI might not be a dominant factor in the phenomena of overheating in dwellings. In a study monitoring 36 London dwellings during Summer 2009, no correlation was established between overheating and distance from the London UHI thermal centre [Mavrogianni et al., 2010]. In this study, the average indoor air temperatures were related to the London UHI thermal centre. This comparison revealed an increase scattering in indoor temperatures as the centre is approached from the outskirts. This could be an indication of the heterogeneity of urban microclimates, potentially overriding the UHI effect [Kolokotroni and Giridharan, 2008; Mavrogianni et al., 2010]. All this suggests that although UHI effect may constitute one factor in the cumulative effect characterising overheating, it may not necessarily be the dominant factor. Related, construction type and microclimate may be more decisive determinants of overhearing, when compared to the UHI effect.

The influence of the location-specific site characteristics (microclimate) has shown to have a marked effect on UHI intensity [Kolokotroni and Giridharan, 2008]. However, there are not sufficient works to include the physical site characteristics into a predictive model [Kolokotroni and Giridharan, 2008].

3.1.4 BUILDING CHARACTERISTICS

Within the building scale, there are some factors that are linked to their thermal performance, and, as a consequence, to the possible incurrence of overheating. The performance of buildings depends on a number of characteristics that (positively or negatively) affect the equation of thermal comfort as well as ultimately energy demand of building. A non-exhaustive list of building characteristics can be listed as follows:

1. Building typology
2. Building layout
3. Building orientation
4. Building materials
5. Building services (HVAC)

3.1.4.1 BUILDING TYPOLOGY

A study using a database from the Ministry of Housing in the Netherlands found that even though occupant characteristic and behaviour significantly affect energy use in dwellings (4.2%), building characteristics are responsible for a larger part of energy use in dwellings (42%). Hence, when considering the energy use of dwellings, the actual building characteristics have 10 times greater impact on the energy use [Guerra Santin, Itard and Visscher, 2009]. It is therefore justified to look at building typology as a potential source of overheating, not only because of the implications a typology may have in consideration of solar gain, ventilation, etc. but also because the building typology partially determines the behaviour of those who live in a building.

With regards to the overheating risk that different typologies pose, monitored studies offered evidence that compact dwellings and purpose built flats are at most risk of overheating. This is due to their reduced external surface areas (which are prone to have lower heat losses in winter) resulting of reduced external heat loss through surfaces and ventilation openings [Gupta and Gregg, 2012].

Even though in the UK purpose built flats as typology does not constitute the vast majority of the building stock, purpose built flats are still the 32% of all new housing [NHBC, 2014]. And this trend should be expected to increase. In addition, the expected performance of flats, even if properly designed for cross ventilation, flats might encounter shortfalls [Palmer et al., 2016]. Tabatabaei Sameni et al. claim that it is advisable to determine which flats –within a building or development- are at higher risk and accordingly to prioritise accommodation of vulnerable groups, since currently these are assign randomly, in overheating risk terms [Tabatabaei Sameni *et al.*, 2015].

3.1.4.2 BUILDING LAYOUT

Closely related to typology we found building internal layout. The arrangement of a plan (and sections) of a building is one the main activities of architectural design and it has great impact on the thermal performance. For instance, having an open kitchen decreases energy use, probably because of the heat generated by cooking and the use of household appliances [Guerra Santin, Itard and Visscher, 2009]. Likewise, it has been found that open kitchens in HIHs with no windows can increase the instances of uncomfortably warm temperatures [Nooraei, Littlewood and Evans, 2013].

In relation to overheating, its risk is higher in new and refurbished properties, small dwellings and flats, and predominantly single- sided properties where cross ventilation is not possible [Dengel and Swainson, 2012]. For instance, the London Plan acknowledges the influence of layout in reducing or managing noise surrounding the development (which can also be related to good opportunities for natural ventilation) and in improving natural ventilation (by encouraging new dwellings to adopt minimum ceiling height of 2.5m) [GLA, 2016], while in other countries this figure is higher.

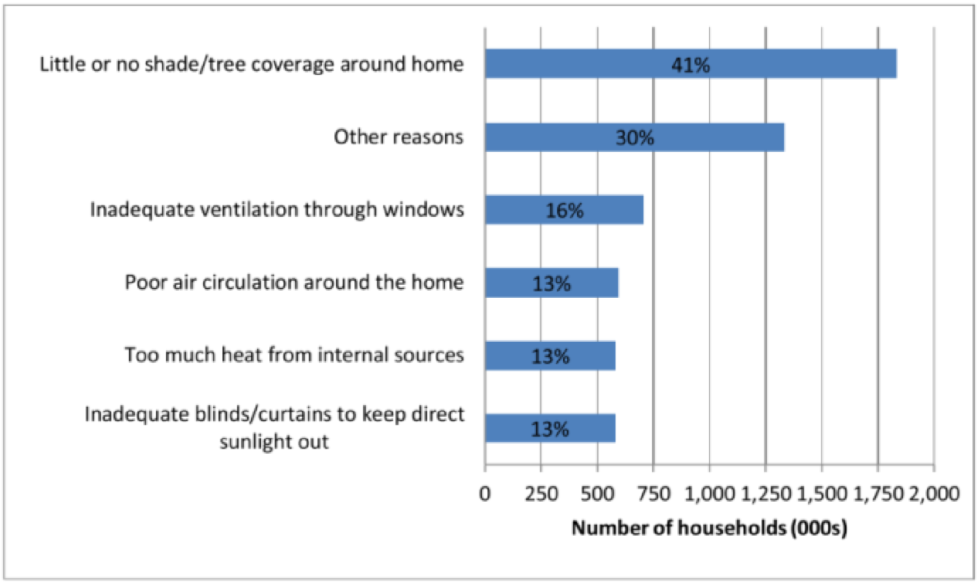
3.1.4.3 BUILDING ORIENTATION

Site planning in the UK has traditionally been characterised by the distribution of an archetype (or typology) throughout the development. In a large study of **traditional English dwelling**, it is claimed that the fact that internal temperatures showed to be consistent across all building forms and ages, explains why traditionally no consideration is paid to the orientation of the English stock [Firth and Wright, 2008]. This tradition may also explain why attitudes of developers and behaviour of occupants may not have changed in respect to solar gain.

In the UK the effects of the excessive solar heat gains were widely known in the early sixties, when studies revealed compared radiation intensities on vertical surfaces higher than those in tropical areas "*…and if admitted through the large windows which are a feature of recent trends in building design, are sufficient to cause overheating in spite of the relatively low external air temperatures*" [Loudon and Danter, 1965].

Studies confirm the potentially undesired effects of solar gains. Porritt et al. also showed that orientation have a substantial; impact on overheating exposure, with reported variations by almost 100% between different orientations in modelled house types [Porritt *et al.*, 2012].

In a large survey, 2011 Energy Follow-Up Survey (EFUS), 2,616 households representative of the English housing stock were interviewed. While the majority of households (80%) did not report any difficulty in keeping rooms cool during the summer; 20% of households reported that at least 1 room in their dwelling was too hot during summer. This 20% of households were asked to provide a reason for this and were asked to choose from a set list of options, with the possibility to provide multiple responses (see fig. 3.3) [BRE, 2013]. The most common reason given relates to the orientation of the dwelling (householders reported problems with 'sunlight'). Other reasons for overheating were high and low levels of insulations, or because householders had to keep their windows closed to reduce noise or to keep their dwelling secure [BRE, 2013]. In this study one can appreciate the emergence of orientation and insulation levels as a context where overheating occurs.



Base: All households in the EFUS interview sample reporting problems with overheating (householders are able to give multiple reasons) (n=539).

Fig. 3.3 Householders' reasons for overheating in their dwellings [BRE, 2013]

3.1.4.4 BUILDING MATERIALS

The importance of materials in relation to overheating in HIHs was emphasised early in 2003 by Orme & Palmer, who stated that "*as house become more highly insulated the fabric loss potential is reduced and the balance of heat flows becomes very finely balanced. Only a* ***small excess of heat gain over loss will cause overheating****. When this is* *considered, controlling heat gains, and the use of thermal mass and ventilation, becomes more important as means of moderating the temperature rise"* [Orme and Palmer, 2003].

The *Reducing Overheating – a designer's guide published by the Energy Saving Trust* - is recommended by SAP[24] assessment to avoid overheating. Among the findings from a simulation study that had a 1940's dwelling as its object, the effect of materials on the summer performance of that dwelling can be noted (fig. 3.4).

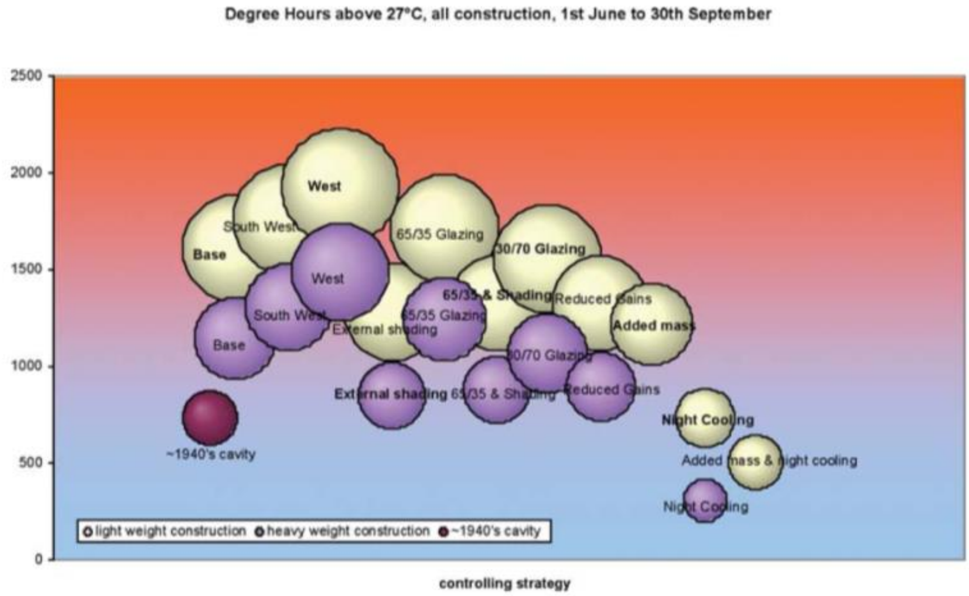


Fig. 3.4 Overheating risk for different design options [Energy Saving Trust, 2005]

Roaf et al. argued that limited attention is paid to traditional means of reducing overheating, such as the inclusion of thermal mass and openable windows for natural ventilation in buildings constructed with the Passivhaus standard [Roaf, Crichton and Nicol, 2009] as cited in Tabatabaei Sameni et al., 2015].

Moreover, the short time constant of a lightweight building should be expected to allow for a quick dissipation of internal temperatures through purge ventilation. However, no studies have been found on whether this is an appropriate strategy for night cooling. In a simulation study by Orme, night cooling is indicated as the most effective strategy to preventing overheating in super-insulated houses, for both thermally heavyweight and lightweight housing. However, the different nature in time constant of the two types of dwellings might justify the suspect that a dwelling with no thermal mass might allow purging heat to allow for a full night sleep in HIHs [Orme, Palmer and Irving, 2003].

[24] SAP or Standard Assessment Procedure will be developed in section 3.2.

Wright et al. found that, during the August 2003 heat wave, when the daily averages of external temperatures were exceptionally high for the UK (20°C), the high thermal mass in some monitored dwellings had the effect that internal temperatures both in Manchester and in London were up to 5K higher than the (night) outdoor air temperature. This suggests that the thermal capacity may restrict the effectiveness of night ventilation to provide comfort at night (even though to a different degree within homes and rooms within a dwelling). This study calls into question the use of high thermal mass in construction [Wright, Young and Natarajan, 2005], especially in contexts in which the UHI occurs.

When questioning the appropriateness of high thermal mass due to mass saturation of high temperatures during a heat wave, it is worth underlining that in the UK heat waves are normally reduced in number and short in time, even though they are predicted to increase in the future [Shaw, 2007].

3.1.4.5 BUILDING SERVICES (HVAC)

Services in buildings have proved to be a source of heat because they are installed within the building envelop [NHBC, 2012b]. Whether that extra gain is desired or not, evidence has shown that poorly executed systems (uninsulated tanks and pipes) may cause all-year-around heat gains [Stevenson, Carmona-Andreu and Hancock, 2013].

The national housing survey shows that the domestic hot water is provided via central heating (not from a heated tank). However, in HIHs (with its little space heating), there may be a trend to reincorporate hot water tanks for domestic hot water. This is due the fact that in HIHs there is no traditional central heating (for instance, Passivhaus-like homes rely on MVHR and perhaps few electric radiators) but they might incorporate a tank for solar panels. These tanks are built inside the thermal envelope contributing to heat gains. Even though the use of photovoltaic (traditionally with no hot water tank) in houses is more popular, when compared to solar hot water, new technology, such as Photovoltaic-Thermal (PV-T), requires a water tank [DCLG, 2016a]. Figure 3.6 shows an increase in photovoltaic systems installed which may require water tanks which are source of potential internal heat gain.

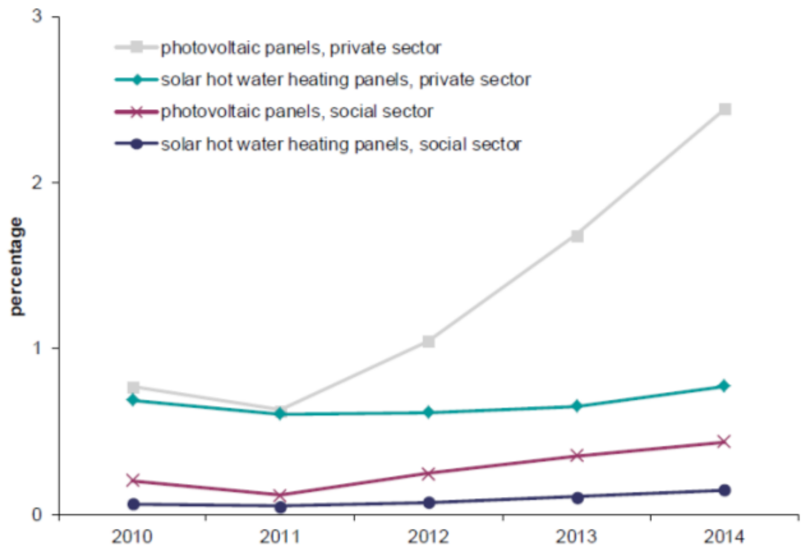


Fig. 3.5 Homes with solar hot water heating and photovoltaic panels (2010-2014) [DCLG, 2016a]

3.1.5 VENTILATION

The Building regulation Part F defines ventilation as the *"supply and removal or air (by natural and/or mechanical means) to and from a space or spaces in a building. It normally comprises a combination of purpose-provided ventilation and infiltration"* [25] [HM Government, 2013a, p.8]. Such definition provides a distinction between *types* of ventilation (purpose-provided ventilation and ventilation by infiltration). Ventilation is achieved in a very different way in traditional English houses and in HIHs. In fact, traditional houses are very leaky (see figure 3.6) and so infiltration is central to their ventilation. HIHs are, by contrast, extremely airtight and so heavily rely on purpose-provided ventilation, which is instrumental to secure both air hygiene and thermal comfort.

[25] "*Infiltration is the uncontrolled exchange of air between inside a building and outside through cracks, porosity, and other unintentional openings in a building, caused by pressure difference effects of the wind and/or stack effect*" [HM Government, 2013a, p.8]. Occurs when there is a corresponding exfiltration.

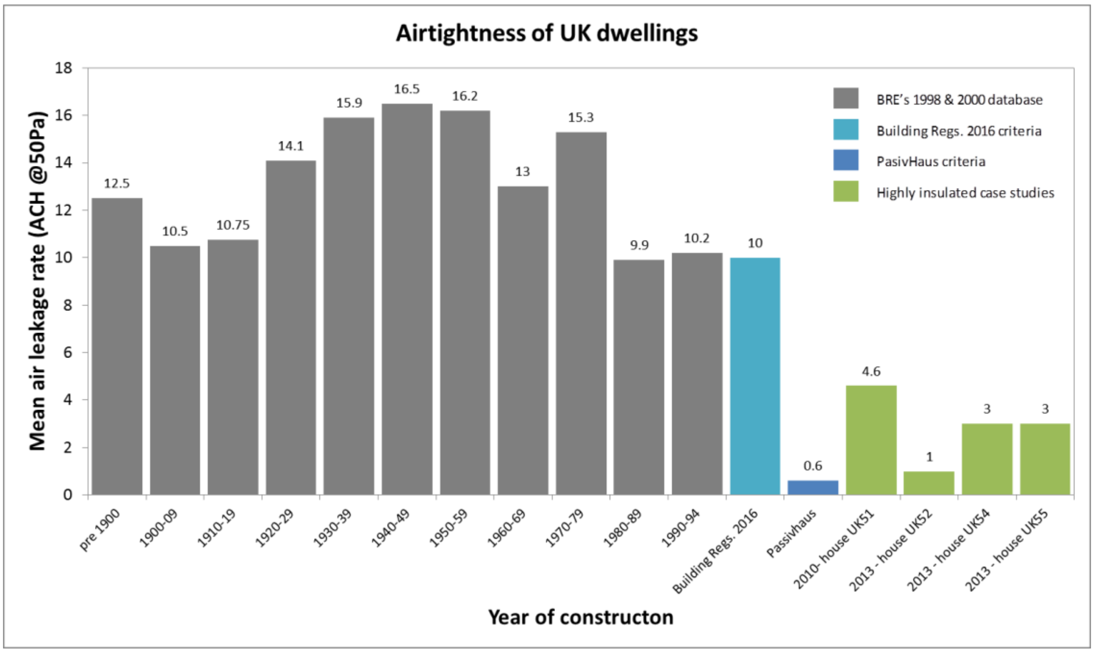


Fig. 3.6 Relationship between dwellings age and air leakage [Johnston *et al.*, 2004 after Stephen 2000; HM Government, 2013b; Toledo, Cropper and Wright, 2016].

The forms of purpose-provided ventilation in HIHs are two: natural (such as opening windows) and mechanical (such as MVHR).

3.1.5.1 NATURAL VENTILATION

The implementation of progressive airtightness in dwellings has the consequence of reducing infiltration. So reliance on natural ventilation to provide summer comfort is reasonably expected to increase. Natural ventilation consists in air driven in and out of a building as a result of pressure differences across the openings (such as windows and doors). Therefore, it depends on the air flow patterns around buildings (resulting from outdoor climate, microclimate and nearby buildings) [Santamouris, M., Asimakopoulos, 2013].

In **outdoor** areas, ventilation is affected by the regional climate and by the local climate. At a regional level, ventilation is characterised by the prevailing winds. At the level of local climate, vegetation can disrupt or block low-level air-flow. In urban contexts, the presence of populations, housing, transport and industry generates warmer temperatures and a scarcely windy, noisy and polluted environment [Met Office, 2014]. In urban areas and dense social housing, flats in particular, the opportunities for ventilating through windows may be limited [McLeod, Hopfe and Kwan, 2013]. This may affect purge ventilation (i.e. quick dissipation of air). As such, ventilation can be seen as a contributing factor to overheating. It should also be seen as an unpractical means for cooling.

Relying on natural ventilation has some **shortcomings**. For instance, while windows operation does not require special training, a BRE study found that occupants were not aware of the need of trickle vents [Dimitroulopoulou, 2012]. In addition, the Royal Society for the Prevention of Accidents (RoSPA) notes that the windows of new build social housing limits the opening to less than 100mm for child safety [RoSPA, 2002]. This can reduce opportunities for natural ventilation, notably in HIHs [Tabatabaei Sameni et al., 2015].

In a survey on 101 homes, Mavrogianni reported on occupants' ventilation habit in both typical days and warm days. Respondents claimed that opening windows is mostly functional to obtain *fresh air* rather than control high indoor temperatures. In addition, more than half of the respondents stated that they do not open the windows due to their concerns over security, while more than one third of them do not open the windows due to high external noise levels. The study also found that even on an average hot day, a number of the respondents (20%) tended not to open windows at night. [Mavrogianni et al., 2016].

There is also anecdotal evidence of the inability of some windows to being able to perform night ventilation due to opening limitation as well as to security and noise concerns [Crump, Dengel and Swainson, 2009].

3.1.5.2 MVHR

While MVHR systems can be considered a HVAC system, they are dealt with in this section because they should be considered as a means of purpose provided ventilation. MVHR is a growing zero carbon technology responsible for the provision of fresh air while recovering heat. In terms of ventilation strategy, MVHR is a whole dwelling ventilation by a continuous air exchange: it then provides fresh air and dilutes water vapour and pollutants not dealt with by extract ventilation [HM Government, 2013a]. Its use is mostly linked with Passivhaus homes and HIHs.

However, there is a substantial amount of evidence of poor installation and commissioning, ignorance of occupants (turn off, run on boost at all times, etc.). [Stevenson, Carmona-Andreu and Hancock, 2013; Sharpe et al., 2016; CIBSE, 2018]. In addition, the average energy consumption of MVHR units was found to be slightly higher than expected [Ridley et al., 2013]. The average ventilation rate depends on the MVHR unit and also on the duct system and how this has been designed and installed, see figure 3.7 [CIBSE, 2018]. Monitored studies found that the average thermal efficiencies on the MVHR units were lower that the manufacturers quoted values, despite the fact that they are still above the PH minimum requirements of 75% [Ridley et al., 2013].

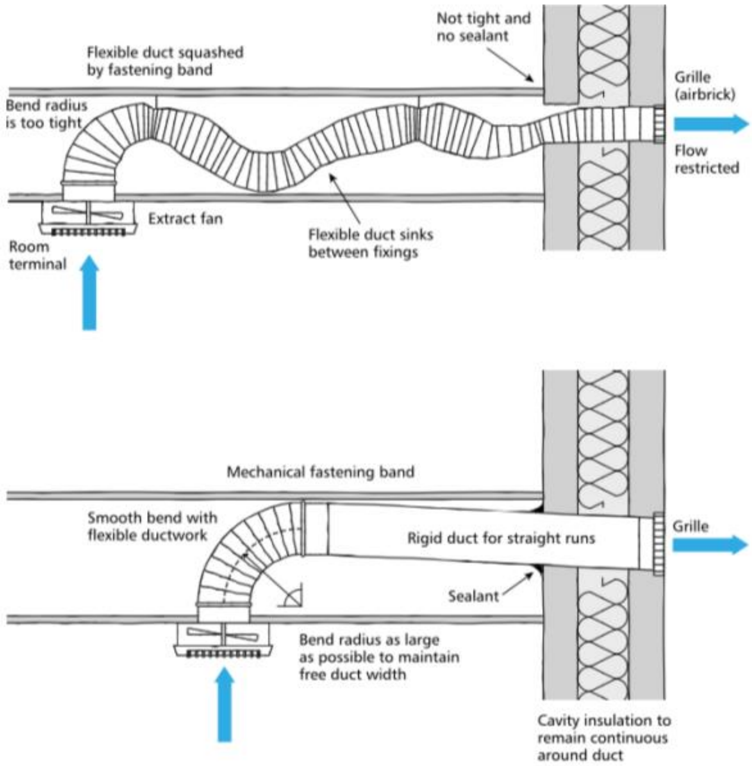


Fig. 3.7 MVHR systems: design and installation of ductwork. Poor practice (top) good practice (bottom) [CIBSE, 2018]

Even in the case of a perfectly balanced system (well designed, properly installed and correctly used) simulation studies have found that MVHR systems are not able to mitigate excess temperatures in buildings with high thermal mass, because they cannot remove sufficient heat to prevent overheating [Orme, Palmer and Irving, 2003].

The presence of MVHR in HIHs is particularly important to preserve a desired level of background ventilation, especially in consideration to the fact that infiltration is dramatically reduced in this type of houses. Within large housing survey of 60 low-carbon homes, McGill et al. found that outside the summer season houses with no MVHR reported significantly higher average and peak temperatures than those with MVHR. However during summer, mean temperatures were significantly higher in homes with MVHR, and this was attributed to lack or summer bypass or complete switch off of the systems with no provision of background ventilation (therefore relying uniquely on intermittent window opening) [McGill *et al.*, 2017].

Sassi [2013] reports that MVHR installers tend to install hard wire MVHR so that the MVHR devices cannot be switched off. This is meant to avoid that occupants forget to switch it back on. Sassi claims that in southern England this means that the MVHR systems operate seven to nine months unnecessary. As a strategy to deal with the possibility that occupiers forget to turn MVHR on, in the Slateford Green housing project in Edinburgh, passive vents rather than mechanically driven ventilation have been installed [Sassi, 2013].

Summer bypass

To prevent uncomfortably warm temperatures, the MVHR system may include a summer bypass. However, finding a shared definition of summer bypass has not been possible. The MVHR industry has been developed in recent years and is constantly adjusting to the requirements of the local market. As such, a unique definition of summer bypass has not found to be available at the time when this thesis has been written (2018) [Zehnder Group UK Ltd, no date; Behar, 2016; Figueiredo *et al.*, 2016]. The researcher has experienced a lack of understanding of this feature by some of the market operators found at the commercial stands in a Passivhaus conference in the UK. In addition, there is currently no reference to summer bypass in Buildings Regulations, specifically in the Approved Document Part F – Ventilation [HM Government, 2013a].

Summer bypass can generally be intended as a method to exclude heat recovery when heat inputs are not required (such as summer). This can be achieved by:

(a) limiting airflow rather than stopping heat recovery: by lowering the MVHR ventilation rates and by so, reducing the (preheated) air supply. It can be activated automatically based on external temperatures set point.

(b) physically bypassing the heat exchanger with the inclusion of a physical bypass of the majority of the airflow volume. It can be activated automatically based on external temperatures set point.

(c) adding a supply air boost feature to be manually activated when outside air temperature can contribute to reducing internal temperature and adjusting humidity levels. on this respect, the Passivhaus institute warns that such method may incur into added electricity demand and that whenever possible the air supply boost should be provided by opening the windows [Passipedia, no date b].

The paragraphs above enable one to get a sense of the complex and ever changing link between ventilation and energy efficiency. This is also reflected in the building regulations: Part F deals with providing means hygiene air (ventilation) and Part L deals with limiting air leakage (via airtightness). These are two explicitly different requirements. But their changes cannot be treated in isolation without incurring in an unbalanced indoor environment, as conceptually represented in figure 3.8.

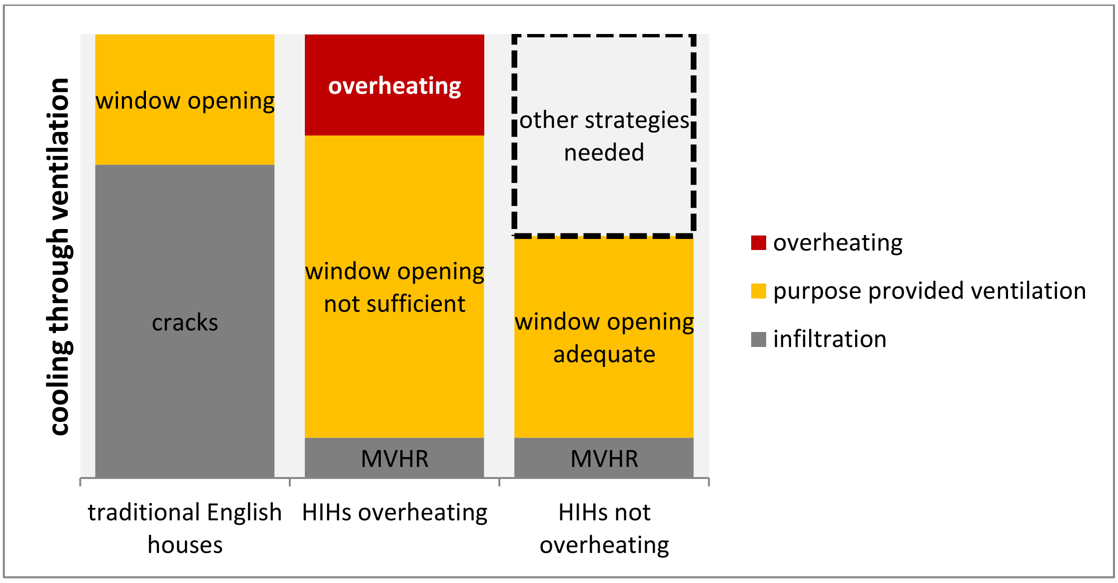


Fig. 3.8 Conceptualisation of ventilation changes in residential leading to overheating

3.1.6 OCCUPANT BEHAVIOUR

Despite the fact that, when it comes to overheating, considerations have been given to occupancy, many studies show that overheating should be assessed during **occupied hours**. For instance, Firth and Wright found that, on a traditional sample surveyed, during occupied hours, living rooms tend to overheat more than bedrooms [Firth and Wright, 2008]. It has also been found that the duration of window opening appears to be positively correlated with occupancy times [Dubrul as reported by Mavrogianni *et al.*, 2014].

Moreover it has been found that the social housing sector has a higher proportion of dense, purpose-built flats, and instances of high rates of overcrowding (see figure 3.9). Therefore, the impact of internal gains is likely to be higher than in other kinds of housing. In fact, in 2016-17, 7% of households of the social rented sector and 5% of households in the private rented sector lived in overcrowded accommodation [MHCLG, 2017].

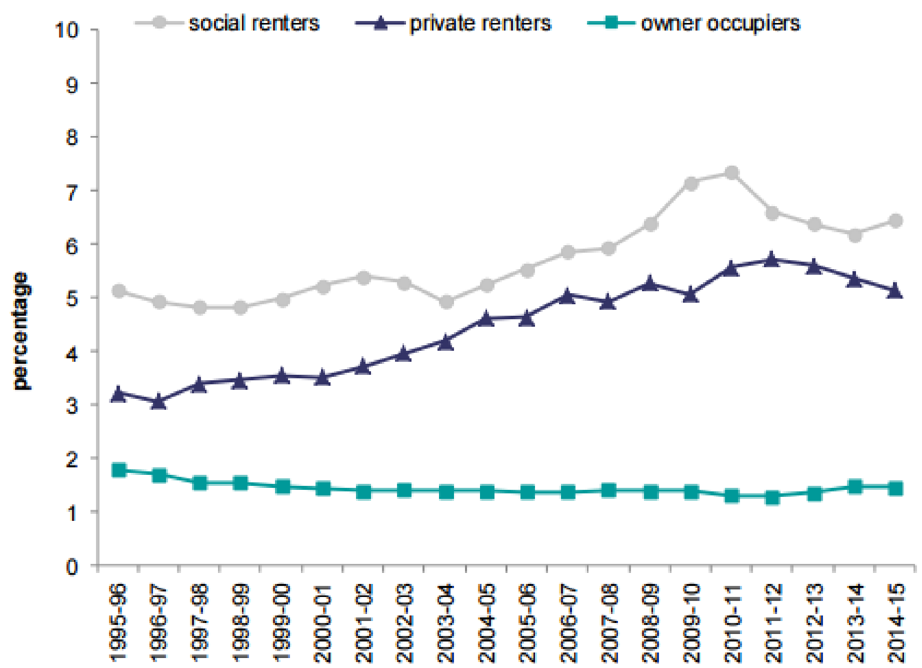


Fig. 3.9 Overcrowding by tenure, 1995-2015, English Housing Survey, Headline Report 2014-15 [DCLG, 2016b]

For the purpose of overheating, this section is mostly interested in focusing on how people relate to building in order to reject excess heat and to dissipate warm temperatures, since this provides a measurable impact on thermal discomfort and health risks associated with their exposure to high indoor temperatures [Mavrogianni *et al.*, 2014].

In Germany, Schnieders & Hermelink (2006) have explored the sensitivity of the energy performance of occupant behaviour and have found that passive houses are less sensitive to occupant behaviour. In the Nederlands, Guerra Santin et al. [2009] have shown that some occupant behaviour is determined by dwelling type or HVAC systems.

The effects of occupancy has been modelled by Mavrogianni et al, who showed the importance of window opening behaviour for indoor thermal performance on the UK stock. In this study, the effects of housing retrofit showed indoor overheating risk as a function of occupancy and behaviour (window opening): temperatures lie within a wider and higher range when windows remain closed and when bedroom windows can be adequately opened, the bedrooms experience lower temperatures than the living rooms [Mavrogianni *et al.*, 2016].

3.1.7 SECTION SUMMARY

This section has shown that overheating can be potentially caused by all the factors concurring in the design of buildings. So, no one single factor can be blamed: remedial actions for overheating involve redressing the balance between heat gains and heat losses, by reducing heat gains or increasing the heat losses or both, as well as the use of thermal mass to act as heat sink to control temperatures swings and avoid sudden changes in the rooms.

In fact, the problem of overheating, as it is presented in HIHs, has emerged as a result of a lack of cooling possibilities (lack of ventilation due to improper use of windows or improper design of windows, no form of solar control, etc.). It should be noted that these "lacking" factors can be seen as the natural consequence of sudden changes in homes design at a time in which users and designers have not yet embedded respectively the tacit and the explicit knowledge of those environments and related design practice.

The problem to redress the balance between heat gains and heat losses in a HIHs starts with buildings design. For this reason, in the following section, the architectural design is explored, with a view of understanding how overheating is a product of contemporary design, the mechanisms in which this happens and the areas of possible change.

3.2 THE REALM OF BUILDING DESIGN

While it is difficult to identify one main reason for the gap between energy efficient and thermally comfortable dwellings [NHBC, 2012a, 2012b], it is clear that design practice needs to respond quickly to the growing evidence of overheating [DCLG, 2012; Garrett, 2014; Sharpe *et al.*, 2014; Taylor, 2014; Morgan *et al.*, 2015; McGill *et al.*, 2017]. The next paragraphs will explore the definition of design, both in general (fig. 3.10) and in the context of low-carbon design, its methods and its challenges, as a part of a process instrumental to best framing the problem of overheating in HIHs and an attempt to draw some links within the design of HIHs' as a practice and overheating in HIHs.

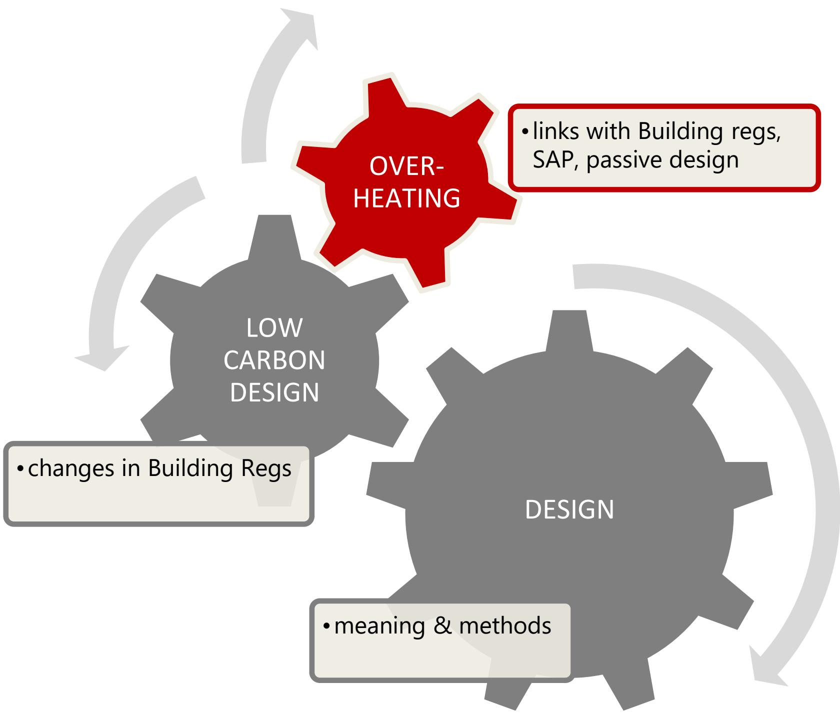


Fig. 3.10 Schematic ideogram of this section

3.2.1 DESIGN

Among some of the different definitions of design listed by Jones [1992], the one that is found more appropriate to **define design** in the context of the present research is:

> *"the optimum solution to the sum of the true needs of particular set of circumstances"* [Matchett 1968, as cited by Jones, 1992]

The above definition focuses on the requirements (or ingredients or inputs) used in the process of designing, and it implies no specific procedure. It is possible to say that, in the design of buildings, traditionally the requirements are linked to climate, law requirements, etc. But in the case of today's aspiration of low-carbon design of buildings, design requires to embed passive design principles (optimised orientation, fabric energy efficiency, low-carbon technologies, etc.) which have brought a high level of complexity for designers (architects). Here, this complexity seems not be fully managed.

The long-time practice of building design may be displaced when new requirements are in place. For instance, until recently (in the UK planning has placed an archetype indiscriminately on a site (see, for instance, the Victorian housing stock) [Olsen, 1964]. While for most experts in HIHs design this archetype is obsolete, since it does not account for the different solar gains in any orientation, relying on such archetype is a well-established practice in the development of British towns.

The scope of design cannot be restricted to requirements only. **Another definition** of design embraced by Jones focuses on the effect of design. At the end of his analysis Jones concludes that "*designing is to initiate change in man-made things*" [Jones, 1992, p.4]. This definition enables one to think **prospectively** and to recognise the influence of design beyond its production (in buildings, the hand over, etc.). By endorsing this prospective thinking in the case of HIHs, it is possible to recognise the changes that come from the climate, the occupancy, and extreme weather events. It can thus be recognised that prospective design may be in contrast with compliance design.

Once all these definitions of design are considered, it seems that for the purpose of this research, design is best accounted as:

> *the act that (intentionally or unintentionally) initiates change in man-made things to deliver the optimum solution to the sum of the true needs of particular set of circumstances.*

In this study, by optimum solution it is meant a HIH; by true needs is meant comfort, and by circumstances it is meant a context (in both terms of climate and societal expectations).

3.2.1.1 METHODS

Jones identifies two generic methods of design: traditional and design-by-drawing [Jones, 1992]. **Traditional design** was performed as a trial and error process: the designer ('craftsman' for Jones) reproduced and modified the object by relying on its empirical acquaintance of the object itself. In this process the whole body of knowledge can be related to folk knowledge, which is both collective and tacit. According to Jones, "*the craftsman's blend of know-how and ignorance can produce works that a scientist would find hard to explain and in which the artistic eye can perceive a high level of formal organisation*" [Jones, 1992, p.19]. This method is characterised by the fact that the product is modified countlessly after failures and successes with the modifications happening one at the time.

BOX 3.1 – HIHs design in Spain

In the case of Passivhaus in Spain, after getting to talk to few architects in the Passivhaus Conference in Barcelona in 2015, it was noted that Spanish designers did not have problems of overheating (they were focused in the IAQ and in preventing mould growth). After visiting one Passivhaus in the outskirts of Barcelona it emerged that both designers and occupants had a high sensitivity for summer comfort to avoid heat gains and to adapt to their environments, in both design and use.

By contrast to traditional design, **design-by-drawing** separates the trial and error process from production by using scale drawings. This method is characterised by (a) the specification of dimensions in advance (b) the possibility of splitting up the production and (c) the manageability of something too big for a craftsman to make on its own, (d) scale drawings as a whole of a product of isolated parts and (e) a division of labour that allows for an increased size and rate of the product. With specific reference to this last point, Jones [1992] highlights that this method need to establish the dimensions of the parts in advance - dimensions that a craftsman would leave undecided by so allowing for, room for *manoeuvre* later in the process. According to Jones, here is where the division of labour may cause loss of quality and leads to the belief that craft products belong to the 'good old days'. It is true that, when coming to buildings, old buildings tend to be characterised by a generosity of space, of light, of materials properties. A good example of this is provided by lightweight new HIHs, which have lost some of those good days qualities , such as the thermal storage from bricks.

When comparing this 'craftsman dimension' to the design of houses, it is possible to draw a direct relation between (a) traditional design of trial-and-error and vernacular architecture where thermal considerations relied on traditional tacit knowledge. Likewise, there is a direct relation between design-by-drawing and HIHs, where thermal calculation is derived from a drawing.

For Jones it is critical that a "*drawing can be made only by one person at a time and that the situation in which it is to fit must be envisaged in a single mind*" [Jones, 1992, p.23] and that only when the critical sub problems have been identified and solved by that one person, the work can be split up between others again. This may seem incompatible with the contemporary practice of building design, which can often result in multidisciplinary teams. Traditionally, in building design, the form of the whole comes before details have been explored. But for Jones, this principle does not work in novel situations for which the necessary experience cannot be contained in one person [Jones, 1992, p.27]. This is also the case with HIHs in which design-by-drawing is actually too simple for the growing complexity of design, where there is a high risk of losing control of the design situation once this is embedded into a systematic procedure.

3.2.1.2 NEW METHODS WHEN DEALING WITH COMPLEXITY

Traditional designers cope with complicated problems by transforming them into simple ones. This break down depends on two things: (a) immediate knowledge of the sensitivity of the problem situation to major change in design and (b) freedom from either personal or social constrains upon alternative thought or action (unconventional thought). In relation to this last point, Jones infers that the directions a designer will take are closely related to his moral and value opinions. Accordingly, the reduction of the complicated design problem is an expression of awareness of the external realities involved and requires a preconception of what is good or bad [1992].

In the case of HIHs, it seems that designers do not possess that experience or imagination; instead they rely upon calculations. But, these calculations may be in a format not yet ready to inform design, and designers may not have the skills to recompose such information in the whole.

3.2.2 DESIGN OF HIHS

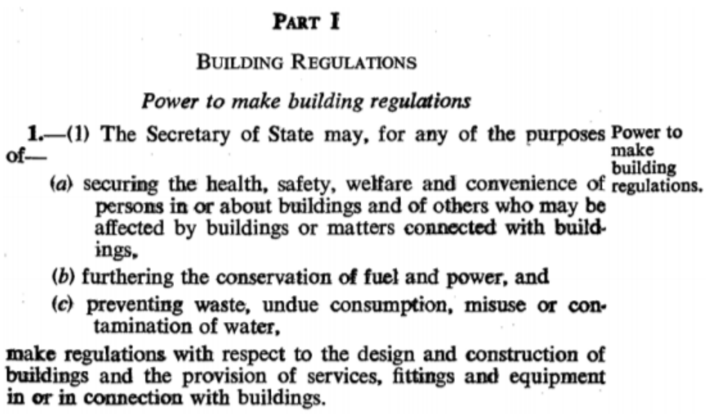
Architects can be considered as designers of the built environment and today they are called to design HIHs in accordance to a set of requirements. This forces them to cope with a new level of complexity in which he/she is not necessarily trained.

The mandatory EU energy efficient requirements have increased the complexity of the design of HIHs as a result of the fact that they introduce a new type of design (for which no vernacular folk knowledge is available), force one to face unknown thermal effects (such as summer discomfort), introduce new technologies (such as MVHR) that are not fully mastered, etc. [Palmer et al., 2016]. The complexity also leads to the fact that some actors are involved in a scattered process in which decisions are taken at different stages. This process occasionally conflicts with the conceptual design (if any).

3.2.2.1 CHANGES IN BUILDING REGULATIONS

Building Regulations are statutory instruments, firstly introduced in 1965, aimed at ensuring that policies are carried out in most of the building work in the UK [Tricker, R., Alford, S. & Algar, 2011]. Building Regulations are "*minimum standards for design, construction and alterations to virtually every building*" [Planning Portal, no date].

The Buildings Regulations in the UK have a fascinating story that goes hand in hand with important historic events. In fact, one may sustain that the remote origins of Building Regulation's can be traced back to the London Building Act (1667), drawn after the Great Fire in order to achieve fire resistance in buildings. More directly, the Building Regulations are rooted in the Building Act 1984 (fig. 3.11), which in turn derives from the Public Health Act (1936) – one of the many Public Health Acts provided as a response to the unsanitary housing conditions following dense urbanisation after the industrial revolution. And the Public Health Act (1936) was hardly the first of its genre, as the first Public Health Act dates back to 1848 and was intended to improve the quality of the water, to regulate the provision of sewage and drains as well as other sanitary dispositions in order to stop the spread of cholera, typhoid, tuberculosis and preventing the infections among the population. However, the first mandatory Building Regulation was introduced in 1966 [Killip, 2005; Tricker, R., Alford, S. & Algar, 2011].


PART I

BUILDING REGULATIONS

Power to make building regulations

1.—(1) The Secretary of State may, for any of the purposes of— (Power to make building regulations.)

(*a*) securing the health, safety, welfare and convenience of persons in or about buildings and of others who may be affected by buildings or matters connected with buildings,

(*b*) furthering the conservation of fuel and power, and

(*c*) preventing waste, undue consumption, misuse or contamination of water,

make regulations with respect to the design and construction of buildings and the provision of services, fittings and equipment in or in connection with buildings.

Fig. 3.11 The scope of the Building Regulations in the UK as stated in the Building Act (1984)

Buildings regulations intended to reduce energy consumption can instead be dated back to 1965. At that time, regulations were prescriptive: a certain U-value was achieved for individual building components. Buildings regulations evolved by tightening up over the years, by thus increasing insulation thickness and limiting glazed areas over facades [Hamza and Greenwood, 2009].

The Ministry of Housing, Communities and Local Government (formerly the Department for Communities and Local Government) has focused on the reduction of energy demand for heating buildings. In order to achieve this objective, the Building Regulation requires for buildings not to exceed a target CO_2 emissions rate. The government has produced guidance on energy efficiency requirement via the approve Document Part L, dedicated to Conservation of fuel and power [legislation.gov.uk, no date].

In order to achieve energy demand reduction as set in target, the Department for Communities and Local Government (DCLG) publishes guidances called ‘Approved Documents' to set energy efficient requirements (among other issues) to comply with the building regulations [GOV.UK, no date a]. Among these documents, the Approved Document L1A: Conservation of fuel and power in new dwellings concerns directly with emission reductions from dwellings [HM Government, 2013b]. It is worth noticing however that the Approved Document F: Ventilation is inevitably linked to energy conservation.

Compliance with the current Building Regulations Part L 2010 edition 2013 requires one to meet five criteria.

1. Criterion 1 requires that "*the calculated rate of CO_2 emissions from the dwelling (the Dwelling CO_2 Emission Rate, DER) must not be greater than the Target CO_2 Emission Rate (TER).*" In addition, there is a provision that requires new dwellings to achieve a fabric energy efficiency target in addition to the carbon dioxide target: "*the calculated Dwelling Fabric Energy Efficiency (DFEE) rate must not be greater than the Target Fabric Energy Efficiency (TFEE) rate.*"[26] TER and DER are calculated using SAP [HM Government, 2013b, p.12].
2. Criterion 2 requires that "*the performance of the individual fabric elements and the fixed building services of the building should achieve reasonable overall standards of energy efficiency, following the procedure set out in the documents.*" This criterion is intended to limit design flexibility, to discourage excessive and inappropriate trade-offs that can occur when, for example, individual building fabric elements with poor insulation standards are offset by renewable energy systems with uncertain service lives [HM Government, 2013b, p.14].

[26] Until 2010, the building regulations Part L used TER and DER only, directing at CO_2 reductions, and by fuel carbon intensity considerations (annual Kg of CO_2/m^2).
Since 2013, enforced in 2014, Part L introduced the TFEER and DFEER to tackle the demand of energy (minimum energy performance requirement, annual kWh/m^2).

3. Criterion 3 requires that "*the dwelling should have appropriate passive control measures to limit the effect of heat gains on indoor temperatures in summer, irrespective of whether the dwelling has mechanical cooling.*" The purpose of this criterion is to limit solar gains and heat gains from circulation pipes to reasonable levels during the summer period, to reduce the need for air-conditioning systems. [HM Government, 2013b, p.16].
4. Criterion 4 is set out to reinforce the outcome of Criterion 1, as it states that "*the performance of the dwelling, as built, should be consistent with the DER and DFEE rate*." It also requires air pressure test results, approved construction details, and fixed services commissioning, which serve to demonstrate the consistency of performance between the predicted (i.e. as- designed) and as-built dwelling [HM Government, 2013b, p.17].
5. Criterion 5 aims to provide the occupant/purchaser with the sufficient knowledge of operational instructions, for an efficient operation and maintenance of services, as it states that "*the necessary provisions for enabling energy-efficient operation of the dwelling should be put in place*" [HM Government, 2013b, p.21].

The above five criteria are intrinsically linked with each other. In fact while compliance with Criterion 1 facilitates the fulfilment of Criteria 2 and 5, fulfilling Criteria 2 to 5 facilitates to meet Criterion 1. In turn Criterion 4 reinforces the outcome of Criterion 1, by providing a double-check of the data inputted into SAP from the predicted phase to as-built [Pan and Garmston, 2012].

3.2.2.2 PROBLEMS WITH BUILDING REGULATIONS COMPLIANCE

The worldwide shift towards the reduction of energy in buildings has resulted in demanding requirements. Implementing such changes may be the cause of difficulties.

First of all, there are difficulties in achieving the many increment governmental requirements for which there is not necessarily enough knowledge. A study conducted by Pan & Garmston examined the profile of compliance of 404 new dwellings and found that only a third of them were compliant with building regulations part L. In addition, semi structured interviews with building control officers revealed (a) a lack of training on building energy regulations for building control bodies and (b) a lack of knowledge attributed to the dramatic reduction of the familiarity period and the transitional period from different Part L's versions [Pan and Garmston, 2012]. This suggests that overheating problem solving cannot rely (only) on compliance.

Non-compliance in practice, as well as a lack of knowledge in implementation, has also been reported internationally. Pan & Garmston refer to cases in the US, Norway, and developing countries [2012b]. The table 3.1 shows the evolution of the building fabric parameters as requested by the Buildings Regulations Part L. In it, it is possible to appreciate that most U-values have been halved in the short span of 10 years.

Table 3.1: Evolution of building fabric parameters, adapted from Approved documents Part L [HM Government, 1995, 2002, 2006, 2013c], In evidence are the values that have change compared to the previous version of Building Regulations.

		B. Regs. 1985 England and Wales	B. Regs. 1991 England and Wales	B. Regs. 2000 England and Wales	B. Regs. 2000 England and Wales	B. Regs. 2010 England and Wales	B. Regs. 2010 England
		ed. 1995	ed. 1995	ed. 2002	ed. 2006	ed. 2010	ed. 2013
	Energy efficiency measures	**"to limit heat loss"**	"to limit heat loss"		**• EPBD incorporated • "area weighted average" • SAP obligatory • U-value replaced by DER**		
Max U-value (W/m2K)	roofs	**0.25**	**0.20**	**0.16 – 0.25**	0.16 – 0.25	0.20	0.20
	walls	**0.45**	0.45	**0.35**	0.35	**0.30**	0.30
	ground floors	**0.45**	**0.35**	**0.25**	0.25	0.25	0.25
	Semi-exposed walls and floors	**0.6**	0.6				
	party wall	/	/			0.20	0.20
	Windows	/	**3.0**	**2.0 - 2.2**	2.0 - 2.2	2.0	2.0
	infiltration air permeability (m3/m2 at 50 Pa)	"to limit infiltrations" diagrams/drawings were provided	"to limit infiltrations" diagrams/drawings were provided	**10**	10	10	10
	solar gains			"benefits from solar gains"	"limit the effects" **SAP2005**	"limit the effects" **SAP2009**	"limit the effects" **SAP2012**
	thermal bridging value	"to limit thermal bridging" diagrams/drawings were provided	"to limit thermal bridging" diagrams/drawings were provided				0.04

3.2.3 SAP

The Standard Assessment Procedure (SAP) is the UK government's methodology used to (a) calculate predicted energy use and resulting carbon dioxide emissions from a dwelling; (b) demonstrate compliance with the Building Regulations Part L1A, with specific regards to the satisfaction of Criterion 1, Criterion 2 and Criterion 3; and (c) to produce the Energy Performance Certificate (EPC) of a completed dwelling [GOV.UK, no date b; ZCH, 2016].

Since 1994, SAP has been mentioned in Part L as a way to assess dwelling performance, as then energy efficiency was the main focus [GOV.UK, no date b]. In the present edition of SAP - **SAP 2012 -** climatic data have been extended to allow regional calculations. As a result, SAP 2012 incorporates an allowance for height above sea level into external temperature data. In addition, CO_2 emission factors, fuel price, and primary energy have been extensively revised. Finally, the options for heat losses from primary pipework have been extended [GOV.UK, 2014].

3.2.3.1 SAP METHODOLOGY

Even though the EPBD instructs measures to ensure energy performance to each Member State of EU, the EPBD does not specify a detailed calculation methodology and leaves such calculation to each Member State. This overall methodology includes aspects concerning the thermal characteristics of buildings (U-values, air tightness), position and orientation of buildings, solar protection, heating ventilation (natural and mechanical), air conditioning, and indoor climatic conditions [Anderson, 2006]. The UK has already incorporated most of that information in SAP assessment, which as a result has become quite extensive and detailed. For this reason, the calculation of carbon emissions requires a comparison with a 'notional building' [Davies, 2013].

In particular, new buildings need to demonstrate that the annual CO_2 emissions will not exceed a target level calculated and established by a notional gas-heated building of identic size and shape. For instance, the improvement factor established by Part L-2002 for dwellings is 20% (see figure 3.12). However, because this target is expressed in terms of CO_2 emissions, the choice of fuel is crucial, since electricity can be up to three times as much energy-intensive as natural gas [Anderson, 2006; ZCH, 2016].

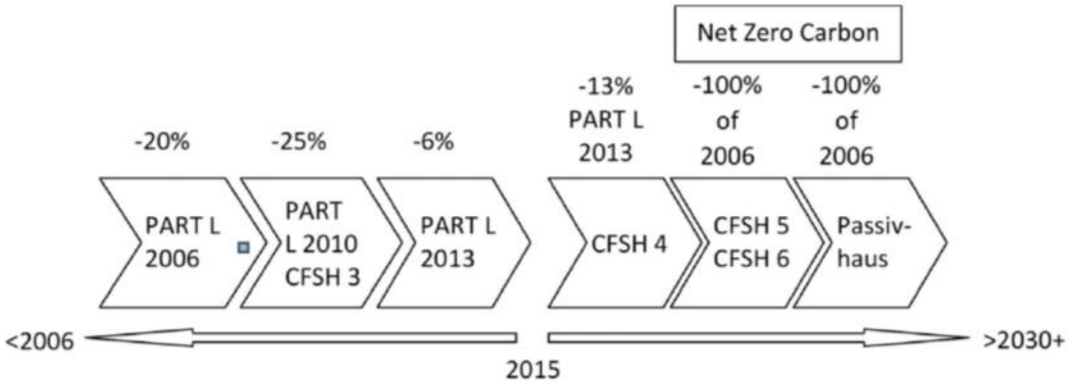


Fig. 3.12 Timeline of energy-related regulations and emerging standards in the UK, including energy-reduction targets [Mulville and Stravoravdis, 2016].

3.2.3.2 SAP OVERHEATING ASSESSMENT

SAP assessment provides a basic overheating check enabling to assess the risk of overheating that a building has (low, medium or high) during summer months. The assessment is based on monthly averages and is used to provide evidence of Part L1A meeting Criterion 3 "limiting the effects of heat gains in summer" [ZCH, 2016].

In SAP, the risk of overheating is calculated through the assessment of internal temperatures in summer, and it does not provide an estimate of cooling needs[27]. This procedure is not integral to SAP and it does not affect CO_2 emissions [GOV.UK, 2014].

Appendix P of SAP 2012 provides a method for assessing the propensity of a house to have high internal temperature in hot weather. It is crucial to note that (a) this assessment does not provide an estimate of cooling needs and (b) the procedure is not integral to SAP and so it does not affect the calculated SAP rating or CO_2 emissions [BRE, 2014].

Appendix P requires one to compare mean summer internal temperature with a threshold temperature and provides an indication of low, medium and high risk of overheating during summer months [BRE, 2014]. The procedure takes into account the following months only: June, July, and August [BRE, 2014]. It requires one to take the following steps:

[27] Differently, Passivhaus Planning Package does provide with an estimate of energy demand for cooling.

I. Calculation of the SUMMER GAINS/LOSS RATIO[28];

$$\boldsymbol{SUMMER\ GAIN/LOSS\ RATIO} = \frac{\boldsymbol{G}}{\boldsymbol{H}} = \frac{G_i + G^{summer}_{\ solar}}{H^{(summer)ventilation} + H^{(all\ year)fabric\ heat\ loss}}$$

II. Allocation of a MEAN EXTERNAL TEMPERATURE (for each summer month)

III. Calculation of the THRESHOLD INTERNAL TEMPERATURE (see table 3.2) which will enable to estimate the tendency to high internal temperature in hot weather.

Table 3.2: levels of threshold temperature corresponding to likelihood of high internal temperatures during hot weather as indicated in SAP [BRE, 2014]

$T_{threshold}$	Likelihood of high internal temperature during hot weather
< 20.5°C	Not significant
≥ 20.5°C and < 22.0°C	Slight
≥ 22.0°C and < 23.5°C	Medium
≥ 23.5°C	High

The points mentioned above lead to some considerations in regards to the risk of overheating, as it is calculated in SAP, Appendix P. First, it can be noticed that there are some gaps in the SUMMER GAINS section. For the internal gains [$\boldsymbol{G_i}$] do not include the heat that is recovered via the MVHR. Even though some MVHR have the summer bypass, anecdotal evidence suggest that there is still a leakage for which even in the rare cases where summer bypass is installed, there will be some form of heat gains through it, unless the system is turned off. So MVHR system becomes a source of heat gain by so exacerbating the effect of solar gains and internal gains.

Secondly, it can be noticed that in the SUMMER HEAT LOSSES section the fabric heat loss in the same value is calculated for summer, and it does not have any adjustment regarding the speed to which the heat loss occurs (which is presumed to be lower than in winter).

In addition, in the light of the new requirements for energy efficiency, one can argue that the 'overheating check' as priced in SAP – Appendix P is insufficient to provide a fair assessment. In fact, in its report Zero Carbon Hub states that the compliance check is too basic, since it is based on monthly averages, and that Building Control uses that assessment as evidence of Criterion 3 being met [ZCH, 2016].

[28] The detail of the SUMMER GAINS/LOSS RATIO calculation is shown in Appendix J.

Moreover, there a number of reasons supporting the thesis that SAP fails to fully capture the potential for overheating. These reasons can be concisely summarised as follows:

- The scope of SAP applies to self-contained dwellings. Accordingly, SAP includes individual flats but it excludes common areas, such as access corridors. Common areas are assessed by using procedures for non-domestic buildings. This fact can be claimed to be a problem, especially in multi storey residential where corridors have been found to overheat by domestic hot water pipes [Compton, 2014];
- The overheating check (Appendix P) is not a compulsory assessment of overheating risk [BRE, 2014];
- SAP refers to another document as guidance for overheating avoidance, Reducing Overheating - a design guide, produced by the Energy Saving Trust (2005) [BRE, 2014], which is not compulsory and may not be adequate for HIHs. Moreover, reducing Overheating does not appear in the SAP software.
- Lastly, Appendix P is concerned with neither CO_2 emissions nor DER.

For all these reasons, the compliance with building regulations does not mean that the dwelling is safe from overheating risk [BRE, 2014].

In consideration of HIHs, it should be noted that SAP is based on BREDEM. Despite the fact that it is a reliable and simple energy calculation procedure for dwellings, BREDEM refers to energy monitoring of houses in the 70’s and 80’s [GOV.UK, no date b; Reason and Clarke, 2008]. It is therefore not specifically conceived for HIHs, as PHPP is. For this reason, SAP, which derives from BREDEM, does not fully embed a calibrated calculation on HIHs. Moreover, the fact that SAP’s compliance is based on CO_2 emissions, which refer to fuel’s carbon intensity, may not be an incentive to low-energy design. As a consequence, if a fuel’s carbon intensity estimation changes, so do the overall SAP score. This does not account for considerations of long term impact[29].

3.2.4 PHPP

The Passivhaus Institute is an independent organisation based in Germany that has developed a low energy efficiency building standard since the mid '90s and has promoted its application not only in Europe but also worldwide. In fact, since the late 1980s, some 37,000 Passivhaus buildings have been constructed worldwide Dengel &

[29] The emission factors and primary energy factors in Table 12 of SAP2012 are for a 3-year projection 2013-2015 [BRE, 2014].

Swainson [Dengel and Swainson, 2012]. Referred as a comfort standard as well as an energy standard, Passivhaus has gained 92% positivity rating by occupants in Germany [Passivhaus Trust, 2016]. Its adoption in the UK has increased as a means from achieving the high UK standards (Code, Zero Carbon House), especially when pursuing a fabric first approach.

The Passivhaus Institute has developed the Passivhaus Planning Package (PHPP), which is a software aimed at assisting with the design of low-energy buildings. Like SAP, PHPP is used to calculate the annual energy demand of a building. The results include (a) the annual heating demand [kWh/(m^2year)] and maximum heating load [W/m^2], (b) summer thermal comfort with active cooling, annual cooling demand [kWh/(m^2year)] and maximum cooling load [W/m^2], (c) summer thermal comfort with passive cooling, frequency of overheating events [%], and (d) annual primary energy demand for the whole building [kWh/(m^2year)] [Passipedia, no date a].

In order to comply with the PassivHaus standard, a building must meet the following criteria:

- Space heating demand: it should not exceed 15 kWh per square meter of net living space per year or 10 W per square meter peak demand;
- Space cooling demand: it should not exceed 15 kWh per square meter;
- Primary energy demand: it should not exceed 120 kWh per square meter of net living space per year (heating, cooling, domestic hot water, appliances electricity);
- Airtightness: a maximum of 0.6 air changes per hour at 50 Pascals pressure (ACH50), as verified with an onsite pressure test (in both pressurized state and depressurized state).
- Overheating: thermal comfort must be met for all living areas during winter as well as in summer, with not more than 10% of the hours in a given year above 25°C [Passivhaus Institut, 2015].

The calculation of the frequency of overheating has been developed for residential HIHs. The software recognises that there could be an underestimation of overheating, especially when occur heavy changes in (a) temperature during the day occur [Feist et al., 2007] (such as a heatwave), in poor heat protection [Feist et al., 2007] (such as the absence of solar protection) or high internal loads [Feist et al., 2007] (such as DHW tanks within the thermal envelope).

A simple summer worksheet contains climate and geometrical information. Similar to SAP, PHPP allows for calculation of the heat gains and losses. However, there are major differences in the energy calculation.

Differently than SAP, PHPP encounters for both adjustments in losses and gains via MVHR and shading factors from the microclimate (from the surroundings buildings as well as vegetation). In addition, the PHPP calculation is verified for overheating against a threshold of 25°C, if this threshold is exceeded for 10% of the time, the building is not compliant with the standard. Moreover, the Passivhaus Institute suggests that the temperature of building should not exceed 25°C for 5% of the time.

PHPP is easy to use and it is both a design tool and a compliance tool. Studies have found that the overheating criteria of PHPP are more robust that the criteria set out in SAP. Accordingly, buildings designed with PHPP have better resilience to overheating when compared to buildings designed with other standards in mind. [Mulville and Stravoravdis, 2016].

It is worth noticing that whereas BREDEM has been developed from some existing and traditional monitored UK homes, PHPP is believed by AEBC (Association for Environment Conscious Building) to be a better software for energy efficiency compliance, because it was made for low-energy buildings [Reason and Clarke, 2008] and because developers update PHPP based on the outcome of experience's feedback from monitored real-world case studies and building simulation calibration in Germany.

3.3 HIHS DESIGN AND OVERHEATING

Design, as a problem-solving activity, is called to respond quickly to the new requirements in building design. However, the design of HIHs does not seem to take into account all new problems (or unintended consequences) that those changes impose in architectural design.

In terms of passive design, Su [Su, 2011] claims that there is not a universal validity of passive design for different locations and climates, and that passive design should be related to the major thermal problems of both local climate conditions and local housing design. Su's findings also support the claim that that ignoring one design factor could damage the entire passive design (in terms of energy efficiency) by weakening or overriding positive impact of changing another design datum: "*For example, the negative* *impact of changing the window wall ratio such as increasing the single-glazed north (equator-facing) window area can weaken or override the positive impact of increasing the north wall area of a house with good orientation (equator-facing*)" [Su, 2011].

In terms of summer comfort, designers have an overwhelming large body of literature and guidance available [CIBSE, 2002, 2006b, 2006a, 2013, 2018; Energy Saving Trust, 2005; Hacker *et al.*, 2005; Shaw, 2007; ARUP, 2008; NHBC, 2012b, 2012a; Dengel and Swainson, 2012; Jentsch *et al.*, 2013; ZCH, 2015a, 2015b]. At the same time reliance on just one compliance tool appears to be insufficient. It should be noticed that the findings of a large body of academic literature are at best preliminary or inconclusive.

As designers face this new complexity, it is no surprise that overheating aspects may be overlooked by designers whose focus rests on compliance with the governmental targets.

Only when the *feedback loops*[30] of low-carbon design are known and understood by designers, HIHs designs may be better equipped at responding to both governmental requirements of CO_2 reductions while providing comfort and by so avoiding the health risks and possible increase demand on cooling from the HIHs stock.

To do so, it is unrealistic to learn project by project in a trial and error process (traditional design). Instead, the dimensions of overheating (or 'scale' to refer to design-by-drawing design) are to be systematically outlined in a (possibly uncompleted) map.

[30] In the US in the seventies, half million Americans' left cities to create experimental communities. They adopted cybernetic ideas instead of organizing, with no hierarchy or control; instead, the central idea is that everyone is part of the system of free individuals giving feedback to the system in order to stay balanced. These feedback loops are the basis of a world as a self-regulated system [Curtis, 2011]. As such, this thesis seeks to understand the feedback loops of HIHs.

3.4 CHAPTER SUMMARY

In this chapter, it was reported that the factors pertaining to the **building physics realm** that contribute to overheating can be categorised in three main areas. In each area single factors, such as climate, urbanization, dwelling characteristics, etc., can play a role. Those factors can have an implication in other factors too. It was not possible to define a hierarchy of 'overheating actions', because neglecting one aspect can have effects on other factors.

The climate was shown to affect the external heat gains. In relation to the design of HIHs, contributions from the sun, especially low angled sun reaching indoors have been found to be attributable to excess heat gains. It was also noticed that heat waves are increasingly an area of concern since 2003, and when room temperatures averages (notice not peak) were above 27°C and 25°C for London and Manchester respectively it was found to be of concern, especially because people tend to spend more time indoors (especially elderly). The potential benefits of thermal mass during heat waves are contradicted in the literature.

In addition, whereas thermal mass is meant to contain temperature swings in a heat wave event the thermal capacity might actually lower the cooling effects from ventilation when compared to a lightweight dwelling.

Even though urbanisation can increase up to 5°C more than its surroundings, simulation studies have found that UHI effect may not constitute one of the dominant factors causing overheating and that construction type and microclimate (solar gains, ventilation) are possible determinant factors which might be greater in magnitude than UHI effects.

It was also found that new flats are at particular risk of overheating, because cross ventilation often is not available. This typology is expected to increase in the forthcoming years due to dense urbanisation, with an enormous potential for demand for cooling.

Natural ventilation strategy for cooling in urban areas with warmer temperatures and less wind may be an unpractical means for cooling. In addition, Part F and Part L of the building regulations do not control ventilation as means of thermal comfort. However, with the increase tendency for airtight buildings, a new requirement for it is emerging[31].

On the other hand, MVHR, which is only aimed at air hygiene, has provided evidence for a large number of pitfalls in terms of manufacturing, designing, commissioning, installing, using.

In relation to the **building design realm**, it was observed that overheating in HIHs is a condition brought by a new complexity in architectural design: the design of HIHs. As a result, the relationships between factors are not fully captured from the design stage to occupancy. Complexity in this case seems dictated by a lack of awareness at the systems level of the hierarchy.

SAP, which is the UK government's methodology used to predict energy use, to demonstrate compliance and to produce EPC, is not a product specifically developed for HIHs and it have shown not to be an appropriate tool for predicting overheating in HIHs. Moreover it does not provide an estimate of cooling needs and therefore of CO_2 emissions in HIHs.

Even in the case of an adequate tool, studies have shown that both in the UK and internationally, there are difficulties in achieving compliance with governmental requirements for energy efficiency.

In conclusion, it seems that in HIHs overheating relates to a deficiency of building cooling capacity, whether that is because of lack or insufficient ventilation or because of slow dissipation of heat gains. In these terms, a definition of overheating is best conceptualised not as an excess of heat (over-heat) but as a deficiency of cooling (under-cooling[32]).

Ultimately, it is possible to claim that overheating is a product of contemporary design in UK, and one must understand the mechanisms in which this happens and the areas of possible change.

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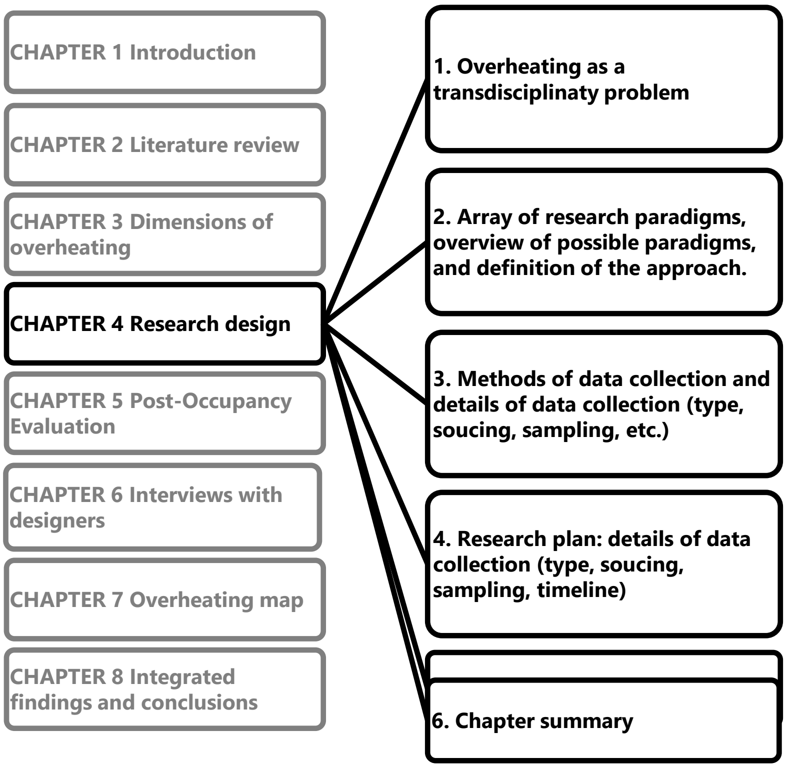
[31] With the new requirements of energy efficiency and the current definitions of ventilation in the Building Regulations, it appears that a new paradigm of ventilation (and hence a new paradigm of requirements) are ought to emerge.

[32] The word overheating is maintained throughout this thesis in order to keep terminology consistency with the published studies.

CHAPTER 4: RESEARCH DESIGN



Synopsis

This chapter sets out the research plan for the study of overheating in HIHs, as it occurs in the UK. It also clarifies the philosophical stance underpinning this study.

The first part of the chapter builds up on the findings from the previous chapters and states the methodological principles that guide this research, by also exploring the limits of some research methods.

Coherently with the discipline of architecture, it is claimed that no single method is sufficient to deal with the problem of overheating in HIHs. For this reason, a multi-case study mixed method approach is proposed.

Finally, the research methods used to collect and analyse data are introduced and dimensions of their validity are discussed.

4.1 OVERHEATING AS A TRANSDISCIPLINARY PROBLEM

The literature review introduced in the previous chapters indicates that overheating in HIHs is (also) a product of the contemporary design of newly built HIHs. In the attempt to understand how the problem of overheating in HIHs has emerged, it is necessary to conceptualise its traits. To do this, it seems relevant to understand the transition of the emergence and spread of HIHs.[33]

Among the several theories of socio-technical change, one -the *multilevel perspective*- argues that innovations first take place as niches and then proliferate and grow at a macro-level scale before beginning to change [Rip and Kemp as cited by Shove, Walker and Brown, 2013]. HIHs can be considered as constituting a niche and, as such, they correspond to the first stage of an innovation process.

The problem that will be studied in relation to HIHs –overheating- is experienced in particular in heating-intensive countries that apply higher standards of energy efficiency. As it was made apparent at the Passivhaus conference in Barcelona (Spain) in 2015, the problem of overheating in HIHs does not necessarily have a worldwide diffusion. Hence, a *nationally/regionally* bounded approach seems to be more suitable than a global-scale approach to address the problem of overheating.

For the reasons just introduced, this study accounts not only for the (thermal) physical considerations but also for the cultural shortcomings of the transition towards the design of HIHs. Related, the findings of this research project are expected to implement the designers' *know-how* of the environment-behaviour relationship, which is aimed to avoid overheating and hence to avoid any for heat stress or increase in energy demands for cooling.

4.1.1 POINTS FROM THE LITERATURE REVIEW (EXISTING RESEARCH) – GAPS IN KNOWLEDGE

The monitoring studies reviewed in the previous chapters provided evidence that the highly insulated stock is more vulnerable to overheating. For they showed that a number of elements of HIHs increase their vulnerability to overheating. Among those elements

[33] *Transition* in this context is defined as "*long-term change in an encompassing system that serves a basic societal function*" [Elzen and Wieczorek, 2005].

are the unavailability, or nonblack of use, of purge ventilation[34], failings of the MVHR system and inappropriate (un-contextualised) use of passive design.

The literature also showed that those elements combine with the main physical causes producing uncomfortably warm temperatures, which can be related to the following factors:

- Insulation as a condition that can both attenuate as well as exacerbate overheating;
- lack of solar control strategy;
- ventilation strategy;
- absence of thermal mass;
- house typology and type of rooms.

The above factors are entangled in the process of design that is increasingly fragmentary. In addition, a number of studies have shown that the tools currently used in the design process are be insufficient to predict thermal discomfort due to warm temperatures and, more generally, inappropriate to cope with the new complexities in design brought by the carbon reduction agenda.

Once all these elements are taken into account, it can be claimed that overheating is largely a product of contemporary design and so a symptom of the transition towards low-carbon designs. This view relates to the concept of *transition in practice perspective* put forward by Shove, Walker and Brown [Shove, Walker and Brown, 2013] claiming that past and localised practices are to be encountered together with aspects that are more widely standardised to properly reduce the demand of energy. Accordingly, a way to move forward when describing the process in which overheating occurs is to pay attention to a set of interrelated elements and design activities.

One of the main assumptions of this study is that, in order to better understand overheating as a complex phenomenon; one should go beyond the disciplinary limits of architecture and building science, by thus embracing an **interdisciplinary approach**. This movement towards interdisciplinarity is hardly something new: architecture as a discipline has always been linked to other disciplines, such as art, ergonomics and

[34] Purge ventilation is a manually controlled ventilation of rooms or spaces at a relatively high rate to rapidly dilute pollutants and/or water vapour. Purge ventilation may be provided by natural means (e.g. openable window) or by mechanical means (e.g. fan) [HM Government, 2013a].

structural engineering. However, in different times architecture has worked in synergy with different disciplines. So what can be regarded as genuinely new is the fact that today the studies of sustainability look into buildings in a more interlinked way. That introduces a new kind of complexity that puts architecture in relation to novel disciplines, such as systems engineering. **Systems engineering** is an interdisciplinary field of engineering that focuses on complex systems to design, build, operate, and maintain such systems. Such approach is significantly different from traditional analysis: whereas the traditional analysis focuses on separating the individual pieces of the subject of study, systems thinking looks into the interactions of the matter of study (here, overheating) with other constituents of the system (such as people, design process, government, etc.) [Aronson, no date][35].

Systems thinking involve the use of various techniques to study systems of many kinds. The idea behind systems thinking, formulated by the German philosopher Immanuel Kant, is an abstract holistic principle used as a means for understanding 'the real world', and later formalised as systems consisting of inputs, transformations, outputs, feedback loops, goals, stakeholders, and external influences that operate within a system' [Frank, 2016].

To apply such approach and reconnect the links leading to overheating, a number of monitored studies were reviewed in Chapters 2 and 3. The monitored studies presented a number of findings:

- There are nether a universal definition of overheating, nor an objective-value-free method for the assessment of overheating. This fact supports the philosophical assumption embraced in this study that the phenomenon of overheating in HIHs in the UK should be approached from a not purely quantitative approach.
- Overheating is a problem that cannot be confined to 'one room.' In order to understand the nature of overheating, then, the 'one-room' approach must be substituted with a 'whole house' diagnosis of overheating. In this context, a whole building overheating assessment better allows for *judgement* about the resilience of a HIH to high temperatures.
- Inevitably, the results of such approach may lead to different conclusions when compared to those generated by a more (traditional) deterministic approach,

[35] Systems thinking, which is the approach underpinning this study, has already been applied to urban studies. Such application has led some to abandon a fragmentary vision of cities in favour of an unbroken understanding [Lefebvre, 1998].

because overheating is intended as a dynamically complex system, which has a great deal of feedback and sources.

One of the conclusions that were drawn on this basis is that the problem of overheating in HIHs relates to a *deficiency of a HIHs in cooling capacity* that may be caused by a lack of or insufficient ventilation, a lack of solar control, and related by the slow dissipation of heat gains. In these terms, a definition of overheating, as it relates to HIHs, is conceptualised not as *excess* of heat (*over-heat*), but as a *deficiency* of cooling (*under-cooling*).

This shift in the conceptualisation allows for a new perspective of problem and new strategies of intervention. The understanding of this issue is required to avoid that a problem of lack of cooling capacity (apparently inherent to HIHs) becomes a (new) kind of demand brought by HIHs design: a demand of cooling, which, at the state of the art of the knowledge in this thesis, appears to be the result of unsuccessful HIHs design. Therefore, the question arises as to whether the sources of heat gain need to be reduced drastically or whether the cooling capacities enhanced in HIHs.

4.1.2 LIMITATIONS OF SOME METHODS

Overheating in buildings has been studied in recent years and different approaches have been adopted. However, the literature has shown some limitations in those approaches, due to the nature of something as innovative as sustainable building design. The following sections focus on the limitations of two methods that are particularly important in the subject: large surveys and DTM.

4.1.2.1 LARGE STATISTICAL SURVEYS

Large statistical surveys are expensive and time-consuming [Beizaee, Lomas and Firth, 2013]. For this reason, they tend to be used sparingly. This is further complicated by the wide range of dwelling types [Beizaee, Lomas and Firth, 2013], a progression of refinement of conditions that does not include UHI and microclimatic conditions [Mavrogianni *et al.*, 2012] and factors directly influential in the internal thermal variation of indoor overheating.

A large sample of HIHs would undoubtedly contribute to a better knowledge of overheating risks in UK. However, for the reasons indicated above, only a collaborative project could rely on such sample. Related, relying on that method does not seem to be an option in a PhD study, also in consideration of the fact that conflicts between data ownership and the limited availability of resources ordinarily associated with a PhD project are likely to arise.

As a result, despite the fact that it provides a picture of how the phenomena of overheating occurs in the UK stock, an approach to the problem of overheating that relies on large statistical survey has not been pursued in this work, which could not count on a sufficiently enough large sample of HIHs.

4.1.2.2 DYNAMIC THERMAL MODELLING (DTM)

The use of DTM (or simulation) when investigating overheating in HIHs is popular among researchers, because of the undeniable advantages of the availability of future climate scenarios and the complete control over inputs and design parameters. In fact, several studies, some of which were presented in Chapter 2, have employed DTM as a method to predict overheating, by manipulating different parameters, such as house types, constructions, occupant behaviours, and climate change scenarios.

However, one should acknowledge the limitations DTM has in representing what actually occurs in HIHs. In particular, DTM fails to record and account for the actual behaviours of occupants and their interaction with the heating and ventilating systems operating in HIHs [Beizaee, Lomas and Firth, 2013].

In addition, a model would represent a purely theoretical reality, which is abstracted from the real-world circumstances. These are likely to be different when innovation is in place. For instance, MVHR systems may be modelled on the assumption that they are built to the best practice.

In addition, the limitations in predictive ability of such models are usually ignored or at least downplayed. For instance, Lomas conducted a modelling study in which the variability of the predicted peak temperature was found to have a simulation resolution of 3°C[36]. This is a great limitation, especially in the assessment of the likelihood of overheating, because if a DTM predicts a particular peak temperature, for instance 27°C,

[36] The simulation resolution is a term introduced by Lomas to provide detail regarding the accuracy of simulation programs, quantifying the variations between different dynamic simulations predictions, and by so providing a weight on their accuracy: "*Simulation Resolution, SR, is the value below which the absolute difference between the predictions of two programs (obtained by skilled users, for the same circumstances) may be expected to lie with a specified probability*" [Lomas, 1996].

another's program DTM may predict a value anywhere between 24-30°C [Lomas, 1996]. Hence, modelling studies may overstate the reliability of their results when ignoring this inter-model variability [Beizaee, Lomas and Firth, 2013].

For this reason, the use of building simulation modelling to predict the inherent uncertainty of the design performance cannot be considered an appropriate method for addressing the research questions this work set out to address.

4.1.2.3 NON-HIH COMPARATORS

The literature review provides that overheating is found not only in HIHs. In such cases, the absence of insulation and fabric design makes homes vulnerable to excess heat. The case of HIHs has a different nature: the super insulated fabric and remarkably low levels of infiltration present an internal environment that could not be comparable with non-HIHs. In HIHs excess heat seems retained within such an efficient thermal envelope.

In other words, non-HIHs are vulnerable to overheating (climate change, UHI, heat waves) while HIHs present a different 'physiology' where overheating appears produced or retained within the fabric. As such, non-HIHs would not constitute a viable comparator.

To stress this point, overheating is not categorised as a feature of non-HIH nor of HIHs. It is recognised that overheating in HIHs occurs in a different way, with the thermal dynamic responding differently to heat gains. This is why overheating in HIHs have been conceptualised as an under-cooling issue (for instance the un-controlled cooling happening via infiltration).

4.2. ARRAY OF RESEARCH PARADIGMS

One of the challenges that this study and its interdisciplinary nature poses lies in the different perspectives that diverse disciplines (such as architecture, social science, building physics science) have on paradigms[37]. In addition to that, following Groat & Wang's statement that "*any research design is necessarily framed by the researcher's assumption about the nature of reality and how one can come to apprehend it*" (Groat &

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[37] Kuhn defines *paradigm* as "*the entire constellation of beliefs, values, techniques, and so on shared by the members of a given community*" (Kuhn as cited by Maxwell n.d., p.42). At the most abstract level instead, Maxwell exemplifies such paradigms as philosophical positions, like positivism, constructivism, realism, pragmatism, and postmodernism, each embodying very different ideas about reality (ontology) and how we can gain knowledge of it (epistemology) [Maxwell, 2005].

Wang 2002, p.21), this study will take the researcher's style[38] to be a factor that influences the way a research question is answered [Canter, 2000]. Such own constructed formulation is combined with other components, such as the researcher's experience, the researcher's speculative thinking, the current non-academic debate, and unpublished papers [Maxwell, 2005], as per figure 4.1.

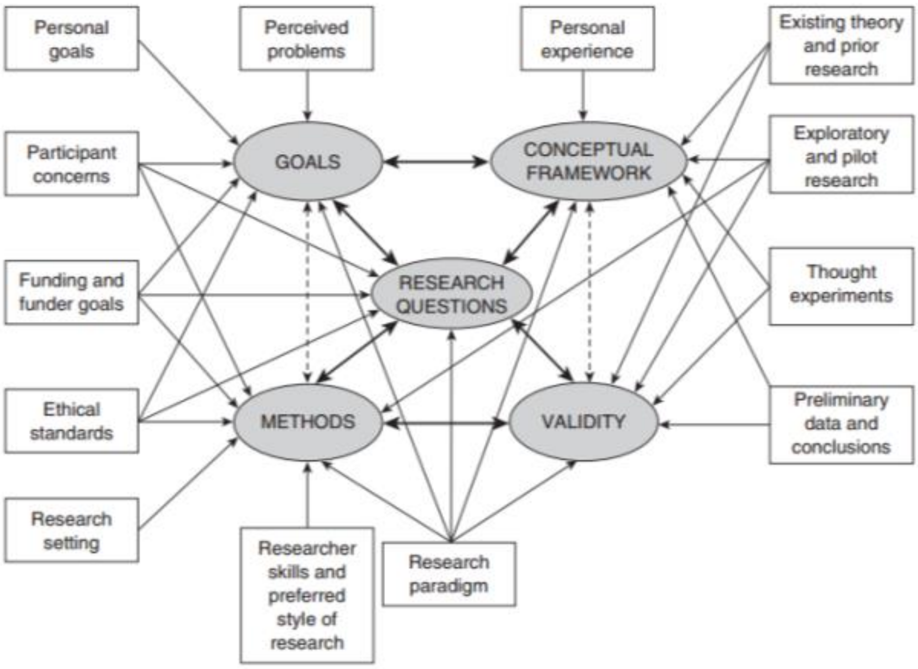

Fig. 4.1 Contextual factors influencing a research design [Maxwell, 2005]

In the field of architecture, ontological assumptions, or *paradigms*, are numerous, because the practice of architecture requires knowledge of a vast array of phenomena and their sub-disciplines within the social sciences, natural sciences, and humanities [Groat and Wang, 2002]. The following paragraphs list some of those paradigms.

1. The most commonly understood research framework is the dichotomous **quantitative/qualitative** framework (that in turn replicates the division between *science* and *myth*). In this framework, quantitative methods and qualitative methods are the opposite ends of an objective vs. subjective reality. This dichotomous framework can often be misleading, since it places the emphasis at the level of tactics employed in the research enquiry (such as laboratory experiment vs. semi structured interviews) [Creswell, 1994; Maxwell, 2005; Groat and Wang, 2013]. Also, such a framework assumes that each paradigm engages

[38] Canter uses the analogy of a jazz improvisation, where a repertoire of techniques is used for developing an original tune [Canter, 2000].

with particular research approach. For instance the quantitative approach would require a deductive – cause and effect / hypothesis testing– reasoning. On the other hand, a qualitative approach aims to generate meanings from the data set collected in order to identify patterns and relationships to build a theory, via inductive reasoning [Dudovskiy, no date].

2. A second research framework is theorised by Joroff & Morse, who see architectural research as a **continuum of research paradigms** [Joroff and Morse 1984, cited in Groat and Wang, 2002, p.29]. This framework consists in a much more fine-grained conceptual framework than the dichotomous quantitative/qualitative distinction. In this alternative framework, research areas are organised in a scale order with different '*degrees of systematisation*'. As shown in fig. 4.2, the left side of the model represents a more subjective paradigm, whereas on the right hand side sits a more objective paradigm. In this framework, research is clearly distinguished from other activities in which architects or designers might engage [Joroff and Morse 1984, cited in Groat and Wang, 2002, p.29].

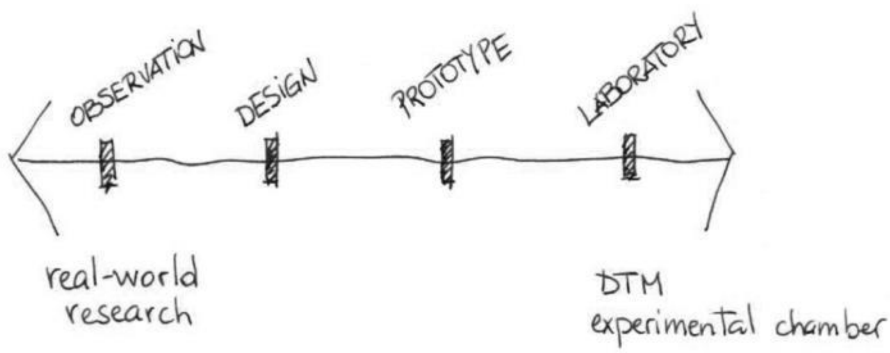

Fig. 4.2 Scalar conceptual framework for architectural research, adapted from Joroff and Morse in [Groat and Wang, 2002]

3. Research can also be framed in terms of a **tripartite framework** consisting in the triadic division of *postpositivism-naturalism-emancipatory*. Postpositivism is characterised by a nuanced belief in an 'out there' reality that can be known with some level of *probability*. It also assumes that *objectivity* is a legitimate goal that can be imperfectly realised. Naturalism, also known as constructivist, is instead based on the premise that there are multiple socially constructed realities and, hence, it is neither possible nor necessary to establish a value-free objectivity. On

this basis, naturalism acknowledges the role of interpretation and creation in reporting findings [Groat and Wang, 2002]. Finally, emancipatory research recognises multiple realities, and it stresses the unconscious role of race, ethnic, gender issues in the social construction of reality.

4. Paradigms that are relevant to qualitative research include interpretivism, critical theory, feminism, queer theory, and phenomenology [Maxwell, 2005]. Of these, Maxwell embraces **critical realism**, which is an approach that has gained broad acceptance in the philosophy of science. It consists in combining two perspectives that were earlier indicated as fundamentally incompatible: ontological realism and epistemological constructivism[39]. In Maxwell's terms, "*every theory, model, or conclusion is necessarily a simplified and incomplete attempt to grasp something about a complex reality*" [Maxwell, 2005, p.43]. Today critical realism is widely embraced both in science [Shadish, Cook, & Campbell, 2002, p. 29] and in everyday lives.

4.2.1 ONTOLOGICAL ASSUMPTION

The present work partly incorporates elements of all the research paradigms just introduced. It presents a component of the **dichotomous** framework because of the nature of the data used (qualitative and quantitative) to gain knowledge from the real-world (**continuum** research paradigm) in a specific context (**interpretivism**).

The combination of such distinct philosophical positions results in a dialogue between different perspectives. Such dialogue is also referred by some authors as a **dialectical approach,** because it combines divergent models to expand and deepen, rather than simply confirm, our understanding. In this scenario, paradigms that reflect different ways of knowing the world are acknowledged without making a systematic attempt to reconcile them [Maxwell, 2005]. The bubble diagram (or *circle relationship* diagram) is used in figure 4.4 to show this dialogue of paradigms: figure 4.3 shows the relationship to or from a central idea (in this case the inquiry of overheating of HIHs). The medium-sized circles represent the different kinds of paradigms to disentangle such enquiry, as they have been acknowledged in this chapter. The smaller (void) circles are there to

[39] *Ontological realism* is the belief that there is a real world that exists independently of our perceptions and theories and this world doesn't accommodate the researcher's beliefs. On the other hand, *epistemological constructivism* claims that our understanding of the world is inevitably our construction no such construction can claim absolute truth [Maxwell, 2005].

acknowledge that these may not well be the only paradigms, though trusted to be the most used, considering the reviewed literature. The distance from the central circle has no specific meaning, and the overall picture aims to represent the researcher foundation for the research design, in the acknowledgment that some interpretivism and an inherent 'imprecision' is embraced.

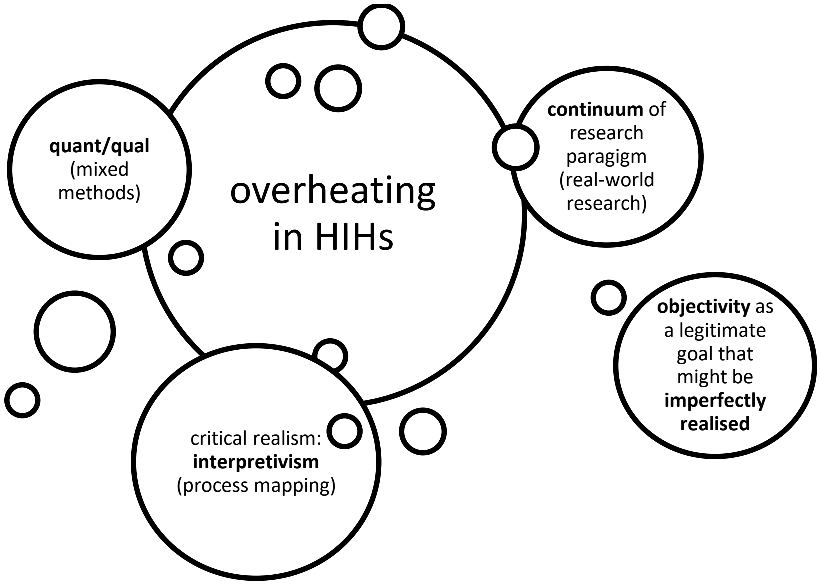

Fig. 4.3 Research paradigm(s) underpinning the present risk of overheating in HIHs

Consequently, this study relies on a mixed-methods approach of data collection (see section 4.2.3). Nonetheless, it seems crucial to remark that the mixed-methods approach, as it is understood and practiced in this study, is not reducible to the juxtaposition of a variety of diverse and possibly fundamentally heterogeneous methods - each informed to some different rationale and to possibly less than immediately coherent general principles. By contrast, in this study those different methods are contextualised in a broader and overarching framework – reality mapping (developed later in section 4.3.3) – that allows and contributes to the interaction, or dialogic exchange, between those different methods. As a result, the different methods relied on have been used in such a way that they can feed one into another in an articulated and integrated way.

This integration is achieved via a *dialogue of paradigms*. In this perspective, contributions from each method connect with the others. As a result, the conclusions of this study will be the output of a process of communication and mutual interchange between different methodologies, which are in turn understood as forming an *integrated whole*, as opposed to a mere bulk of different inputs.

4.2.2 EPISTEMOLOGICAL ASSUMPTION

Because the main purpose of the built environment is to enhance human lives, by its own nature the study of energy efficiency and thermal comfort in HIHs lies at the intersection of building physics and social science.

This inherent crossing of disciplinary boundaries is at the very basis of architecture, as Vitruvius noted in 15 B.C.. In Vitruvius's view, a building must embed three fundamental qualities: (a) *firmitas,* (b) *utilitas,* (c) *venustas*, that is, (a) stability, (b) ergonomic and (c) beauty [Morgan, 1960]. As such, the study of HIHs cannot just take into consideration the energy efficiency component of those building and so neglect the interaction between HIHs and their occupants (ergonomic aspect). Figure 4.4 depicts the just acknowledged crossing-between-disciplines; here, the shaded area represents the ideal approach to research in order to favour advancement of knowledge in architecture.

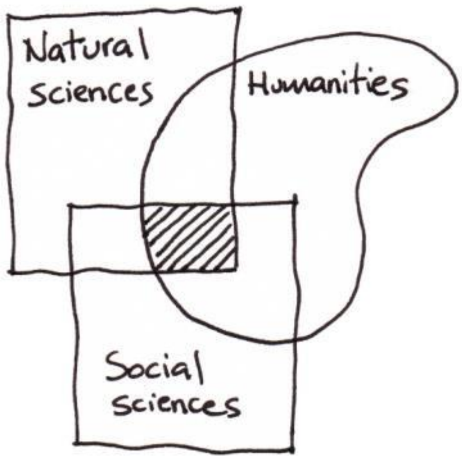

Fig. 4.4 Ideogram of research in architecture. Shaded, the ideal approach to research in architecture.

This research project is characterised by an **interpretivist perspective** that explicitly acknowledges, and takes into account, the intrinsic uncertainties in understanding occurrences of overheating in HIHs. Accordingly, the results this study arrives at should be considered a reasoned prediction of how the different involved factors contribute to impact on the overall phenomenon of overheating and how the process of design of HIHs can be informed by the new knowledge acquired from this study case studies.

It should be noted that in adopting the interpretivist perspective this research moves from a "problem-solving" process of research to a "problem-finding" process of research, also known as *sympathetic method of design* [Takahashi, 2000]. This method understands the relationship environment-behaviour as a transactional relationship, where person and environment are united as whole in an ever changing reality[40]. In this research the belief is also embraced that it is never possible to experience the same situation twice [Morgan, 2014]. As a consequence, any belief is provisional and knowledge is acquired.

4.2.3 A CASE-STUDY MIXED METHODS APPROACH OF DATA SOURCING

As suggested by Groat & Wang [2002], an increasing proportion of architectural practice involves dealing with unfamiliar circumstances beyond the expertise of individual practitioners and beyond the conventional wisdom of the profession as a whole. This is the case with HIHs, whose history is recent and design is adjusting to the new government requirements for energy efficiency.

From a pragmatist point of view, a research is a form of action aimed to meet the goals structured by its main questions [Morgan, 2014, p.43]. This dimension links the approach endorsed in this study to the design practice itself. In fact, here architectural research is conceived as an aid of systematic inquiry directed towards the creation of knowledge, which in turn may ultimately form an integral component of the design process. Groat & Wang claim that architectural research is extremely important to the success and viability of the architectural profession [2002]. Likewise, some architects embed research in their profession. All in all, there seems to be an intrinsic complementary nature of research and design. Such complementarity indicates an internal connections between the two activities [Groat and Wang, 2002], as reported in fig. 4.5.

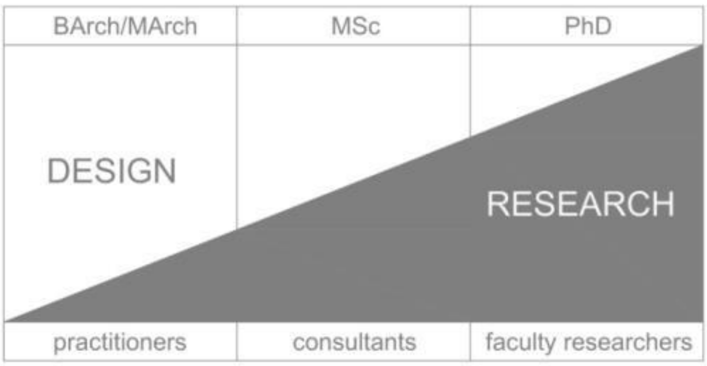

Fig. 4.5 The complementary nature of research and design, after [Groat and Wang, 2002]

[40] Post-occupancy evaluation records the environment-behaviour situation and it observes the environment-behaviour relationships changes over time. See devoted section, later in this chapter (section 4.3) for details on planned observations.

To contribute to this body of knowledge, the present study engages with a case study research because it is meant to produce real-world knowledge. More specifically, the research can be categorised, in Yin's terms, as a **descriptive and explanatory case study**, in which the thermal behaviour of HIHs is described and on this basis an explanation of the overheating of HIHs will be attempted [Yin, 1993]. In addition, in this study **multiple cases** are selected in such a way to grant some degree of replicability, and so predictability. This is why in this study only HIHs are taken in consideration, and the phenomenon of overheating is then described as it unravels in each case.

This study also incorporates some aspects of ethnography and participant observation, because it is largely immersed in a group of people (people who live in HIHs) for a long period of time interviewing, listening, etc. (**longitudinal** study). However, the present study has not been defined in such terms, because it is not dominated by participant observation. Rather, it is a form of observation aimed at aiding the interpretation of the monitored data.

There is a tendency of associating case studies with qualitative research. But from the perspective taken in this study this tendency is misleading, or even altogether incorrect [Bryman, 2015]. In fact, the present study deploys a variety of data sources within the same cases. For this reason as well as because of the way the data are treated, this study too qualifies as a **mixed method** research. In mixed method research, "*the researcher bases the inquiry on the assumption that collecting diverse types of data is the best to provide an understanding of a research problem*" [Creswell, 2003, p.21].

The argument against mixed method research tends to be based on two types of arguments (a) the belief that a research method carries an epistemological commitment and (b) the idea that quantitative and qualitative research are two separate paradigms. To deal with this twofold criticism, this study will rely on **pragmatism** (as theorised by Creswell & Plano) and so will make use of diverse approaches that value both objective and subjective knowledge. This way, not only the research question becomes central (more than the philosophical worldview and method used), but also it abandons the dichotomy between post-positivism and constructivism [Creswell and Plano Clark, 2007] as well as the reliance on metaphysical concepts, such as *truth* and *reality*.

To sum up, the present study can be characterised as indicated in table 4.1:

Table 4.1 Study typology

(Pragmatic) critical realism	A dialogue of divergent mental models to expand, deepen and reflect on the nature of overheating in HIHs
Mixed methods	Integration of data of different sources type: POE, interviews, process mapping, focus group
Multiple case study	In-depth study of four HIHs in England (descriptive and explanatory multiple case studies)
Longitudinal study	Data collected over a period of 11 months, to cover four seasons.

4.3 METHODS OF DATA COLLECTION

As listed in Chapter 1, this research will examine HIHs and try to establish if the design process delivers comfortable homes. Its specific focus will be on investigating the design issues that can lead to overheating. This study is then instrumental to gain an understanding of the actual performance of HIHs and to identify any risk that could lead to overheating. This will be achieved by linking the thermal performance of HIHs with the design thinking and process behind HIHs, and by clarifying how they interact in the context of design.

The two basic research questions orienting this study listed in Chapter 1 (namely **I.** *Do HIHs provide an uncomfortable indoor environment for their occupants?*, and **II.** *If so, how can the process of designing HIHs be improved to reduce the risks of overheating?*) can be related to the real-world performance (see fig. 4.6).

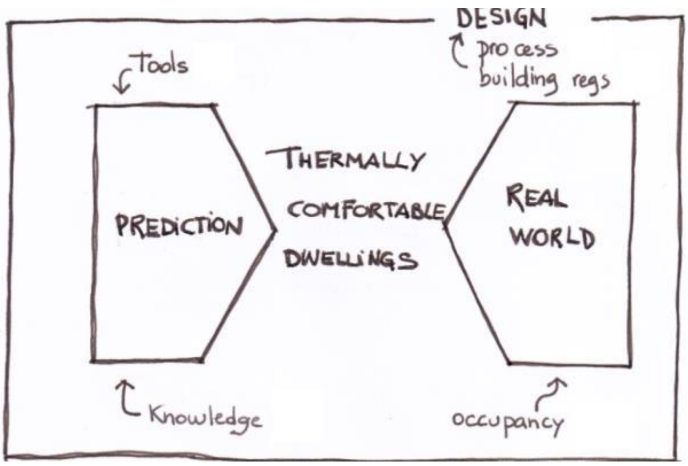

Fig. 4.6 Overview of proposed methodology of research with main areas of enquiry

The several objectives identified in Chapter 1 as building blocks of the two fundamental research questions (and replicated in figure 4.7) will be addressed by working from two main areas of enquiry: (a) the thermal performance of real-world HIHs case studies, through some post-built measurements (i.e. post-occupancy evaluation) and (b) a deep insight into the prediction informing the design of monitored HIHs (i.e. interviews with designers). This dualism is embedded in each objective.

Here, post-occupancy evaluation (POE) is employed to evaluate the capacity of HIHs to deliver comfort (cf. **obj. 1, obj. 3** and **obj. 4**). The deliverables related to this area of study are (a) overheating assessment, (b) summer temperatures analysis, and (c) analysis of occupants' questionnaires. In addition, in this research POE contributes to provide an understanding of the role that occupancy plays in the thermal performance and exacerbation of overheating (cf. **obj. 4**). Ultimately, these elements contributes to map the occurrence of overheating, as it related to the physical factors - introduced in Chapter 3- which then fed into the interpretative map of the risks factors of overheating in HIHs in the overall process of design (cf. **obj. 5**).

The interviews with designers are aimed at examining the design process that delivered the case study houses. The interviews are also aimed at evaluating architects' and designers' current knowledge (explicit or tacit) of how their HIHs designs affect thermal comfort (cf. **obj. 2**).

In addition, interviews provide information regarding the tools and verification techniques used by designers (cf. **obj. 3**). Eventually, the interviews will contribute to map the occurrence of overheating, as it relates to the design factors introduced in Chapter 2. Those factors then fed into the interpretative map of the risks factors of overheating in HIHs in the overall process of design (cf. **obj. 5**).

Data collected in the previous stages will be broken down via interpretative analysis into a process map. The compilation of this overheating map (cf. **obj. 1**) will show if and when HIHs are more prone to overheat, and where overheating occurs in the built process. In order to translate this map into a simplified model for designers, and so to evaluate the usefulness of this overheating map, a *focus group* was organised The focus group is also functional to test the validity and usability of the proposed map.

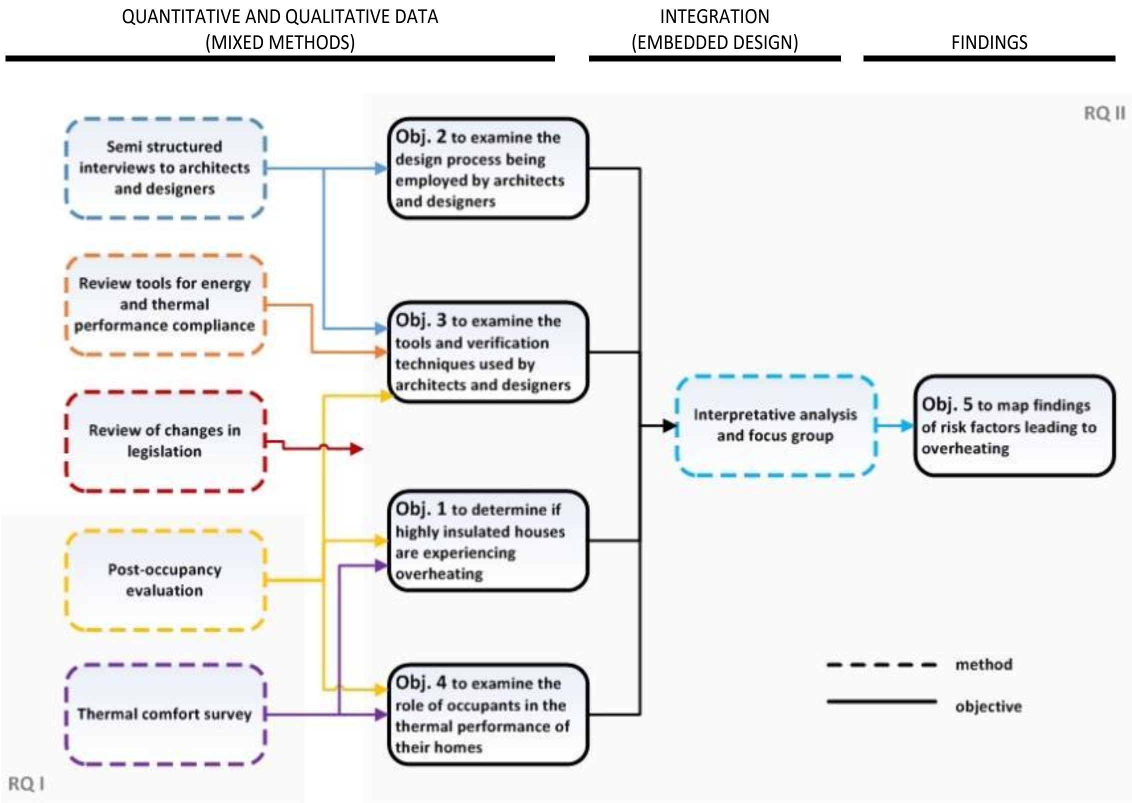

Fig 4.7 Overview of research activities in relation to research objectives, evidencing the type of mixed methods design

The above areas of enquiry are of a mixed methods nature, and the combination of such data can be categorised as *embedded design*. Embedded design mixed methods are aimed at enhancing either the quantitative or the qualitative research with the other approach [Bryman, 2015]. In the present project, data collection is instrumental to understand the phenomenon of overheating.

The methodology of the proposed research relies on a mixed methods research design with four main stages, as shown in figure 4.8 (and developed in detail in sections 4.3.1, 4.3.2, 4.3.3, and 4.3.4). The first stage consists of a longitudinal study. The longitudinal study involves repeated surveys over a period of just about one year in order to assess the thermal performance of four case-study houses. The longitudinal study is a type of quantitative research approach, based on post-occupancy evaluation (POE), thermal comfort survey, and questionnaires to the occupants.

BOX 4.1 – Temperatures monitoring pilot

The use of questionnaires, in addition to environmental monitoring, was also recommended by personal experience. During the doctoral programme, there was an opportunity to respond to a real-world problem, which was a primary school in Leicester where some rooms reported 'overheating' by its occupants. The rooms in question were monitored during July 2014 by means of recording air temperatures for a period of two weeks. The analysis of each room's temperatures showed not to fully explain the mechanisms behind uncomfortably warm temperatures or perceived overheating, as experienced by the building's occupants.

The second stage of this research is based on qualitative data sourcing via semi-structured interviews to members of the design teams of the selected case study houses. This qualitative compound of the research is, paraphrasing Groat and Wang, 2002, aimed at studying overheating in its natural setting, by thus attempting to make sense and to interpret overheating in terms of the meanings for the designers [Groat and Wang, 2002].

The third stage consists in triangulating data from POE (buildings *in-use*) and the interviews (*design* of buildings) by means of a process modelling methodology. The outcome of the triangulation is an 'overheating map' aimed at providing and bringing together aspects of the design and of the performance of the case studies, by so providing a map of overheating production in contemporary HIHs.

Finally, during the fourth stage, the 'map of overheating' is presented to an audience via a focus group in order to gain feedback on its usability.

Each stage (fig. 4.8) and corresponding techniques is elaborated in the following paragraphs.

Fig. 4.8 Four stages of the research methodology of this study

4.3.1 STAGE 1: POST OCCUPANCY EVALUATION (POE)

CIBSE defines POE as a tool to investigate how and why buildings may fall short of the designer's aspirations. POE's aim is not confined to understand the energy consumption of HIHs, as it POE also assesses comfort and so establishes how well the building functions from the occupants' point of view [CIBSE, 2013]. For Stevenson, POE constitutes an essential part of improving sustainable design because it lies on evidence-based assessment [Stevenson, 2008] POE provides a complete picture of how the building performs in terms of perception compared to physical performance and how it does so in multiple seasons. So, for Stevenson POE is an essential part of the total design process. In addition, by relating physical monitoring and occupancy feedback, POE spans across the disciplines of building science and social science [Stevenson and Leaman, 2010].

Recently, Göçer et al. have used the feedback from POE to close what they call "the building performance feedback loop" by means of a *spatial mapping* based on POE results. In this way, they link existing POE methods to the visualisation of information that can be used in building information modelling (BIM) at different stages of the design and construction processes [Göçer, Hua and Göçer, 2015]. This way, Göçer et al. outline an approach that includes "*POE as a self-evident part of the architectural design process*" [2015].

In the specific case of investigating overheating, the approach of POE consists in asking occupants questions, such as "*Does the building overheat in summer/winter?*" That is, survey participants are asked about the building in general and not just the current state of the indoor environment.

CIBSE claims that the best way to identify overheating is by asking its occupants questions about overheating. Even though CIBSE recognises that such an assessment is subjective, the responses of a sufficiently high number of building users can indicate whether occupants perceive internal temperatures as uncomfortably warm and, if so, when this is the case [CIBSE, 2013][41].

Preiser classifies POE studies as (a) indicative, (b) investigative, and (c) diagnostic. In a nutshell, (a) indicative POEs are based in quick walkthrough evaluations involving interviews with key stakeholders; (b) investigative POEs employ questionnaires in

[41] However it is clear that there is a difference between saying that a building is too hot (instantaneous assessment) and saying that the building overheats over a period [CIBSE, 2013].

addition to photos (or videos) and physical measurements; lastly, (c) diagnostic POEs are based on long term data gathering aimed at providing a wide range of performance evaluations [Preiser, 1995].

Because diagnostic POE relates to in-depth research in a focused topic area, this study undertakes diagnostic POE by deploying techniques of inquiry to map areas of concern between dwellings and their relation to the problem of overheating in HIHs. Those techniques are purported to:

- Examine how HIHs are actually performing thermally. This requires one to evaluate the physical environmental measurements and the occupants' opinions on how comfortable their houses are.
- Examine the role occupants play in the thermal performance of their houses. This requires one to study how houses are used and managed. That way it is possible to evaluate the occupants' level of understanding on how to maximise thermal comfort.
- Investigate how the design and the use of HIHs can be improved to reduce uncomfortably warm temperatures.

In this study, POE is performed by means of physical environmental monitoring, occupant questionnaires and a thermal comfort survey. These means are described in some detail in the following paragraphs.

4.3.1.1 PHYSICAL ENVIRONMENTAL MONITORING

In this research, longitudinal physical environmental monitoring has been performed in two ways: (a) continuous measurements and (b) spot measurements.

(a) Continuous measurements have been recorded via calibrated[42] HOBO sensors (see table 4.2). The HOBO sensors that were used are self-contained data loggers positioned and left in households for the duration of the study. Those sensors have thus recorded the key environmental parameters in each room of the homes. Two types of sensor were used: (a) HOBO UA pendant sensors for recording internal temperatures (˚C); and (b) HOBO U12 for recording internal temperatures (˚C), Relative Humidity (%) and in some cases CO_2 (ppm)[43]. The sensors recorded the relevant variables at 10 min intervals from

[42] Calibration was performed after the environmental monitoring on some of the temperatures sensors via a controlled water bath calibrator.

[43] The measurement of the CO_2 levels is intended as an indicator of poor ventilation. This measurement was not intended to evaluate the indoor air quality (IAQ) since in the latter case, a number of added parameters should have been recorded, such as volatile organic compounds,

summer 2015 until spring 2016. This recording interval was selected in order to have a high resolution measurement and so to capture the short term temperatures fluctuations.

The loggers were installed by the researcher, with the permission of the occupants, and were located within the house carefully avoiding heat sources or direct sunlight. Careful attention has been placed to ensure that the loggers would not interfere with the occupants' daily life (such as, cleaning) and so to ensure that they would not disrupt normal living activities. For instance, loggers have been attached with blue tack on the back side of furniture. In addition black tape was used to cover the intermittent light from loggers that may disrupt bedroom darkness at night.

Due to the limited internal memory of the recording devices, data from the loggers had to be downloaded regularly. This resulted in a close control of both placement and reliability of the sensors.

(b) Spot measurements were collected just once, during the second survey in August 2015 (see data collection timeline in fig. 4.7, later in this chapter).

The spot measurements formed part of a full thermal comfort survey, which included a thermal comfort sensation questionnaire, Q2 (see section 4.3.1.3 below). The environmental parameters have been measured using a Dantec Dynamics 'ComfortSense' system, which is compliant with EN13182, ISO7726 and 7730, and ASHRAE Standards 55 and 113 [ISO, 1998; BSI, 2002, 2005, ASHRAE, 2013a, 2013b] (see table 4.3). The recorded environmental parameters were (a) air temperature ˚C; (b) operative temperature ˚C; (c) relative humidity % and (d) air velocity (m/s) at three different heights (foot, core and head).

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formaldehyde, carbon monoxide, nitrogen dioxide, particles, mites, bacteria, fungi, radon, ozone, semi-volatile organic compounds in dust, carbon dioxide and air exchange rate. Protocols for data cleaning and preparation for analysis is been detailed in Chapter 5.

Table 4.2 Technical specifications of the HOBO sensors [ONSET, no date a, no date b]

(a)	(b)
HOBO 64K Pendant Temperature Data Logger *UA-001-64*	HOBO Temperature/Relative Humidity/2 External Channel Data Logger *U12-013*
	
Measurement range **Temperature:** -20° to 70°C	**Measurement Range** **Temperature:** -20° to 70°C **RH:** 5% to 95% RH
Accuracy [a] **Temperature:** ± 0.53°C	**Accuracy** [a] **Temperature:** ±0.35°C **RH:** ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5% External input channel: ± 2 mV ± 2.5% of absolute reading
Resolution: **Temperature:** 0.14°C at 25°C	**Resolution** **Temperature:** 0.03°C at 25°C **RH:** 0.05% RH
Response time in airflow of 2 m/s **Temperature:** 10 minutes, typical to 90%	**Response time in airflow of 1 m/s** **Temperature:** 6 minutes, typical to 90% **RH:** 1 minute, typical to 90%
Time accuracy [b] ± 1 minute	**Time accuracy** [b] ± 1 minute
Operating Range **(in air)** -20° to 70°C	**Operating Range** -20° to 70°C; 0 to 95% RH (non-condensing)
Weight: 15 g **Dimensions:** 58 x 33 x 23 mm	**Weight:** 46 g **Dimensions**: 58 x 74 x 22 mm
[a] For the temperature range of 0-50 °C	
[b] At 25 °C	

Table 4.3 Technical specifications of the Dantec Dynamics 'ComfortSense' system [Dantec-Dynamics, no date a, no date b]

ComfortSense main frame  Anemometer channels up to 16 Output channels 2 (monitoring channel 1 & 2) Interface USB 2.0 Built-in A/D converter, 16 bit, 250 kS/s
Probes  ***Robust Velocity and Temperature onmidirectional probe*** Velocity range: 0.1 - 30 m/s Accuracy: 0.2 - 20 m/s: ± 2% - 20 - 30 m/s: ± 5% Time constant – velocity: Typically 2-3 sec. Time constant - temperature Typically 4-5 sec. Temperature compensation error on velocity, in the temperature range 0ºC to 45ºC: less than 0.2% of reading per 1°C change in air temperature Temperature reading range: -20ºC to +80°C Accuracy at velocities above 0.5 m/s, radiation excluded: ± 0.5K
Humidity onmidirectional probe Humidity range 0 - 100% RH (Relative Humidity) Accuracy From 0 to +10°C: +2% RH From 10 to 30°C: +1.5% RH From 30 to 45°C: +2% RH Dynamic response Time constant 10 minutes. 90% response: 30 minutes (when air velocity less 0.1 m/s) Stability. Typical values in normal air. Drift less than 1% RH per year and 0.1 K per year
Operative temperature onmidirectional probe Temperature range 0 to 45°C Accuracy From 0 to 10°C: ±0.5 K From 10 to 40°C: ±0.2 K From 40 to 45°C: ±0.5 K Dynamic response Time constant 2 minutes 90% response: 7 minutes (All values established in environment with air velocity less than 0.1 m/s)

4.3.1.2 OCCUPANT QUESTIONNAIRES

Occupancy feedback is central to this study and instrumental to better understanding the actual building performance in relation to the designer's intentions and the user's response to the house design and equipment. The occupants' questionnaires used are of three types:

- Q1a, administered on the first home survey;
- Q1b, submitted at every seasonal home visit; and
- Thermal comfort sensation questionnaire Q2, submitted multiple times.

Questionnaire (Q1a)

During the first visit of each case study house, a questionnaire (Q1a) was submitted (see table 4.4 for rationale; complete questionnaire is in Appendix C). This questionnaire was aimed at collecting the background information of the dwellings and its tenancy. In particular, the questionnaire was meant to collect the following sets of information: (a) information about the dwellings and its tenancy (such as, tenure, occupancy, etc.); and (b) information about the physical environment (such as, microclimate, physical dimensions, etc.). This questionnaire was performed only once.

Table 4.4 Questionnaire Q1a rationale

questionnaire	aims	description	type of questions
Q1a Background information questionnaire.	Aimed at collecting information about the house and generic perceptions about the house. It is submitted only on the first survey, with the input of the researcher Total of 1 questionnaire per house.	Questions from 1 until 9 were aimed at collecting physical information about the house. These questions regarded general information about the physical house, such as location, microclimate, availability of solar control and type of building systems. They are obtained by asking the occupants and walkthrough. There is space for notes, schematic drawings.	Closed and open questions
		Questions from 10 until 26 were aimed at describing the household background. These questions are aimed at understanding both the demographic of the household (gender, age, occupancy, etc.). Also it seeks understanding on the spaces available and their effective occupancy (hourly and week/weekend distinction). There are also questions regarding the background of the occupancy, their normal use of heating and their generic perception of comfort in their homes.	Closed questions
		Questions from 27 until 31 were aimed at collecting the occupants overall opinion about the house. These questions are intended to explore the relationship of the occupant with the house in terms of enjoy/delight. These are intended to explore the broader comfort of the occupants (likes/dislikes, troubleshoots, the appropriateness of the home design in general,)	Open questions
		Questions from 32 to 33 were looking at the health conditions of the homes. Designed to spot any health issues that might be the result of poor indoor environmental quality.	Closed and open questions
		Questions from 34 until 35, were aimed at collection information about the overall opinion about comfort, in order to spot any uncomfortably warm temperatures in different periods of the year and where in the house.	Closed and open questions

This questionnaire included some open questions in order (a) to enable participants to provide more detailed and insightful answers by thus providing a richer picture of a topic [Bryman, 2015]; and, (b) to enable the researcher to spot unforeseen issues in the building performance [Stevenson, 2008]. Box 4.2 above referred to a personal experience in which open questions enabled the identification of an unanticipated problem.

BOX 4.2- The value of open questions in occupant's questionnaire

When performing post occupancy evaluation in a multi-storey residential building in Wales, prior to commencing the doctoral programme, the researcher realised that the deployment of open-ended questions revealed that occupants were unable to store chocolate in their kitchen cabinets all year around due to excessively high temperatures inside the building in some periods of time. Likewise, the rubbish had to be cleared one or twice a day due to bad odour. After further inspection, it was clear that the (whole building) domestic hot water pipes distribution (running all year and located in the main building corridor, nearby the apartments' kitchens) was transferring heat to the adjacent kitchen flats.

Questionnaire (Q1b)

In addition, during the first visit a second questionnaire (Q1b) was submitted (see table 4.5 for rationale; complete questionnaire is in Appendix C). The same questionnaire was then repeated seasonally. This questionnaire was aimed at collecting *overall* seasonal information, relating to (a) what occupants thought of their thermal environment and (b) how occupants adapted/interacted with their thermal environment (CLO, controls, technology, etc.).

The purpose of repeating this questionnaire seasonally was to check whether the opinions of those living in the case study HIHs changed over time. This way it was also checked whether there was any problem in the design and whether or not the occupants' response accounted for the 'forgiveness' factor, namely, for the fact that "*occupants tolerate less than perfect conditions because they like the overall feel and design quality of a building*" [Nicholls, 2008, p.282].

Table 4.5 Questionnaire Q1b rationale

questionnaire		description	Type of questions
Q1b Seasonal comfort	Aimed at collecting seasonal information about comfort. It is submitted in every visit Total of 5 questionnaires per house.	Questions from 1 to 9 were aimed at listing the conditions before, during and after the interview. These questions record the environmental condition at the start of the interview.	Closed questions
		Questions from 10 to 11 were aimed at collecting information abot the comfort during hot weather. These questions explore the air motion practices for cooling in the homes (via windows, fans and air conditioning units).	Closed, and one open question for additional comments from occupants.
		Questions from 13 to 16, focused on comfort during this time of the year, looked into when and where in the homes the uncomfortably warn temperatures are difficult to keep cool.	Closed, and one open question for additional comments from occupants.
		Questions from 17 to 19 Controls (interaction user-house) Exploring the adaptive capabilities that occupants have through their given environment: their interactions with windows, systems, blinds, etc.	Closed, and one open question for additional comments from occupants.
		Questions from 20 to 23 explored occupants' behaviour (interaction user-adaptive behaviour) by looking at the adaptive capabilities that occupants are undertaking to keep comfortable, from clothing to systems.	Closed questions

4.3.1.3 THERMAL COMFORT SURVEY

The approach adopted in this research project also combined detailed subjective data gathering with objective environmental monitoring of indoor and outdoor thermal conditions in people's homes.

Occupant's questionnaire (Q2)

The subjective monitoring was conducted through the thermal comfort questionnaire (Q2) (see table 4.6 for rationale; complete questionnaire is in Appendix C). This questionnaire asked information about activities and behaviours immediately prior to, as well as at the time of, completion. This enabled the researcher to estimate the closeness to steady state conditions. In addition, this questionnaire was instrumental to gather information about the use of air motion devices (inclusive of windows, doors and equipment) and the proximity (distance and direction) of the participant to those devices. Moreover, the questionnaire collected information about the presence or absence of any solar radiation incidence upon parts of the participant's body.

BOX 4.3 – Thermal comfort pilot in Brazil

Prior to commencing the longitudinal monitoring, the researcher took part in an academic exchange in Brazil. There, access to a rural development provided an opportunity to test Q2 in a hot-climate context. When the residents were asked to rate their comfort feeling in a 1 to 7 scale (ASHRAE thermal comfort scale), a resident had difficulty translating their comfort 'state' into a numerical scale. The only response obtained was "*feliz da vida*" (literal translation: "happy about life"), which reflected a general feeling of satisfaction. While bringing up questions about the global applicability of a comfort scale (especially with regards to the cultural obstacle to numerically 'rate' things, this response gave an insight into the psychological component of satisfaction.

The questionnaire was designed to be submitted remotely and at multiple times during the study. Paper-based versions were provided to two case study HIHs where online questionnaire submission was not a viable solution for the occupants.

Table 4.6 Questionnaire Q2 rationale

Q2 Subjective right now thermal comfort sensation questionnaire	Aimed at collection right now thermal comfort responses. The questionnaire was submitted online (by paper if internet was not available) several times during the study. The total responses are different per each house.	Questions from 1 to 4, aimed at knowing the demographics of the respondent. Questions from 5 to 6, aimed at knowing the clothing (different for female and men) of the respondent. Questions from 7 to 9, aimed at knowing the activity (15 minutes prior and during questionnaire completion) of the respondent. Questions from 10 to 19 Right now thermal comfort questions for respondents: • ASHRAE scale • air movement feeling (in different parts of the body) • actions to keep cool • Position in respect to windows and doors • Any solar radiation in different parts of the body.	Closed questions

4.3.2 STAGE 2: INTERVIEWS WITH ARCHITECTS AND DESIGNERS

This activity was intended to investigate the contribution of the design process of the case studies in their thermal performance and in their contribution to overheating. This investigation was performed by interviewing the designers involved in the case studies of the present research. Typically, two designers two for each case study were interviewed. The interviews were carried out face-to-face for just over one hour.

Due to the nature of the design process, qualitative research, in the form of semi-structured interviews to architects and designers, was used in order to complement the data derived from POE. The interview guide[44] was formulated by considering literature regarding guidance on sustainable buildings design [Lewis, 1999] and the available literature on overheating avoidance guidance [Dengel and Swainson, 2012; NHBC, 2012b]

The interviews to the designers and architects took the form of semi-structured interviews. A semi structured interview consists in a list of questions relating to specific subject to be covered. The questions may not follow an exact structure (like questionnaires). This way, the responses result from a less constrained structure [Bryman, 2015].

The objectives behind semi structured interviews are to gain knowledge on:

- How architects and designers assume their designs to perform once built? What do they know?
- What do architects and designers assume occupants to do to achieve and control thermal comfort?
- Do architects and designers have the knowledge to avoid overheating?
- How architects and designers relate to the standards and regulations of energy efficient design?

In order to obtain responses concerning the issues of whether overheating (a) is the result of lack of knowledge, a fragmentary process of design or of construction etc., (b) or it is a problem of decision-making and control over the project, or (c) it is a problem

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[44] In a semi-structured interview, the researcher has a list of topics to be covered - this is often referred as *interview guide* since questions might not follow an outlined schedule in order to allow flexibility within a fixed framework [Bryman, 2015].

of occupant behaviour, it was necessary to develop a framework that could sustain and guide the questions to the designers.

In creating the framework that directed the questions, they were considered both the factors influencing the thermal performance of buildings in general and the dynamics in which overheating occurs. Such dynamics was attributed in previous chapters to (a) external heat gains (sun, UHI), (b) internal heat gains (occupancy, appliances) and (c) inadequate ventilation [Dengel and Swainson, 2012]. The resulting framework developed in detail in Chapter 6, channelled the formulation of the interview guide.

The rationale of the questions structuring the semi-structured interviews was that of looking at how overheating in the design phase can be prevented and what can be improved. The questions were presented in a generic fashion, by so allowing the interviewee to the chance to elaborate on their views and express themselves freely. The questions contained a number of prompts, though. Those prompts were purported to direct the conversation with the interviewees and so to ensure that the information needed could be obtained (see table 4.7).

Table 4.7 Semi structured interview questions to architects and designers

QUESTIONS		EXPECTED INFORMATION OBTAINED
Q1:	Can you please tell me a bit about your background as a designer and your role in this case study?	knowledge
Q2:	What do you think is(are) the most important factor(s) in thermal design of homes	knowledge
Q3:	What triggered the project of this case study?	process of case study
Q4:	Can you take me to the design process of this case study? How do you start the design of this energy efficient house?	knowledge and of the design process
Q5:	Do you know how the house is performing? Why? – If not, how do you think the house is performing?	process (do designers go back to learn?)
Q6:	Were all decisions taken at the design stage (especially those having a thermal effect) implemented in the construction phase?	process & control of the built process
Q7:	Did you produce any document (handed to the client/developer) that would explain the occupant how to interact with the house?	process
Q8:	In your experience, do you try to avoid overheating, if so how?	knowledge, of the process & tools employed
Q9:	In your experience, has the role of architects changed in consideration of the requirement of more energy efficient homes?	process
Q10:	Researcher questions about the house	process and knowledge
Q11:	Do you have any questions about the house?	

4.3.3 STAGE 3: REALITY MODELLING: PROCESS MAPPING

In order to describe the reality in which overheating occurs, it was considered necessary to adopt a model system that reflected both (a) the complexity of building thermal performance (as a result of materials, layout, user behaviour, microclimate, and urban considerations) and (b) the information and knowledge to date about that reality and the flow of information from the initial requirements and the concept design of such dwelling until its delivery to residents.

In order to model such a complex system, the discipline of systems engineering provided the methodologies able to model organisms, organisations and structures. Some of these methodologies rely on traditional methods, such as data flow diagrams; other methodologies instead rely on methods specifically developed in recent years for manufacturing. The method chosen - IDEFØ (Integrated computer-aided manufacturing definition methodology) - belongs to the latter category: IDEFØ is a functional modelling language addressing information models and database design issues [Ang *et al.*, 1997].

So far IDEFØ has successfully been used to assess post occupancy in schools [Hassanain and Iftikhar, 2015], with the intention to represent the sequential processes (or steps) conducted in post-occupancy evaluation and enabling to identify defects and remedial actions, comprehension of consequences of decisions made during the design, and operation of school facilities. In the context of this work, IDEFØ is used to facilitate the legibility of the POE conducted, as it illustrates the interactions between activities in terms of inputs and outputs.

For the purpose of the present study, IDEFØ provides a structured analysis methodology that is capable to graphically represent the functional relationships in the different stages of the building process[45]. In this study, IDEFØ enabled the researcher to triangulate data about the physical reality (from POE, with data of both quantitative and qualitative nature) and the outputs of the interviews with designers, by so linking prediction and performance.

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[45] However, other means of structured analysis, such as IDEF3, were also considered. Whereas IDEFØ is a methodology for function modelling, IDEF3 is developed for process description capture. IDEF3 was considered because it provides a temporal perspective of a process, allowing implementing a solution. IDEFØ, by contrast, focuses on the output of a process to ensure the design is purposive.

4.3.4 STAGE 4: FOCUS GROUP

The previous paragraphs illustrated how the problem of overheating[46] in HIHs in the UK is explored in this research, i.e. by monitoring four HIHs across England (*stage 1*) and by interviewing members of the design teams of those homes (*stage 2*) in the attempt to look how the design process of HIHs could be improved to avoid overheating. Especially in consideration of the fact that this problem has often been analysed by looking at the factors contributing to overheating, thereby isolating the parts of the problem, this study has attempted to reconnect the missing links of the processes leading to overheating (*stage 3*). This objective has been pursued by making use of a process mapping tool (IDEFØ). The conviction behind this choice is that the main physical factors contributing to overheating may be overlooked at the design stage. The assembled output corresponded to an 'overheating map'.

So, in order to validate this attempt to reassemble a hitherto scattered process of housing design, *stage 4* has been implemented. Through this stage, feedback has been gained about the usability of the 'overheating map' through a focus group.

The focus group is a specific interviewing technique, with at least four participants, in which a specific theme is explored in depth [Bryman, 2015]. The most important feature of a focus group is that, in contrast to the process of one to one interview, in a focus group an individual has the opportunity to answer in a certain way but at the same time to listen to other people responses. As a result, a participant may change their view during the focus group. This means that focus groups allow for a joined construction of meaning [Bryman, 2015].

During the focus group carried out as part of this research, a brief background of the process mapping methodology was presented by the researcher. Then, the audience, divided into 5 groups of two people each, was invited to reflect and elaborate on the map presented in order to propose a more generic 'overheating map'. After that stage, the audience commented on their maps as well as on the usability and appropriateness

[46] The conceptualisation of overheating in HIHs as an issue of "under-cooling" (as shown in the conclusions of Chapter 3 – Dimensions of Overheating served the purpose of provide a nature (or dimension) of this problem and hence disconnect it with an issue of possible future climate change overheating. Then, throughout the thesis the term overheating has been kept to provide consistency with academic publishing. The word overheating is maintained throughout this thesis in order to keep terminology consistency with the published studies.

of the chosen process map methodology (IDEFØ map). Finally, the findings of the discussion were analysed and the feedback obtained provided suggestions for improvement of a possible 'overheating aiding tool'.

4.4 RESEARCH PLAN

4.4.1 SAMPLE

The type of sampling used for the HIHs surveyed in this study has been variegated and representative of the British housing stock. Academic contacts have been used to identify recently completed HIHs. In particular, the researcher has relied on the connections the housing industry that the Institute of Energy and Sustainable Development (De Montfort University) has in the Midlands and in Yorkshire.

This capitalisation of opportunities, which is referred by Bryman [2015] as *opportunistic sample*, has also been facilitated by the IESD connections with social housing providers and housing trusts, which have granted access to the case studies.

The fact that among all the housing association's houses only highly insulated buildings have been included in the study defines the sampling used in this research project as a *purposive sampling*. Purposive sampling is a non-probabilistic form of sampling [Bryman, 2015].

The sample size has been determined in light of the availability of time and resources for a longitudinal study. In that respect four case studies should be considered a manageable quantity. The four case study HIHs are located in England and are of different typology, orientation, design strategy). As a result, they have provided as much diversity as possible within a HIHs group.

Likewise, each HIH formed part of a longitudinal study in which the houses were visited five times. The number of visits is justified by the need to download data from the recording loggers and to submit a questionnaire to the occupants in each season of the year (in addition to the first visit questionnaire). See table 4.8., where it can be noticed that a house UK53 is missing (because the residents dropped out of the study just prior to the first visit).

Table 4.8 Case studies composition

	Coded name	house type	location
Case study 1	**House UK51**	Retrofit Victorian terrace	Leicester (UK)
Case study 2	**House UK52**	New Passivhaus-like bungalow	Sandiacre (UK)
Case study 3	**House UK54**	New highly insulated end of terrace	York (UK)
Case study 4	**House UK55**	New highly insulated detached	York (UK)

As to the interviews of designers, the sample size has been directly related to the number of houses. Members of the design team of the Yorkshire development did not respond to the requests to interview them, though. By contrast, an architect from a Passivhaus development in Leicester accepted to give an interview (see table 4.9). This last interviewee was suggested by one of the previous interviewees (*snowball sampling*). The sampling is then composed as follows:

Table 4.9 Interviewees list

	Coded name	role in case study	background
From case study 1	**D1-UK51**	Project initiator	designer and planner
From case study 1	**D2-UK51**	Specification consultatnt	building surveyor
From case study 2	**D3-UK52**	Passivhaus consultant	physicist
From case study 2	**D4-UK52**	Design architect	architect
Linked to case study 2	**D5**	Project manager	architect

As to the focus group, its aim consisted in gaining feedback from a specialised audience. For this reason, the group size had to be controlled. The typical size of a focus group is six to ten members [Bryman, 2015]. In this case, to control both participation and management of responses, ten participants (from a specialised audience of designers, both engineers and architects) were invited (see table 4.10).

Table 4.10 Specialised audience designers, academics and industry participants.

Coded name	background		architecture	engineering	Housing association
FGP1	designer	academia and industry	1		
FGP2	architect	industry	1		
FGP3	engineer	academia		1	
FGP4	engineer	industry		1	
FGP5	housing provider	industry			1
FGP6	engineer	academia		1	
FGP7	engineer	academia		1	

4.4.2 ETHICAL CONSENT AND RISK ASSESSMENT

The research obtained ethical approval as requested by the internal regulations at De Montfort University. In addition, written consent has been obtained from all the participants involved in the study prior to data collection. The information letter and consent forms can be found in Appendix B.

> *BOX 4.4 – Ethical consent, the South American experience*
>
> During the doctoral programme, the researcher conducted two distinct sets of interviews in South America: one in Brazil (2015) and one in Perú (2016). In both cases, ethical consent was required by the De Montfort University's protocols to ensure transparency and information to the respondents. In Brazil, the host professor introducing to the case study suggested that the researcher should not ask for signed consent, because this fact alone would have generated suspicion in the respondents. In lieu of the respondents' signed consent the researcher obtained of the Brazilian professor who took the time to explain the respondents what the research was about. In Perú the same problem was experienced.. But in this case, the interviews were preceded by a recorded audio consent.

4.4.3 PROJECT MANAGEMENT

The table below summarises the study timeline, evidencing both (a) the period of data collection and (b) the events that have influenced the study design. Note that the period of POE has been zoomed to show details of activities within it (fig. 4.9).

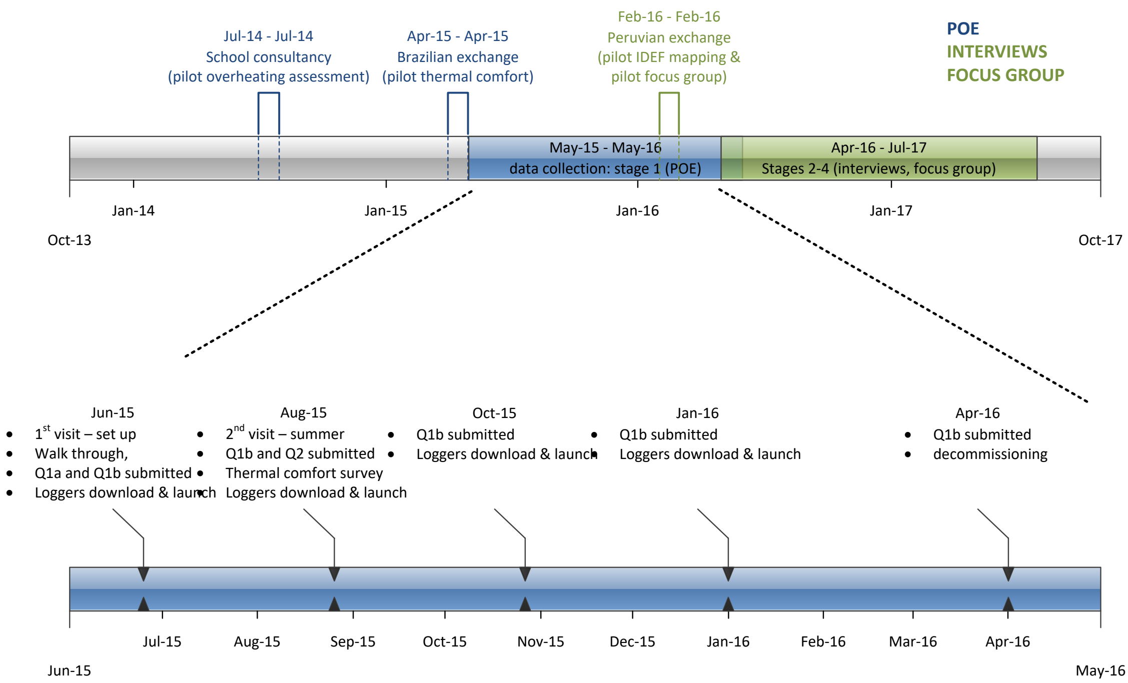


Fig. 4.9 Study timeline

4.5 VALIDITY

As stated earlier in this chapter, the present research embraces a pragmatic philosophy that combines diverse approaches that proved to be effective in similar contexts. Such approaches value both objective and subjective knowledge from the natural sciences, social sciences and humanities realms. As such, the quality standards relate to each method and approach used.

4.5.1 OBJECTIVITY (QUANTITATIVE APPROACH RELATED)

The quality standards of a post-positivist system of inquiry are listed by Groat & Wang. The validity of the post-positivistic paradigm is based on the truthful representation of the object of study (objectivity) and its applicability to a larger world. In this process, bias can be avoided by the use of standardised/calibrated equipment [Groat and Wang, 2002].

In the present study, the quantitative aspects related to the environmental monitoring involved in the post-occupancy evaluation have been calibrated and the thermal comfort survey have been performed according to the ASHRAE Standard 55 [ASHRAE, 2013a].

4.5.2 TRIANGULATION AND REFLEXIVITY (NATURALISTIC APPROACH)

From the standpoint of a naturalistic paradigm (in accordance to which there is "no value-free objectivity") data and its interpretation should be confirmable rather than objective. Confirmability is achievable through a combination of triangulation and reflexivity. While triangulation is achieved by the use of multiple methods and sources, reflexivity requires the investigators to reveal their epistemological assumptions, their influence on the framing of the research questions and any changes in perspective that might emerge during the study [Groat and Wang, 2002].

In the present study, the method itself is treated as a tool for triangulating results and, hence, for showing that sets of information acquired from different sources (interviews, documents, observations, etc.) point in the same direction [Yin, 1993, p.69].

4.5.3 CONSTRUCT VALIDITY (CASE STUDY RELATED)

A test of validity and reliability of the case study research design lies in its *construct validity*, which deals with the use of "*measures that accurately operationalize the* *constructs of interest in a study"* [Yin, 1993, p.39]. Construct validity is achieved through a strategy of multiple measures of the same construct.

In this study, a variety of measures have been taken into consideration to construct the problem of overheating. The study has also relied on a valid parallel with the *continuum of research paradigms* theorised by Joroff & Morse (see paragraph on architectural research paradigms at the beginning of this chapter). On such view, different degrees of systematisation characterise the different research methods and consequently the research construct [Joroff and Morse 1984, cited in Groat and Wang, 2002, p. 29].

The present study, in sum, deploys different methods depending on whether the realm of systematisation is social or physical.

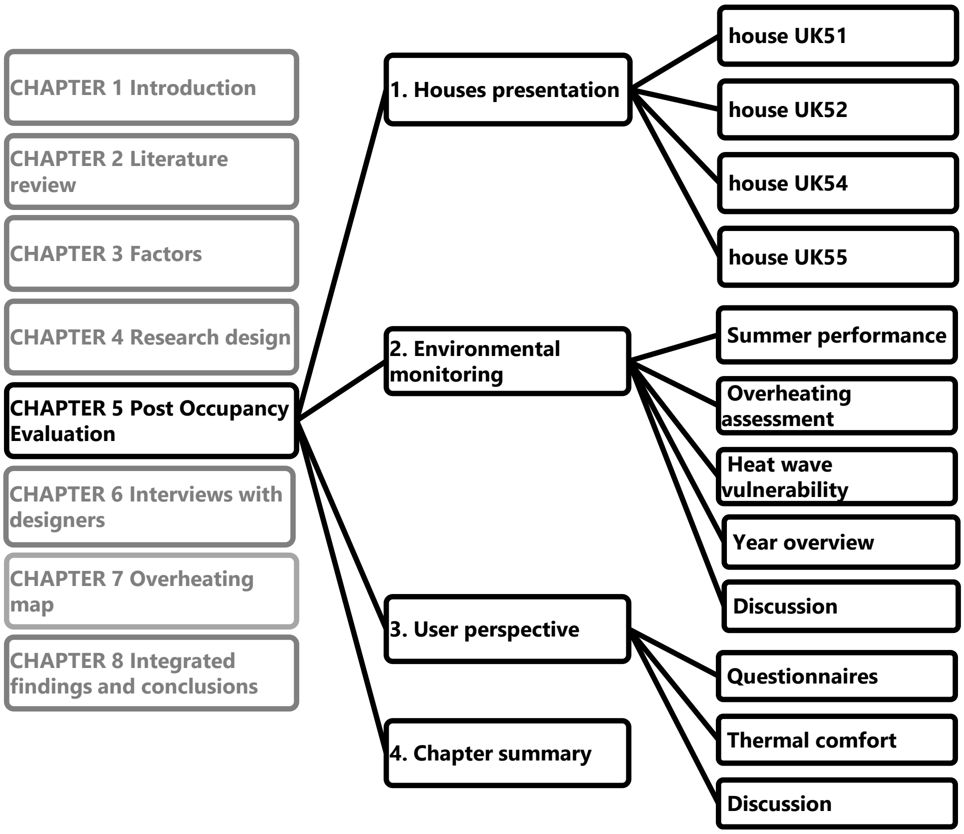
4.6 CHAPTER SUMMARY

This chapter has characterised the thesis as a transdisciplinary study carried out within the research paradigm of **pragmatic critical realism**. On this basis it has been concluded that a descriptive and explanatory multiple case study mixed methods approach to research and data collection best suits the exploration of the risk of overheating in HIHs and enables one to gain an understanding that other methods cannot secure.

In the context of this work, the reliance on a mixed-methods approach of data collection is not understood as a mere combination of a variety of diverse methods - each informed to a different rationale. By contrast, those different methods are contextualised in a broader and overarching framework, via the implementation of a four stage-method of collection (described in section 4.3) Finally, sections 4.4 and 4.5 have listed the details of the research plan and the validity of the paradigms adopted.

Based on the methodological premises set out here, the next three chapters will present analysis and findings of this research. Chapter 5 will deal with the physical arrangement of the case study HIHs, Chapter 6 will discuss the findings of the interviews to designers, and Chapter 7 will triangulate those findings by breaking them into a process map, then validated via a focus group.

CHAPTER 5: POST-OCCUPANCY EVALUATION



Synopsis

This chapter is predominantly concerned with the real-world component of the present research and, especially, with the overheating-related the performance of HIHs.

The chapter begins with the detailed presentation of the four case studies. It then moves to introduce the data collected by means of longitudinal temperature recordings, questionnaires, and the thermal comfort survey.

The chapter then provides evidence of overheating, and a tentative explanatory reason for this, by looking at the temperature recordings in different ways, by applying standard methodologies for overheating assessment, and by asking questions to the occupants of these HIHs. This combination of both objective and subjective measurements is aimed at determining the likelihood of overheating and the sources of overheating risk.

The findings will support the conclusion that overheating occurring in some of the houses. Accordingly, the first research question, namely *Do HIHs provide a comfortable indoor environment for their occupants?*, finds an at least partially negative answer. In this context, it was found that HIHs in this study are characterised by a number of factors increasing the risk of overheating. Likewise importantly, the outcomes of this chapter will contribute to the overheating map, as developed later in Chapter 7.

5.1 CASE-STUDY HOUSES PRESENTATION

As stated in Chapter 4, this research is based on a multi-case study research aimed at gaining real-world knowledge. The quality of the research is both descriptive and explanatory, since this work both describes the thermal behaviour of HIHs and provides a tentative explanation of the occurrence of overheating in HIHs.

In this study, four English super-insulated houses are taken into consideration as cases study (see fig. 5.1). The houses selected for this study present substantial differences (in terms of context, typology, layout, orientation, materials). As a result, the research has the potential to examine the phenomenon of overheating in HIHs in different contexts.

Fig. 5.1 Location of case study houses across England

5.1.1 HOUSE UK51

The first case study – House UK51 - is a Victorian terrace house from the late 19th century located in Leicester. This typology of house constitutes one of the most widespread archetypical houses in urban areas of the UK. Its layout is organised in terms of a front room and a rear room over two floors. Traditionally, it is built on solid brick walls with a narrow front and deep layout, a relatively large space standard, no insulation, and high levels of air leakage.

Fig. 5.2 East façade view of the Victorian terrace (late 19th century) retrofitted to Passivhaus-like standards UK51

Terrace house rows are part of the characteristic UK *urbanscape,* with its externally rendered brick walls.

Fig. 5.3 Aerial view of house UK51 location in the urban context of Leicester

This east-facing pre-1919 property was completed with a rear addition for the kitchen and bathroom. It is constructed with 230 mm solid brick walls and has a traditional cut rafter roof with a slate covering. The right-hand ground floor wall is exposed to a passageway shared with the neighbouring property. The ground floor throughout the property has been upgraded to concrete and insulation, with the first floor being of suspended timber. This house is owned and managed by a registered social landlord in the Midlands[47].

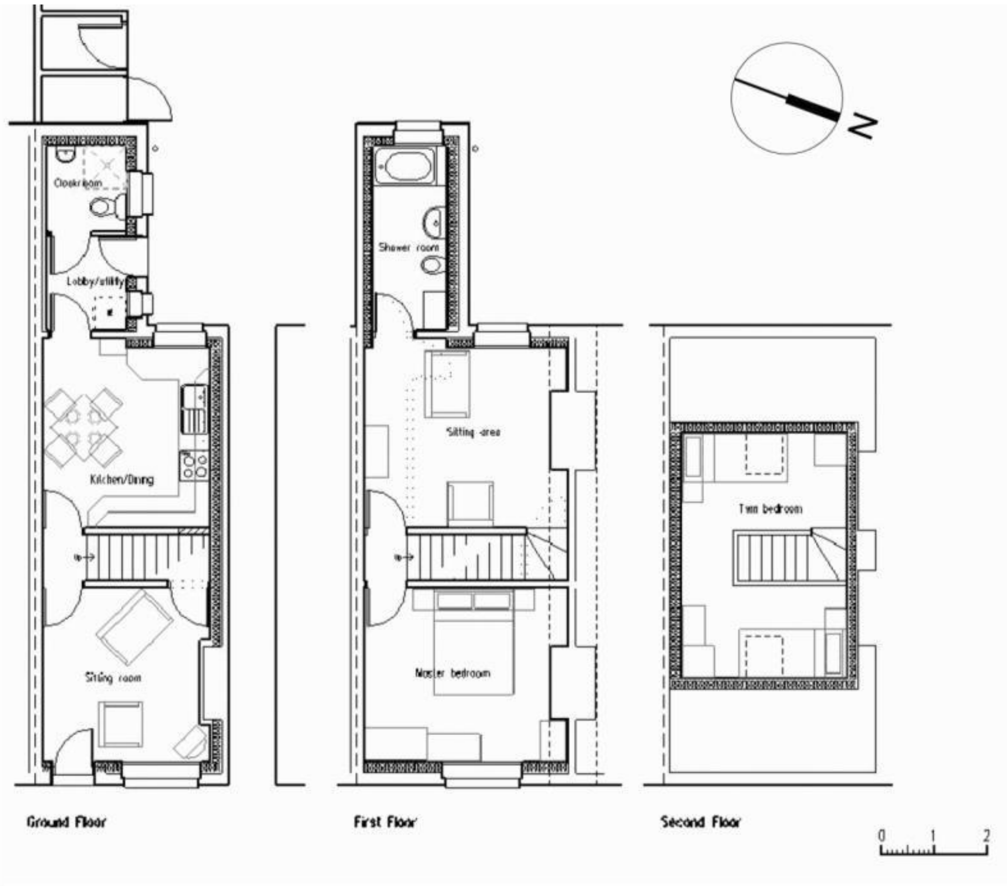


Fig. 5.4 Plans UK51

Pre-1919 dwellings adds up to 21% of the English dwelling stock [MHCLG, 2015c]. On the assumption that new housing in the UK will supplement, and not replace, the old stock, refurbishing such houses is a reasonable and straightforward way to reduce the overall CO_2 emissions from buildings.

[47] It is known that around 20% of the UK housing stock is social housing, and within this, around 350,000 properties are pre-1919 (as of this terrace age band) [MHCLG, 2015c]

In 2010, this terrace house underwent an extensive refurbishment [Crilly *et al.*, 2012], which was aimed to meet the requirement of 80% reduction in carbon emissions and was focussed on a fabric first approach.

This project is retrofitted to near Passivhaus standards, following Passivhaus principles and using PHPP as a tool for the calculation of the energy performance. In this project, walls are internally insulated (U=0.12 W/m^{2}K). On the front side, new high-performing wood-framed sash windows are used to guarantee reduced energy dispersion, security and effective summer ventilation. In addition, to reduce infiltration, a vapour barrier to well below new build Part L maxima has been implemented.

The PHPP verification document retrieved shows that the Passivhaus standard is not met. It seems worth noting that at the time of the retrofit was undergoing EnerPHit was not available (fig. 5.5).

Specific Demands with Reference to the Treated Floor Area

	Applied:	Monthly Method		PH Certificate:	Fulfilled?
Treated Floor Area:	91.2	m^2			
Specific Space Heat Demand:	12.9	kWh/(m^{2}a)		15 kWh/(m^{2}a)	Yes
Pressurization Test Result:	4.6	h^{-1}		0.6 h^{-1}	No
Specific Primary Energy Demand (DHV, Heating, Cooling, Auxiliary and Household Electricity):	61.6	kWh/(m^{2}a)		120 kWh/(m^{2}a)	Yes
Specific Primary Energy Demand (DHV, Heating and Auxiliary Electricity):	38	kWh/(m^{2}a)			
Specific Primary Energy Demand Energy Conservation by Solar Electricity:		kWh/(m^{2}a)		CO_2 kg/m2	14.7
Heating Load:	7	W/m^2			
Frequency of Overheating:	0	%	over	25 °C	
Specific Useful Cooling Energy Demand:		kWh/(m^{2}a)		15 kWh/(m^{2}a)	
Cooling Load:	5	W/m^2			

We confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The calculations with PHPP are attached to this application.

Issued on:

signed:

Fig. 5.5 PHPP verification sheet of UK51

There is a distinctive part of this project that consists in the off-site manufactured roof pod (see figg. 5.6 and 5.7). The roof pod provides an additional room in the roof. The proposal reads "*an internal insulation solution was chosen, and the consequent loss of floor space compensated for by adding an attic pod manufactured off-site. The pod provides a second-floor bedroom with warm roof, and whole-house ventilation services preinstalled. This is both an innovative solution to replacing floor space lost due to internal insulation and (by providing an extra bedroom) enables an additional sitting room on the first floor to meet local cultural needs*" [Project Cottesmore, 2009]. The attic pod, manufactured off-site, has a pre-installed MVHR unit in the roof space. The idea behind the prefabricated roof pod is to manufacture -in a controlled environment- a custom unit that uses the latest technology and low energy envelope with a warm roof with no thermal bridges.

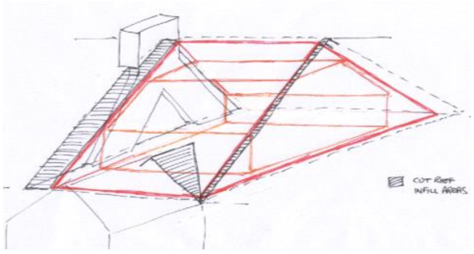


Fig. 5.6 Roof pod early sketches.

Fig. 5.7 Roof pod installation on-site

BUILDING SYSTEMS

The provision of fresh air is achieved via MVHR. In this case, no provision for summer bypass is in place. Each inhabitable room has a supply air valve for fresh air provision and each wet room and kitchen is provided with an air extraction valve. Air extraction valves are located on the ground floor kitchen and the first-floor bathroom. There is a boost ventilation switch located in the kitchen. Energy demand for heating (which was substantially reduced after refurbishment) is met via a condensing gas boiler system with traditional piped radiators.

Fig. 5.8 UK51 solar thermal: rear (left) and detail (right)

OCCUPANCY

Family members comprise a female adult, her brother with his wife, and their new-born child. The arrival of the baby occurred during the monitoring period and meant that the house was occupied at all times in at least one bedroom. Responses to questionnaires, as well as house details, were provided by the male occupant.

5.1.2 HOUSE UK52

The second case study – House UK52 - is a bungalow, built in 2013 and part of a redevelopment in Sandiacre, near Nottingham (see fig. 5.9). This house typology (see fig. 5.10) is less common than traditional terraces; in fact it constitutes about 9% of all dwelling types in the UK [MHCLG, 2015c]. The layout is developed on one floor. The whole development is built to Passivhaus standards; however, as it is commonly the case due to financial reasons, only a few houses in that development are Passivhaus certified. Built to Passivhaus standards, the bungalow is *not* a certified Passivhaus.

Fig. 5.9 Aerial view of development where house UK52 is located in Sandiacre

Fig. 5.10 View of the uncertified Passivhaus bungalow UK52 (shaded the entrance facing west)

Fig. 5.11 Passivhaus development where UK52 is located

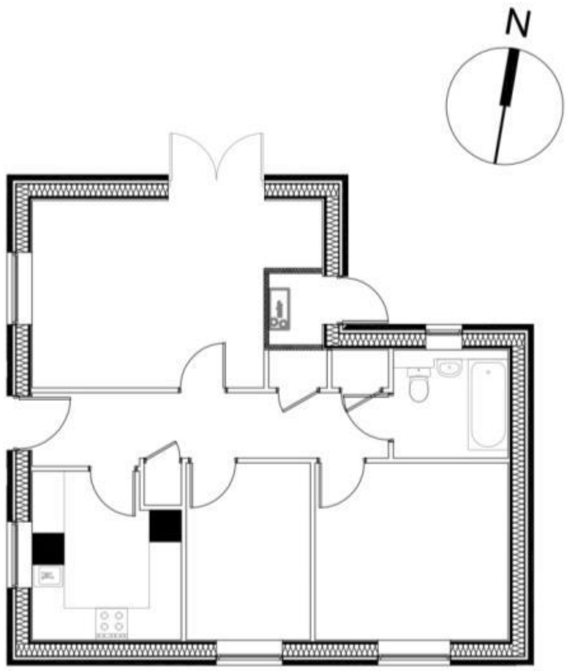


Fig. 5.12 Plans of UK52

This house is part of a large Passivhaus development owed by a housing association in the Midlands. The development aimed at achieving the Code for Sustainable Homes 4. This objective was pursued through a fabric-first approach. House UK52 is characterised by the use of lightweight materials, while external bricks and other features (such as the fake chimneys) were intended to adhere to the traditional idea of housing in the UK [interview with designer D3-UK52, 2015].

The PHPP verification document retrieved shows that the Passivhaus standard is not met. The achieving of the Passivhaus standard is here penalised by the typology (bungalow) and its high surface to volume ratio (fig. 5.13).

Specific building demands with reference to the treated floor area				use: Monthly method	
	Treated floor area	58.7	m²	Requirements	Fulfilled?*
Space heating	Annual heating demand	**33**	**kWh/(m²a)**	15 kWh/(m²a)	no
	Heating load	**13**	**W/m²**	10 W/m²	no
Space cooling	Overall specific space cooling demand		**kWh/(m²a)**	-	-
	Cooling load		**W/m²**	-	-
	Frequency of overheating (> 25 °C)	0.2	%	-	-
Primary Energy	Space heating and cooling, dehumidification, household electricity.	**143**	**kWh/(m²a)**	120 kWh/(m²a)	no
	DHW, space heating and auxiliary electricity	104	kWh/(m²a)	-	-
	Specific primary energy reduction through solar electricity		kWh/(m²a)	-	-
Airtightness	Pressurization test result n_{50}	**0.6**	**1/h**	0.6 1/h	yes
				* empty field: data missing; '-': no requirement	
Passive House?					no

We confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The PHPP calculations are attached to this application.

Name:	**Registration number PHPP:**
Surname:	**Issued on:**
Company:	**Signature:**

Fig. 5.13 PHPP verification sheet of UK52

BUILDING SYSTEMS

The provision of fresh air is operated via MVHR. In this case, no summer bypass provision is in place. Each inhabitable room has a supply air valve and the bathroom and kitchen are provided with extract air valves. There is a boost ventilation switch located in the kitchen. In addition, there is a heat-boost located in the living room to provide an extra level of comfort from the air supply valve.

OCCUPANCY

This house is occupied at all times by a couple of retired residents. The second bedroom is occasionally used by the couples' son. Responses to questionnaires as well as house details were provided by the female occupant.

5.1.3 HOUSE UK54

The third case study – House UK54 - is an end of terrace house, built in 2013 as part of an exemplar development in a suburban area in York. In that development high standards of fabric efficiency are combined with other aspects of sustainable community. The development is characterised by a modern design, which integrates non-traditional and passive architectural features such as balconies, loggias and sunspaces. This house combines the use of external bricks and an exposed internal thermal mass.

Fig. 5.14 Aerial view of development where house UK54 is located in York

Fig. 5.15 South street façade view of UK54

Fig. 5.16 Plans for house UK54

BUILDING SYSTEMS

In this house, the provision of fresh air is achieved via mechanical ventilation extract (no heat recovery) and so by extracting air from each room. Interestingly, the house's mechanical extract has been turned off by the occupants, who preferred to manually manage the provision of fresh air through the windows. In this house background ventilation is also provided in each window by trickle vents. This house has a traditional radiator system connected to the district heating in the development.

Fig. 5.17 UK54's mechanical ventilation system MEV (no heat recovery)

OCCUPANCY

This house is occupied at all times by a couple of retired residents. The second bedroom is occasionally used by the couples' daughter. Responses to questionnaires as well as house details were provided by both the male occupant and female occupant.

5.1.4 HOUSE UK55

The fourth case study – House UK55 - is a detached house, built in 2013 as part of an exemplar development in York, whose high standards of fabric efficiency are combined with other aspects of sustainable community. House UK55 is located in the same development as house UK54 and has the same fabric characteristics as house UK54.

House UK55 is characterised by its modern design, which integrates non-traditional and passive architectural features, such as balconies, loggias and sunspaces. This house combines the use of external bricks and an exposed internal thermal mass.

Fig. 5.18 Aerial view of development where house UK55 is located in York

Fig. 5.19 East street façade view of UK55

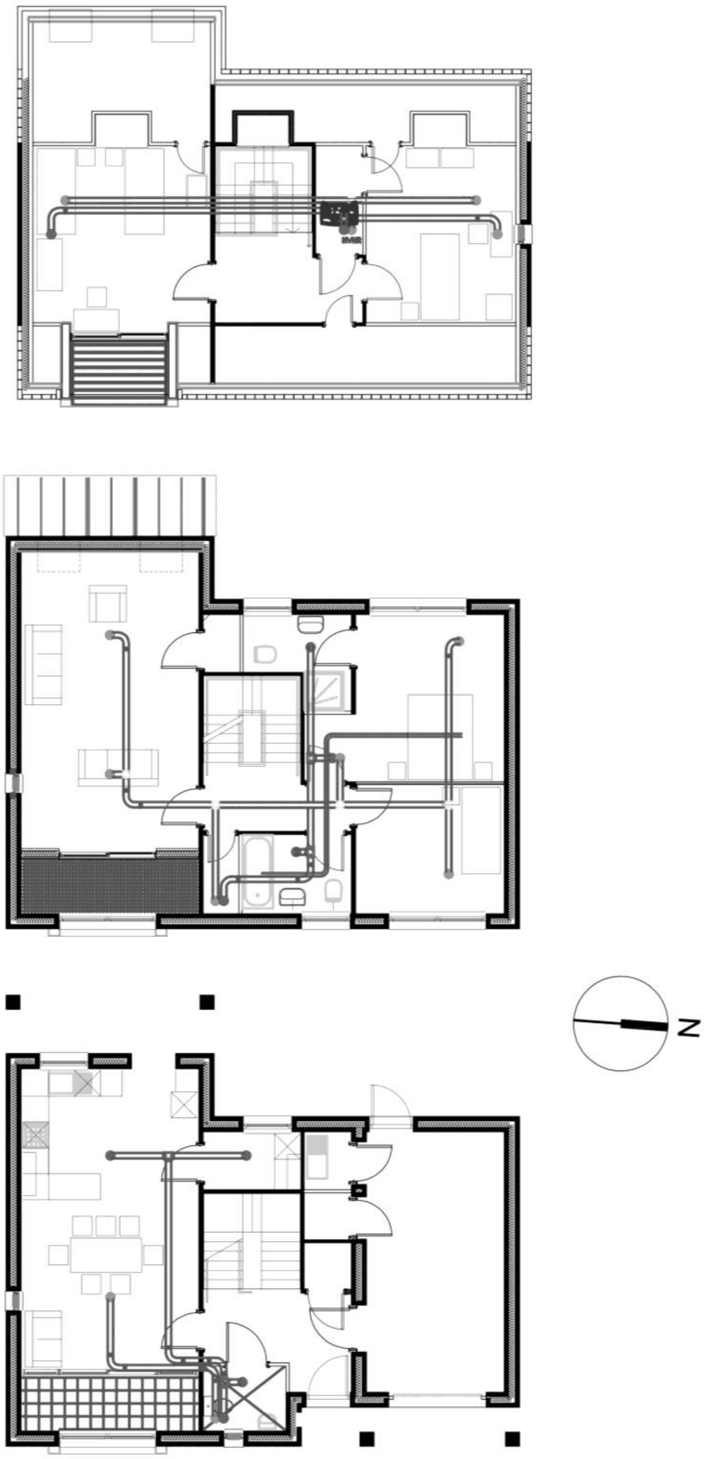


Fig. 5.20 Plans for house UK55

BUILDING SYSTEMS

The provision of fresh air is achieved via mechanical ventilation with heat recovery. In this case, no summer bypass provision is in place. Each inhabitable room has a supply air valve and each wet room and kitchen is provided with an extract air valve. Extract air valves are located in the ground-floor kitchen and the first-floor bathroom. This house has a traditional heating system connected to the district heating in the development. Unlike house UK54, house UK55 incorporates a sunspace (marketed as a “winter garden”)

Fig. 5.21 Sunspace: view from first floor living room

OCCUPANCY

This house is occupied at all times by a couple of retired residents. The second bedroom is occasionally used by the couples’ daughter. Responses to questionnaires as well as house details were provided by the male occupant, who happened to be an air flow engineer and, unsurprisingly, was engaged with the system (air flow control, filters maintenance, etc.). The occupancy in this house could be considered as vulnerable, because one of its occupants suffers from a neurological condition that may affect the perception of heat.

Fig. 5.22 Occupant showing to the researcher the filter component of the MVHR system

5.1.5 SUMMARY OF HOUSES

The houses are of different types, as presented in Table 5.1. None of the houses made use of any cooling devices such as fans or air conditioning units. It is worth noting that UK51 was the only house refurbished to a near-Passivhaus standard thermally.

Table 5.1 – Overview of case studies houses with main construction characteristics

House code	*House type & location*	*U-value ext. walls (W/m2.K)*	*Internal floor area / floor to ceiling high*	*Thermal mass exposed*	*Prevailing orientation (solar gains)*	*Ventilation type*	*Cross ventilation*	*Solar control*
UK51	Refurbished terrace Leicester (UK)	0.12	91 m² / 2.5 m	NO	E-W	MVHR (no summer by-pass)	YES	internal blinds on Velux windows
UK52	New detached bungalow Sandiacre (UK)	0.09	59 m² / 2.5 m	NO	N-S	MVHR (no summer by-pass)	YES	NO
UK54	New end of terrace York (UK)	0.19	141 m² / 2.5 m	YES	N-S	MV on wet rooms (turned off)	YES	internal blinds on Velux and some external overhangs
UK55	New detached York (UK)	0.19	167 m² / 2.5 m	YES	E-W	MVHR (no summer by-pass)	YES	internal blinds on Velux and some external overhangs

Table 5.2 – Overview of energy efficiency related measures. Notably, the very low DER of UK55, largely due to fuel type

	UK51	**UK52**	**UK54**	**UK55**
Tfa Area (m2)	91	64		185
Storey height (m)	3	2		3
Volume (m3)	230	157		496
SAP rating / EPC rating	**87 B** / 68 D	**84 B** / 84 B	**not retrieved** / 84 B	**81 B** / 81 B
SAP Target CO2 Emission Rate	21.34	22.81		91
SAP Dwelling CO2 Emission Rate	n/a (SAP 2005)	15.17 (PASS) gas		8.35 (PASS) biomass
SAP MEAN TEMPERATURE	18.23 (1 value)	22.2-22.3		17.8
AIR PERMEABILITY	4.6 (h-1)		not retrieved (assumed 3)	3

5.2 ENVIRONMENTAL MONITORING (OBJECTIVE MEASUREMENTS)

As anticipated in Chapter 4, this stage of the research methodology engages with diagnostic POE [Preiser, 1995]. As such, this section looks into the quantitative part of the longitudinal study, in order to examine how HIHs perform thermally. The chosen methodology requires one to evaluate the physical environmental measurements and then investigate how the design and the use of HIHs can be improved to reduce uncomfortably warm temperatures.

The physical environmental monitoring was conducted both by means of high-resolution interval measurements and by means of spot measurements. The interval measurements of air temperature (°C) and relative humidity were recorded every 10 minutes through Onset Hobo pendant sensors placed in every room and one outside each house monitored during a period of just over 11 months (from June 2015 until May 2016). In this research, air temperature (as recorded by the loggers) is used in the various analyses that require operative temperature. The reason for such choice lies in the fact that in "*well-insulated buildings and away from direct radiation from the sun or from other high temperatures radiant sources, the difference between the air and the mean radiant temperature (and hence between the air, the globe, and the operative temperatures) is small*" [Nicol, Humphreys and Roaf, 2012, p.95]. This was also confirmed by the visual inspection performed on recorded globe and air temperatures in two rooms (one with thermal mass exposed and one with no thermal mass exposed).

For the purpose of analysis data were broken down into three periods (see fig. 5.23): (a) the entire year's performance, in order to provide a panoramic of the temperatures distribution across all houses; (b) the summer performance, in order to perform a summer analysis and the overheating assessment, and (c) the (short) heat wave performance, in order to analyse heat wave vulnerability.

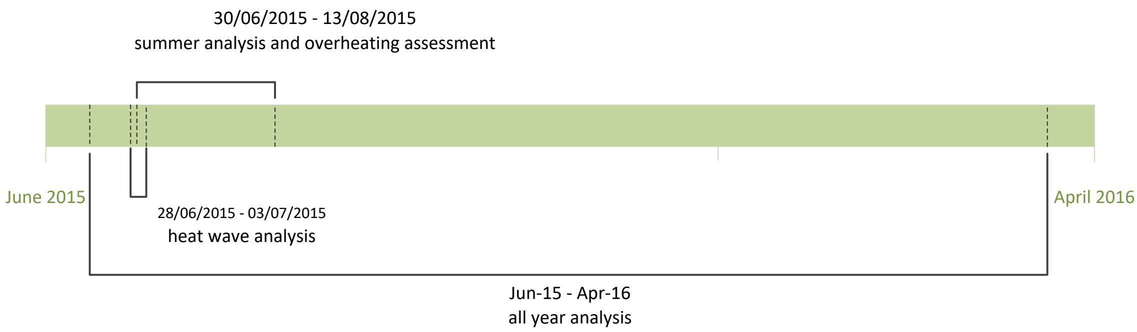


Fig. 5.23 Environmental monitoring timeline. This shows the period in which temperatures have been recorded (green shaded), and the three periods of analysis (black brackets)

5.2.1 SUMMER PERFORMANCE

5.2.1.1 BACKGROUND TO ANALYSIS

The summer analysis presented here takes into account the loggers' recordings from 30 June 2015 until 13 August 2015. A questionnaire was submitted both at the beginning and at the end of this period, and temperature results were interpreted in light of the questionnaire responses for explanation. In this section, the objective findings are thus linked to the opinions (or changes of opinions) expressed by the house occupants over this short time span.

The recorded temperatures have been analysed to map the most problematic areas or rooms in the house. This includes a short heat wave that occurred in England (from 30 June 2015 until 2 July 2015).

5.2.1.2 RESULTS OF SUMMER PERFORMANCE

When looking at the internal temperatures (see table 5.3) it can be appreciated that most of the high temperatures were located in the bedrooms on the upper floors (this tendency was also observed in the heat wave analysis as well as in the year analysis). The living rooms performed better in terms of summer comfort. In fact, living rooms in houses UK51 and UK52 only exceeded the 28°C threshold during the short heat wave experienced in the UK that summer. This is not a surprise, since living rooms tend to be bigger, may have crossed ventilation, and may be shielded from solar gains, especially in an urban context.

The temperature-related conditions of bedrooms and living rooms in the houses under review have been described in terms of (a) mean temperatures, (b) minimum temperatures and (c) maximum temperatures and temperature variation.

Mean temperatures: in general, the mean temperatures of all rooms in all HIHs are in the range 22-25°C. The mean temperatures in the living rooms were lower than those of the bedrooms in all houses, mostly under 23°C. In the bedrooms, mean temperatures were up to 2°C higher.

Minimum temperatures: overall, minimum temperatures ranged from 16-21°C. In houses UK51 and UK54 minimum temperatures were about 21°C. UK54's temperatures were comfortably maintained with no high peaks in temperature (as opposed to the other houses).

Both houses UK52 and UK55 showed lower minimum temperatures in the living room and kitchen, respectively. This suggests a different ventilation management in such rooms, since the dining room is located next to the kitchen and some extra heat gain could be expected to contribute to the resulting temperatures. This was later confirmed by the occupants.

Table 5.3 - Descriptive statistics for all houses (beds and living rooms), period summer 2015.

Descriptive Statistics

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
°C UK51 bed 1	14544	11	19	29	23.42	1.440	2.075
°C UK51 bed 2	14544	16	18	34	23.53	2.022	4.088
°C UK51 living	14544	10	19	28	22.60	1.472	2.167
°C UK52 bed 1	13309	11	19	30	23.04	1.653	2.732
°C UK52 living	13309	14	17	30	21.34	2.080	4.328
°C UK54 bed 1	15901	8	19	27	22.13	1.508	2.275
°C UK54 living	15901	8	18	27	21.68	1.279	1.635
°C UK55 bed 1	15870	13	19	31	23.66	2.016	4.063
°C UK55 living	15870	11	19	29	23.39	1.860	3.460
Valid N (listwise)	13308						

Maximum temperatures and temperature variation: With the exception of house UK54, the houses' maximum temperatures were between 27-34°C. The hottest room, the loft bedroom in house UK51, was later confirmed by the occupants as being too hot – occupants found this room uninhabitable during the heat wave. At the cooler end, UK54 presented the lowest maximum temperatures among all houses.

Another extreme room was found in the house UK55's sunspace, where temperatures swung from a min. of 20°C to a max. of 42°C. This can most likely be attributed to the lack of both ventilation and solar control; which can be confirmed by the sunspace's orientation (East), the lack of solar shading and by the fact that the occupants did not open the windows. All these elements may have contributed to the heat gains in the adjacent rooms.

Here it seems crucial to note that whilst houses UK52 and UK54 have almost similar average temperatures (between 22-23°C) (see fig. 5.24), there is a remarkable difference in temperature range and maximum temperatures. These two houses (UK52 and UK54) were designed to optimize the use of natural ventilation through windows being opened. In addition, both houses' bedrooms face south. The main difference consists in the fact that house UK52 has higher levels of insulation (U-value walls 0.09 W/m^{2}K), has no thermal mass exposed and the bedroom has no external solar shading. On the other hand, house UK54 has lower levels of insulation (U-value walls 0.19 W/m^{2}K), has thermal mass exposed and external solar shading. The combined effects of solar gains and levels of insulation could be a possible cause of the high peaks.

Hence, it may be noted that an average temperature of, in this case, 23°C can hide remarkably variable internal temperatures. This was confirmed by the occupants' questionnaires: whilst the occupants of house UK54 reported that they felt 'protected' against heat, the occupants of house UK52 said that at times they would go to the living room at night to find some heat relief.

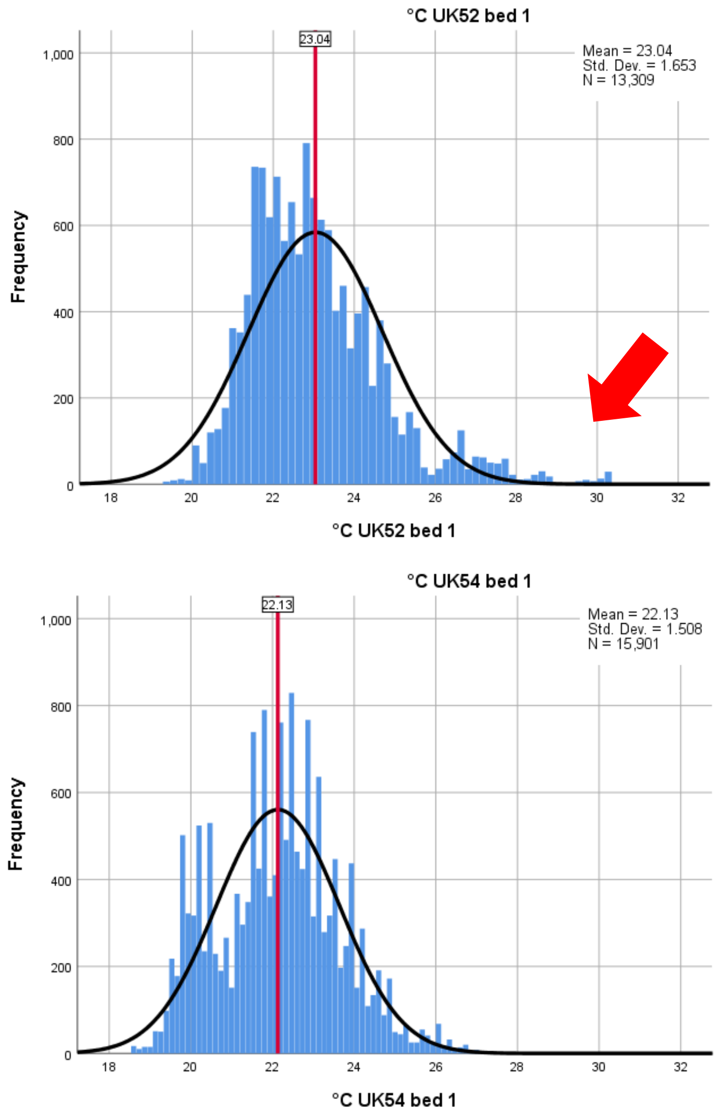


Fig. 5.24 Histograms and normal distribution charts of the main bedrooms of houses UK52 and UK54. The reference line in red shows the temperature average. The red arrow instead show the uncomfortably high temperatures recorded in house UK52.

Temperatures distribution

The former CIBSE Guide A [CIBSE, 2006a] indicates 23°C as the general indoor comfortable operative temperature for bedrooms and 26°C as the threshold operative temperature. These ranges are used here to describe internal temperatures.

Although to different degrees, all bedrooms exceeded the 26°C threshold. Houses UK51 and UK55 recorded the most severe cases of high internal temperatures: in house UK55, 23% of the monitored hours in bedroom 1 were above 26°C; house UK51 recorded 15% of monitored hours above 26°C in bedroom 2 (see figure 5.25). In such figure, only bedrooms that were inhabited (and not intermittently used by a visiting relative) are shown. Results show temperatures at all times.

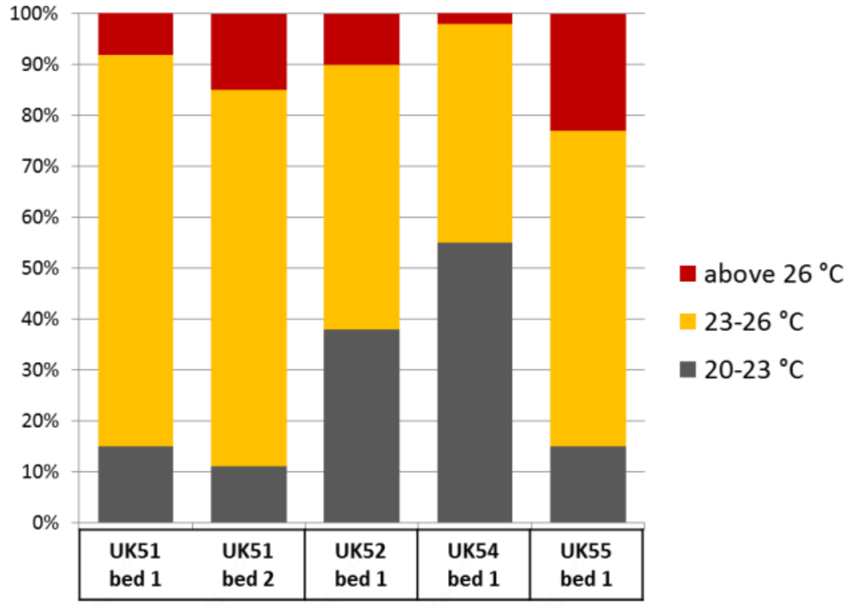


Fig. 5.25 Stacked bar charts showing air temperature ranges of bedrooms

Looking at figure 5.25 and the hours in which the temperature was "above 26°C", one can immediately notice that the worst-performing bedroom (in UK55) and the best-performing bedroom (in UK54) are located in the same development and have the same materials and building specifications. The difference in these cases may partly be explained by the different orientation, different ventilation system and ventilation management of the two houses. In fact, whereas house UK55 delegates the provision of thermal comfort to the MVHR system, the occupiers of house UK54 managed ventilation manually, by thus keeping the heat out during the day (when windows remained closed) and ventilating during the night (by opening the windows). This suggests that ventilation and occupant behaviour may play a crucial role in limiting overheating.

In a similar vein, the two houses that rely most on natural ventilation (UK52 and UK54) had a reduced number of hours above 26°C. By contrast, the houses that manage ventilation through MVHR presented the highest number of hours above 26°C in this range and, consequently, may be considered to have a greater chance of overheating.

Another noticeable finding that emerged from this part of the research is the distribution of hours in the range "between 23°C and 26°C". This temperature range can be classified as the range in which a building is at high risk of overheating, since temperatures can quickly increase above the threshold. In this respect, the houses that applied natural ventilation (houses UK52 and UK54) recorded the fewest hours between 23°C and 26°C. By contrast, houses UK51 and UK55 (MVHR operated) recorded 70% of hours between 23°C and 26°C in bedrooms.

5.2.1.3 DISCUSSION OF SUMMER PERFORMANCE

Uninformed and poor design choices

As far as the maximum temperatures are concerned, house UK51 recorded the highest temperatures in bedroom 2, which was the outcome of a loft conversion. Here, at first, internal blinds appeared to be insufficient to control effectively solar gains. However, after surveying this house and taking into account the responses from the occupants, a number of additional factors were deemed to contribute to the excessively high internal temperatures.

It thus became apparent that the design of the house (open stack stairs leading to bedroom 2) may well have led to higher temperatures. This hypothesis was confirmed by the fact that the occupant complained about kitchen smells in the room. Later, and after complaints from the occupant who at times had to open the windows at night to lower indoor temperatures, it was found that. even though this room is provided with an air valve supply for fresh air (tested to work properly), it suffered from a lack of air flow due to the fact that the nearest air valve extract is located in the lower floor bathroom (see figure 5.26).

It can hence be hypothesised that the reorganisation of the spaces after the retrofit may incorporate a number of factors leading to unexpected temperature exacerbation. While these factors alone might not seem problematic, bedroom 2 has shown the multiplying effects when a real-world scenario is considered.

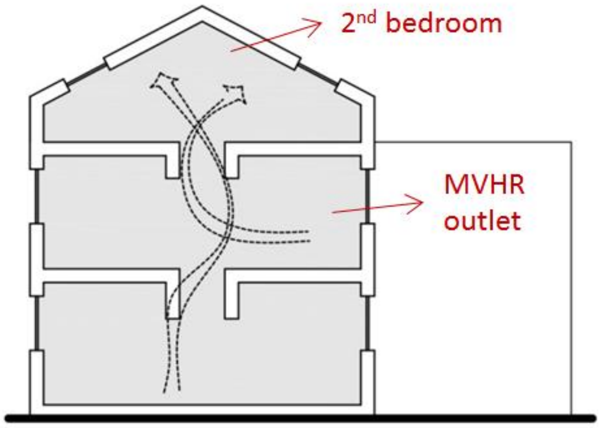


Fig. 5.26 Representation of the stack effect through the stairwell in house UK51

Unmanaged passive architectural elements

In house UK55, the highest temperatures were recorded in the sunspace (see fig. 5.27). The sunspace (or winter garden) is an architectural feature that during summer effectively acted as a greenhouse incorporated within the building volume and then as a heat collector. However, the occupant did not receive instructions regarding the proper use of sunspace, nor he applied the advice provided by the researcher, to the effect that temperatures were left to raise (no ventilation or shading were performed). According to the inappropriate use (unmanaged) of the sunspace may have led to unwanted heat gains and higher temperatures in the main house, which further contribute to overheating, as shown in this case study.

Such a situation opens a question as to whether too much innovation can be easily handled by the occupants.

Fig. 5.27 Images of sunspace in house UK55

5.2.2 OVERHEATING ASSESSMENT

5.2.2.1 BACKGROUND TO ANALYSIS

For the same summer period (summer 2015), a series of overheating assessments were carried out using a set of guidance published by CIBSE and extensively referred to in the literature. While this set of guidance is intended for assessment of simulated data, here it has been applied to monitored data, using air temperature. The assessments here presented, consider the occupancy reported by the occupants in the first visit questionnaire (Q1a).

When considering the thresholds assessments (CIBSE 2006 and 2017) whenever "hours above a threshold" are required, interval resolutions of 10 minutes were kept. Namely, one hour above a threshold was calculated by adding six-time slots (above such threshold); these slots were not necessarily in succession. While this procedure is neither explicitly encouraged nor discouraged in the standard, here high-resolution intervals (10 minutes) were maintained in order to avoid averaging the high-temperature peaks over an hour.

CIBSE Guide A-2006

CIBSE *Guide A: Environmental design* provides overheating criteria based on a fixed temperature method for overheating assessment—the so-called "threshold approach" [CIBSE, 2006a]. For the sake of clarification, it is important to note that the CIBSE Guide A-2006 is no longer the current version, as it has been superseded by CIBSE Guide A-2015. Nonetheless, it is considered in this analysis in light of its wide use in academic papers concerning overheating and because these criteria would have applied at the time when the houses were designed.

CIBSE TM52-2013

CIBSE *Technical Memorandum 52: The Limits of Thermal Comfort: Avoiding Overheating in European Buildings* is a methodology focussing on the “adaptive approach” to comfort, which is informed by the theory that in naturally ventilated buildings people’s thermal experience is largely based on recently experienced temperatures [CIBSE, 2013]. This second methodology was intended to improve on the threshold approach from CIBSE Guide A-2006 [CIBSE, 2013]. CIBSE TM52 has been embedded in the last version of CIBSE Guide A-2015. In accordance with the standard set by CIBSE TM52, a naturally ventilated building is affected by overheating if that building (or one of its rooms) fails at least two of the three criteria provided by CIBSE TM52 [CIBSE, 2015] see table 5.4.

The CIBSE TM52 methodology for assessment required a number of intermediate steps:

I. Calculation of the exponentially weighted *Running Mean Outdoor Air Temperature* (T_{rm}). This was achieved by using the formula 3 in EN 15251-2007 [BSI, 2007]

$$T_{rm} = (T_{od\text{-}1} + 0.8\, T_{od\text{-}2} + 0.6\, T_{od\text{-}3} + 0.5\, T_{od\text{-}4} + 0.4\, T_{od\text{-}5} + 0.3\, T_{od\text{-}6} + 0.2\, T_{od\text{-}7}) / 3.8$$

where $T_{od\text{-}1} + \alpha\, T_{od\text{-}2}$ are the daily mean temperatures for yesterday, da day before, and so on. The running mean outdoor air temperature consists of a ‘weighted' temperature (calculated from the temperatures experienced over the previous days of the analysis) and so it accounts for human adaptation.

II. From this weighted temperature, a *Comfort Temperature* (T_{Comf}) is derived from formula 6 on CIBSE TM52 [CIBSE, 2013]

$$T_{comf} = 0.33\, T_{rm} + 18.8$$

III. At this point, a *Maximum Acceptable Temperature* (T_{max}) and an *Upper temperature Limit* (T_{upp}) were derived [BSI, 2007]. These temperatures depend on the categorisation of the buildings in order to allow consideration of the level of comfort expectation. CIBSE TM52 states that careful consideration should be taken if the comfort expectations might be higher [CIBSE, 2013].

IV. The analysis presented here took into consideration the reality of the case studies: buildings were considered in both categories, i.e., category I ("vulnerable groups of people") and category II ("normal expectation of recently built and refurbished buildings"). The double standard for buildings was chosen as it was found to more accurately reflect the level of comfort expected considering the actual occupancy (in the cases at hand, there was a pregnant lady and a new-born baby among the occupants which will place the building in the building category I). CIBSE TM52-2013 also requires consideration of occupied hours, which was provided by the questionnaire submitted. Such extra categorisation is presented in the results in a shaded area.

Table 5.4 - CIBSE TM52 conditions to overheating (repeated from Chapter 2)

Criterion 1 – *Hours of exceedance (He)*	It sets a limit on the number of hours that the operative temperature can exceed the threshold comfort temperature (i.e. the upper limit of the range of comfort temperature) by 1 K or more during the occupied hours of a typical non-heating season (1 May to 30 September). The number of hours (He) during which ΔT is greater than or equal to one degree (K) during the period May to September inclusive should not be more than 3% of occupied hours[48].
Criterion 2 – *Daily weighted exceedance (We)*	It deals with the severity of overheating within any one day, the level of which is a function of both the rise of temperature and its duration. This criterion sets a daily limit of acceptability. To allow for the severity of overheating, the weighted exceedance (We) must be less than or equal to 6 on any one day where: $We = (\Sigma\, he) \times WF$ $= (he0 \times 0) + (he1 \times 1) + (he2 \times 2) + (he3 \times 3)$ where the weighting factor WF = 0 if ΔT ≤ 0, otherwise WF = ΔT, and hey is the time (h) when WF = y.
Criterion 3 – *Upper limit temperature (Tupp)*	It sets an absolute maximum daily temperature for a room, beyond which the level of overheating is deemed unacceptable. The recommended definitions for the criteria set that the absolute maximum value for an indoor operative temperature is set as follows: the value ΔT shall not exceed 4 K. This absolute maximum temperature is one in which adaptive actions are inadequate and cannot restore occupant comfort.

CIBSE TM59-2017

CIBSE *Technical Memorandum 59: Design methodology for the assessment of overheating risk in homes* consists of a standardised methodology to assess the risk of overheating in residential. It incorporates aspects of the "threshold" approach as well as the "adaptive"

[48] If data are not available for the whole period (or if occupancy is only for a part of the period) then 3 per cent of available hours should be used.

approach. Homes that are (predominantly) naturally ventilated, including those with MVHR (as is the case in three of the houses discussed in this study), are required to pass two criteria: one using an adaptive threshold for living rooms and the other for bedrooms, and a fixed temperature threshold for bedrooms (see table 5.5).

For the living areas, it is required to follow the steps I and II of the TM52. With regards to the occupancy of these bedrooms, the analysis considered both (a) 22:00 until 07:00 for bedrooms and (b) the actual occupied hours as reported by the occupants for the living rooms. Here a threshold criterion is applied.

Table 5.5 - CIBSE TM59 conditions to overheating [CIBSE, 2017] [CIBSE, 2013](repeated from Chapter 2)

Criterion 1	Living areas Kitchens and bedrooms	CIBSE TM52 criterion 1 (hours of exceedance)	The number of hours (He) during which ΔT is greater than or equal to one degree (K) during the period May to September inclusive should not be more than 3% of occupied hours
Criterion 2	Bedrooms from 22:00-07:00	26°C	No more than 1% of annual occupied hours shall exceed operative temperature of 26°C (1% of annual hour between 22:00 and 07:00 for bedrooms is 32 hours, so 33 or more hours above 26°C will be recorded as fail).

5.2.2.2 RESULTS OF THE OVERHEATING ASSESSMENT

Overheating assessments carried out using the three methods indicated that overheating occurred predominantly in bedrooms. The CIBSE 2006 ‘threshold’ assessment and the CIBSE TM59-2017 assessment produced similar results. By contrast, it was found that the CIBSE TM52-2013 assessment indicated fewer occurrences of overheating. These findings are examined in detail in the following sections.

House UK51

In house UK51 (see table 5.6), overheating was found in both bedrooms using both CIBSE-2006 and CIBSE TM59-2017 assessments. By contrast, the CIBSE TM52-2013 assessment indicated that overheating did not occur. In addition, CIBSE TM52-2013 was found not to be consistent with the occupants' responses, who considered bedroom 2 as being too hot for most of the summer.

To reflect on what has been perceived as the actual thermal comfort expectation of this building, during the TM52 analysis house UK51 was also considered to be a category I building [BSI, 2007], since there was first a pregnant lady and then a new-born baby, both of whom could be considered vulnerable occupants. Also, the room (bedroom 2) where vulnerable occupants resided was considered to be occupied at all times (that way the analysis reflected the actual use of the room). Only in this case, bedroom 2 was found to overheat. While no implications are here drawn in order to support a change to the building categorisation to achieve a 'correct' assessment, it seems of paramount importance to recognise the possible differences in thermal perception when real-world data is applied to an analysis.

With regards to the living room, overheating assessment passed according all three methods.

Table 5.6 - House UK51 overheating assessments: note the extra TM52 assessments (in shaded) to reflect varying conditions of the house

UK51	*CIBSE A-2006*	*TM52-2013*				*TM59-2017*		
	RESULT	C1	C2	C3	RESULT	C1	C2	RESULT
bedroom 1	X							
bedroom 2	X							
livingroom	√							
bedroom 1 (Cat. II)		PASS	PASS	PASS	√			
bedroom 2 (Cat. II)		PASS	FAIL	PASS	√			
livingroom (Cat. II)		PASS	PASS	PASS	√			
bedroom 2 (Cat. II - all times occupied)		PASS	FAIL	FAIL	X			
bedroom 2 (Cat. I)		PASS	FAIL	FAIL	X			
bedroom 1 (hours between 22:00-07:00)						PASS	25 hrs	√
bedroom 2 (hours between 22:00-07:00)						PASS	59 hrs	X
livingroom						PASS	n/a	√

House UK52

Similarly to the previous case study, in UK52 (see table 5.7) overheating was found in bedrooms 1 and 2 using both the CIBSE-2006 and the CIBSE TM59-2017 assessments. With CIBSE TM52-2013, instead, overheating was not detected in bedroom 1. Also, in this case the CIBSE TM52-2013 assessment is not consistent with the responses of the occupants, who said that they needed to leave the bedroom during the night to find some relief from the heat.

With regards to the living room, overheating assessment passed using all three methods.

Table 5.7 - House UK52 overheating assessments: note the extra TM52 assessments (in shaded) to reflect varying conditions of the house

UK52	*CIBSE A-2006*	*TM52-2013*				*TM59-2017*		
	RESULT	C1	C2	C3	**RESULT**	C1	C2	**RESULT**
bedroom 1	X							
livingroom	√							
bedroom 1 (Cat. II)		PASS	PASS	PASS	√			
livingroom (Cat. II)		PASS	PASS	PASS	√			
bedroom 1 (Cat. I)		PASS	FAIL	PASS	√			
bedroom 1 (hours between 22:00-07:00)						PASS	51 hrs	X
livingroom						PASS	n/a	√

House UK54

UK54 was found to be the best-performing house with regards to summer comfort. The only room that overheated (and only when assessed against the standard set by CIBSE-2006 assessment) was the small office on the first floor (see table 5.8). This room is south oriented and has two Velux windows, which were kept closed at all times during that summer. So, one may well expect to find lower temperatures when natural ventilation was restored in this room. This house is N-S oriented and is known to be naturally ventilated by its occupants, who reported being cooler indoors during the heat wave.

Table 5.8 - House UK54 overheating assessments: note the extra TM52 assessments (in shaded) to reflect varying conditions of the house

UK54	*CIBSE A-2006*	*TM52-2013*				*TM59-2017*		
	RESULT	C1	C2	C3	**RESULT**	C1	C2	**RESULT**
bedroom 1	√							
livingroom	√							
bedroom 1 (Cat. II)		PASS	PASS	PASS	√			
livingroom (Cat. II)		PASS	PASS	PASS	√			
bedroom 1 (Cat. I)		PASS	PASS	PASS	√			
bedroom 1 (hours between 22:00-07:00)						PASS	PASS	√
livingroom						PASS	n/a	√

House UK55

UK55 was found to be the worst performing house in terms of summer comfort (see table 5.9). This finding was supported by one of the occupant's responses (the other occupant, who suffers from a neurological condition that affects their thermal perception, did not report overheating, at least at the beginning of the summer).

Both bedrooms were found to overheat, though they are located on different floors and have different orientations. This suggests that external gains were not the main driver for overheating in this case study. To elaborate on this point, bedroom 1 had uncontrolled solar gains from the west, whereas bed 2 (east oriented) had incorporated external solar shading provided by the external loggias.

It is known from the occupant's responses that the entire house's ventilation is managed through MVHR and the residents do not open the windows. In fact, in this house MVHR is managed in the belief that it provides the necessary purge ventilation by so (perhaps wrongly) delegating the provision of summer comfort to the MVHR.

Table 5.9 - House UK55 overheating assessments: note the extra TM52 assessments (in shaded) to reflect varying conditions of the house

UK55	*CIBSE A-2006*	*TM52-2013*				*TM59-2017*		
	RESULT	C1	C2	C3	**RESULT**	C1	C2	**RESULT**
bedroom 1	X							
livingroom	X							
bedroom 1 (Cat. II)		PASS	FAIL	FAIL	X			
livingroom (Cat. II)		PASS	FAIL	PASS	√			
bedroom 1 (Cat. I)		FAIL	FAIL	FAIL	X			
bedroom 1 (hours between 22:00-07:00)						PASS	75 hrs	X
livingroom						PASS	n/a	√

5.2.2.3 DISCUSSION OF OVERHEATING ASSESSMENT

Differences between the assessments

The cases studies UK54 and UK55 in Yorkshire (thermal mass/highly insulated) provided results that concur in all three methods: for house UK54, no overheating with all three methods; for house UK55, overheating with all three methods. These houses were identical in terms of constructive details but different in terms of layout, orientation and ventilation management, which are considered to be the main factors in their relationship to overheating.

The case studies UK51 and UK52 (internally insulated retrofit and lightweight bungalow, respectively) were shown not to be affected by overheating when assessed with TM52 and instead to be affected by overheating when assessed with TM59. In detail, in both case studies the TM52 upper limit (TM52-criterion-3) passed; by contrast, it did not pass the fixed threshold of 26°C in the bedrooms. In other words, the TM52 assessment reported an environment that was somehow acceptable, whereas TM59 assessment reported the same environment to be unacceptable.

This difference was further investigated by taking a deeper look into the temperatures, and particularly T upp. In house UK51 (taking bed1 as an example), the recorded external temperatures were used to calculate a derived indoor comfort temperature of 25.1°C. From this value, a derived maximum acceptable temperature (T max) of 28.1°C and a derived upper limit temperature (T upp) of 32.1°C were established (see evidence in table 5.10). It can be argued that T upp, as it was calculated, will hardly be reachable in the north of England (in fact, only UK55 failed TM52-criterion-3) and that TM52-criterion-3 will hardly ever fail. Therefore, the condition of overheating will effectively rely almost entirely on the other two criteria (TM52-criterion-1 and TM52-criterion-2).

Table 5.10 - House UK51 bedroom 1: detail of the TM52 overheating assessment evidencing the calculated comfort (T comf) and upper limit (T upp) temperatures from TM52

	C° external (MEASURED)	C° MEAN OUTDOOR TEMP	C° RUNNING MEAN	C° "T comf"	C° "T max"	C° "T upp" II	occupied (1=yes)	C° UK51 bed1 (MEASURED)
01/07/2015 02:00	22.0	23.1	19.2	25.1	28.1	32.1	1	26.2
01/07/2015 03:00	22.0	23.1	19.2	25.1	28.1	32.1	1	25.9
01/07/2015 04:00	21.8	23.1	19.2	25.1	28.1	32.1	1	25.7
01/07/2015 05:00	21.8	23.1	19.2	25.1	28.1	32.1	1	25.4
01/07/2015 06:00	22.0	23.1	19.2	25.1	28.1	32.1	1	25.8
01/07/2015 07:00	22.8	23.1	19.2	25.1	28.1	32.1	1	26.0
01/07/2015 08:00	24.4	23.1	19.2	25.1	28.1	32.1	1	26.9
01/07/2015 09:00	26.1	23.1	19.2	25.1	28.1	32.1	0	27.5
01/07/2015 10:00	27.3	23.1	19.2	25.1	28.1	32.1	0	27.6
01/07/2015 11:00	28.3	23.1	19.2	25.1	28.1	32.1	0	27.6
01/07/2015 12:00	28.2	23.1	19.2	25.1	28.1	32.1	0	27.7
01/07/2015 13:00	29.0	23.1	19.2	25.1	28.1	32.1	0	27.8
01/07/2015 14:00	28.8	23.1	19.2	25.1	28.1	32.1	0	27.9
01/07/2015 15:00	29.9	23.1	19.2	25.1	28.1	32.1	0	28.1
01/07/2015 16:00	29.6	23.1	19.2	25.1	28.1	32.1	0	28.2
01/07/2015 17:00	29.7	23.1	19.2	25.1	28.1	32.1	0	28.5

KEY:
temperature < 23°C
23°C ≤ temperature < 26°C
26°C ≤ temperature < 28°C
temperature ≥ 28°C

From this remark, it can be ascertained that TM52-criterion-2 (weighted exceedance) is effectively the only criterion to compare with TM59-criterion-2 (threshold 26°C in bedrooms from 22-7). However, the weighted exceedance of TM52-criterion-2 fails when a temperature limit is surpassed for a prolonged period during a day, while TM59-criterion-2 fails with just one instance of reaching this threshold. In this respect, TM59 can be considered a more restrictive assessment than TM52.

Because in TM52 a pass in two out of three criteria are necessary and TM52-criterion-3 may be prone to pass easily (see claims in the previous two paragraphs), effectively the TM52 overheating assessment depends on just one out of the two remaining criteria. From these criteria, if TM52-criterion-3 is overlooked, the remaining two criteria do not apply a fixed threshold temperature in a similar manner to the threshold approach. From the above, it can be concluded that TM52 is a more relaxed assessment than the other two, at least when using monitored data.

Interpretability of results

Both assessments CIBSE 2006 and TM59 picked up the occurrence of excessively warm temperatures, and this was closely in line with occupants' perception. These assessments can then be claimed to be a quick tool for identifying areas of possible concern in a house.

At first, TM59-criterion-2 (max. temperatures below 26°C, from 22:00-07:00) seemed to limit the time-occupancy of a bedroom with no consideration of different sleeping hours (like the one of a new born baby) and consequently to consider fewer 'occupied hours'. In fact, things turned out to be different in the presence of new scenarios (for instance, illness or the new born-baby). A risk that a different occupancy is underestimated seems possible; so designers and researchers should carefully consider the actual occupancy (as opposed to assumed occupancy).

Temporary vulnerability

The applied occupancy was based on to occupants' questionnaires. However, this indication was not necessarily reflective of the occupancy throughout a long period of monitoring. For instance, house UK51 had a new-born baby. In addition, its bedroom 2 (which was already the worst performing) was used most of the time. Not only did the occupancy here change, but also the category of the building should have been changed (albeit briefly) to consider the needs of a pregnant woman as well as the needs of a new-born. The implications for design in light of this consideration would affect the maximum acceptable temperature (T max) and upper limit temperature (T upp), restricting these thresholds.

Moreover, house UK55 reported a case of vulnerability to high temperatures due to lack of thermal sensation, which exposed one of its occupants to a higher risk. In other words, the fact that in two out of four houses occupants turned out to be vulnerable, (one temporarily and the other permanently) raises the question of whether the level of comfort expectation is an appropriate criterion for assessing British houses.

Overall, the complex reality of building performance and houses occupancy may mean that all the standards of assessments accounted for in this study are too prescriptive and so fail to match the reality of the houses to which they apply. On this basis, it can be concluded that results require not only judgement but also a revision of building categorisation and a flexible occupancy expectancy during the building's life span.

Finally, one should explicitly acknowledge the limitations of the overheating analysis, if such an analysis is performed using monitored data and for a shorter proportion of time. This is the reason why it should be noted that this analysis is not compatible with predicted assessments based on standard weather years and annual basis. However, within these limits, the conclusion holds that TM59 constitutes an advanced tool by which to understand (if not measure) overheating more realistically.

5.2.3 HEAT WAVE VULNERABILITY

5.2.3.1 BACKGROUND TO ANALYSIS

As noted in Chapter 3, heat waves are expected to increase in terms of intensity as well as duration in the next decades. Because a heat wave is an extreme environmental condition — it can pose heat stress on building occupants — and HIHs are designed to protect against external weather, HIHs should be expected to cope (also) with heat waves by mitigating their effects, as examples of extreme weather conditions, by virtue of the fact that HIHs provide a thermally insulated environment.

This analysis is an attempt to disentangle areas of potential risk for HIHs in relation to heat waves. As a part of this attempt, the current section provides a graphical and statistical description of the four case study houses during the 2015 heat wave only. It will focus in particular on the analysis of the internal and external temperatures (hourly averages) recorded during the brief but sharp heat wave peaking at above 30°C on 1 July 2015 in England (an occurrence that also coincided with high solar gain). While this period corresponds to summer in the UK, it has purposely been kept separate from the analysis of the data of the remainder of the summer due to it representing an extreme event.

Deciding the exact period to consider for the heat wave analysis was not a straightforward process because there is no one unique definition of heat wave. The American Meteorological Society defines heat wave (also referred as *hot wave* and *warm wave*) as a period of abnormally and uncomfortably hot and usually humid weather. According to this definition, a heat wave should last at least one day and possibly from several days to several weeks, with a maximum shade temperature reaching or exceeding 32.2°C [American Meteorological Society, 2012].

LOCAL Threshold temperatures

Threshold maximum day and night temperatures defined by the Met Office National Severe Weather Warning Service (NSWWS) region are set out below.

Maximum temperatures (°C)

NSWWS Region	Day	Night
London	32	18
South East	31	16
South West	30	15
Eastern	30	15
West Midlands	30	15
East Midlands	30	15
North West	30	15
Yorkshire and Humber	29	15
North East	28	15

Fig. 5.28 Threshold temperatures across UK [Public Health England, 2013]

In the UK, the Met Office adopts a more relativist definition "*a heat wave is an extended period of hot weather relative to the expected conditions of the area at that time of year…when the daily maximum temperature of more than five consecutive days exceeds the average maximum temperature by 5°C, the normal period being 1961-1990*" [Met Office, 2015b].

Day and night threshold temperatures have been defined by the Met Office National Severe Weather Warning Service (NSWWS) by region, as shown in the figure 5.28. The regions where the HIHs considered in the present research are located are East Midlands and Yorkshire & Humber. Both of them have external temperatures threshold values of 15˚C night (min) and 29˚C/30˚C day (max) [Public Health England, 2013].

For the present analysis, the chosen period matches the generic definition of heat wave as a "*period of abnormally and uncomfortably hot and usually humid weather*" [American Meteorological Society, 2012]. It also satisfies two further conditions that are often associated with a heat wave, namely, (a) daily averages of external temperatures were above 20°C, and (b) the Met Office National Severe Weather Warning Service NSWWS threshold peak temperature was reached [Public Health England, 2013]. The graphical representation below is able to best represent this period, which corresponds to 28 June - 3 July 2015 (figure 5.29).

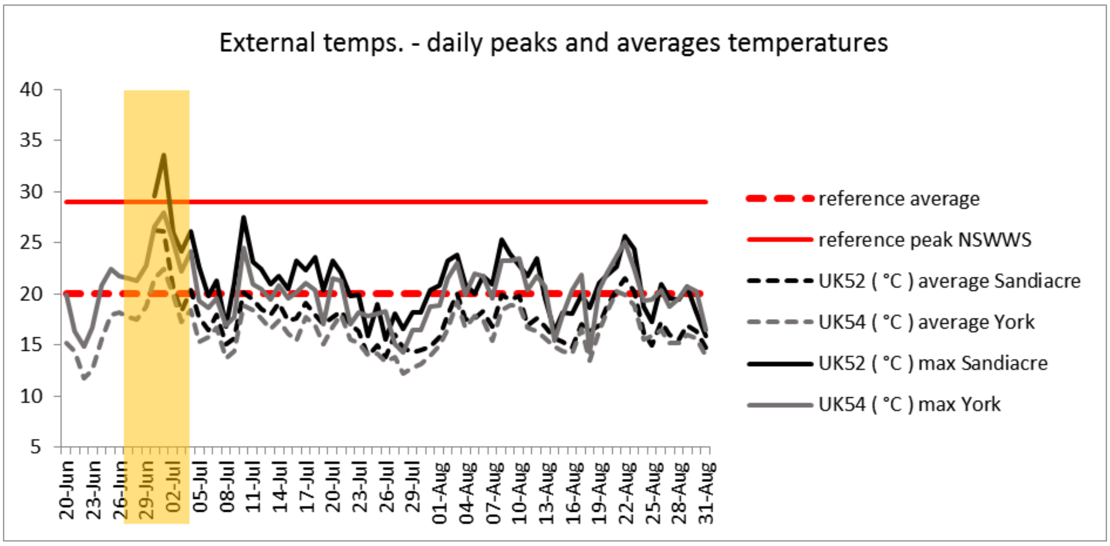


Fig. 5.29 External temperatures recorded in case study houses, evidencing (shaded area) the period considered to be a heat wave

5.2.3.2 RESULTS OF HEAT WAVE VULNERABILITY

Descriptive statistics

Figure 5.30 shows the median, interquartile range (box) and max/min values over the period considered. In general, the internal/external median differences lay between 4 and 8°C. This fact confirms what was found in the reviewed monitored studies presented in Chapter 2 and Chapter 3). Also, the graph signals the extreme values, as circled in red. They are: (a) in house UK52, the room containing the water tank for domestic hot water, and (b) in house UK55, the east facing sunspace with no solar protection. Both spaces are located within the thermal envelope of the houses and could reasonably be expected to contribute to overall heat gains.

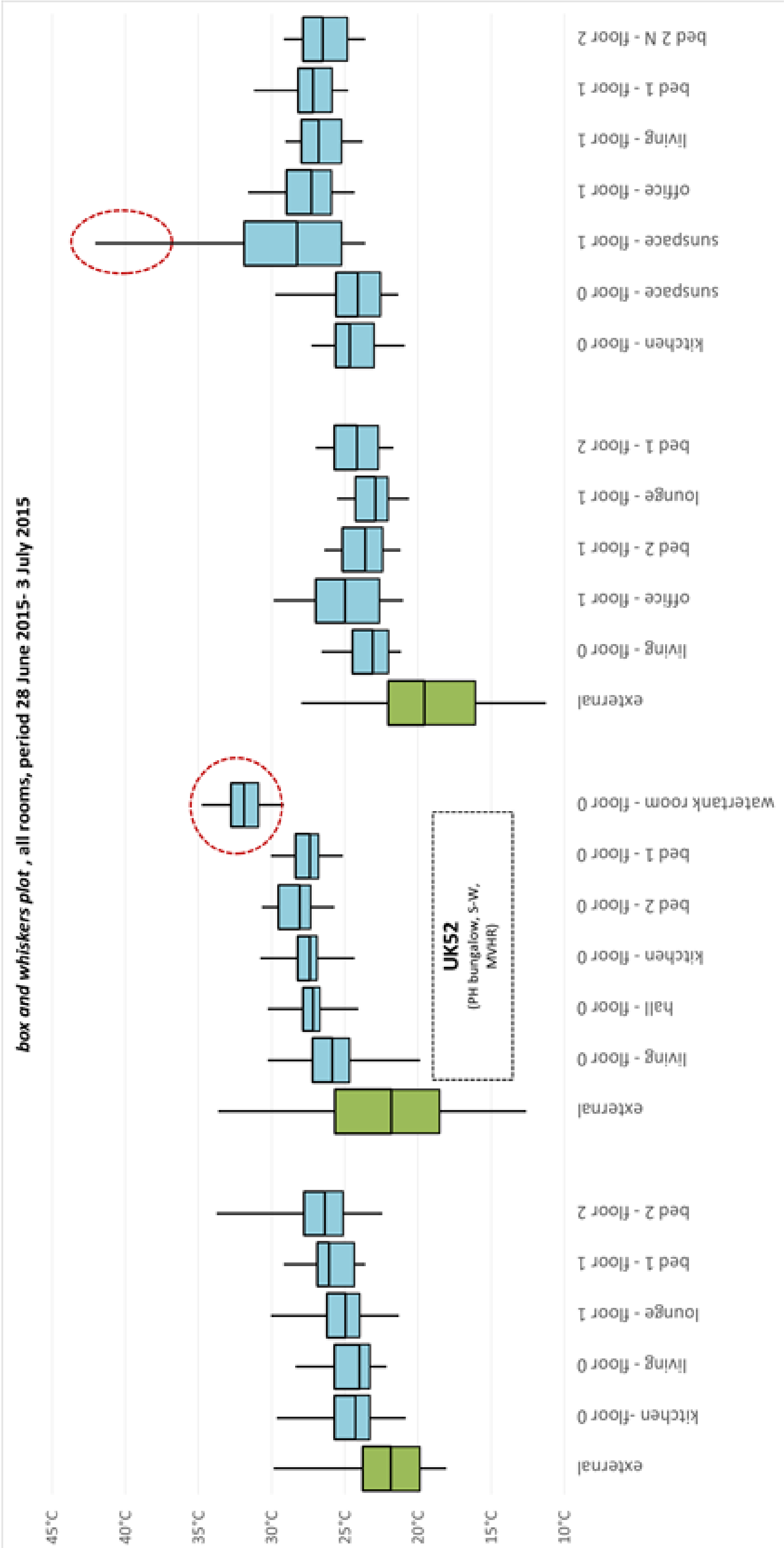


Fig. 5.30 Box and whiskers plots all houses, period from 28 June 2015 to 3 July 2015

In house UK51, the highest temperature ranges were found in bedroom 2, located on the second floor loft conversion and provided with two windows in the slope of the roof facing east and west. Here, temperatures were revealed to be too uncomfortable for sleep during the heat wave, to the point that the occupants of this room slept in the living room on a lower floor during this period.

House UK52 bedroom showed less variation compared to the other houses (see table 5.11). The living room proved to be the coolest space of this house, presumably due to the provision of cross ventilation within that room. The bedrooms temperatures, on the other hand, were always above 25°C. The occupant reported leaving the windows slightly open (in a lockable position) during daytime. However, in consideration of the fact that house UK52 is a bungalow of lightweight construction, temperatures were expected to fall quickly as the night progressed. This was not the case, though. This different than expected performance could be due to the fact that the bungalow had MVHR with no summer bypass or due to the fact that windows remained closed during hours of sleep (as reported by the occupants). In this case, the performance of the bungalow would confirm the hypothesis that small volumes of fresh air do not provide significant night cooling, as reported by Orme & Palmer [2003].

House UK54 performed the best of all the case studies. In contrast with all the other houses, this house is the only one managed via natural ventilation (extract mechanical ventilation was available but the occupant had turned this off for the summer).

In house UK55, where most windows were kept close during the heat wave, and MVHR was 'left to do the job', the biggest internal-external median difference was found. This finding provides an initial indication that MVHR system ventilation is an inefficient means of purge ventilation. The coldest room was found to be the kitchen, which was managed via window opening by the other occupant. Elevated indoor temperatures appeared to be exacerbated by the uncontrolled morning solar gains and lack of window opening. The east-facing sunspace with no solar control presented the highest peak temperatures, with a difference with external temperatures up to 18°C. The high night time temperatures in all rooms suggest that no night cooling was applied. It was reported by the occupants that at certain times they could only find thermal relief outdoors.

Table 5.11 - Descriptive statistics for all houses, period from 28 June 2015 to 3 July 2015

Descriptive Statistics

	N	Range	Minimum	Maximum	°C Mean	Std. Deviation	Variance
°C UK51 living (f 0-E)	144	6.2	22.1	28.4	24.590	1.6004	2.561
°C UK51 bed 1 (f 1-E)	144	5.6	23.6	29.2	25.891	1.5741	2.478
°C UK51 bed 2 (f 2 -E&W)	144	11.3	22.4	33.7	26.728	2.5676	6.593
°C UK52 living (f 0/N&W)	82	10.4	19.9	30.3	25.894	2.3023	5.301
°C UK52 bed 2 (f 0/S)	82	5.0	25.7	30.7	28.492	1.3245	1.754
°C UK52 bed 1 (f 0/S)	82	4.9	25.1	30.1	27.615	1.1622	1.351
°C UK54 living (f 0/N&S)	144	5.4	21.2	26.5	23.260	1.3362	1.786
°C UK54 bed 2 (f 1/N&S)	144	5.2	21.2	26.4	23.749	1.5116	2.285
°C UK54 bed 1 (f 2/ N&S)	144	5.3	21.7	27.0	24.248	1.5115	2.285
°C UK55 living (f 1/S&W)	144	5.3	23.8	29.1	26.664	1.4869	2.211
°C UK55 bed 1(f 1/W)	144	6.4	24.8	31.2	27.142	1.5254	2.327
°C UK55 bed 2 N (f 2/W)	144	5.6	23.6	29.2	26.360	1.6431	2.700

From the above paragraphs, one can draw the conclusion that in the above HIHs, some rooms were not only uninhabitable (such as bed 2 in house UK51) but also actively collecting unneeded heat, which was then distributed to the rest of those houses (such as the water tank room in house UK52 and the sunspace in house UK55).

Hottest day temperatures

During 1 July 2015, all room temperatures in house UK51 varied between 25-34°C (most rooms between 25-30°C). When external temperatures were at their lowest, around 5:00-6:00 am, internal temperatures were 3-6°C higher.

During 1 July 2015, in house UK52, all room temperatures were between 23-31°C. When external temperatures were at the lowest, around 5:00 am, internal temperatures were 8-10°C higher. During the 1 July 2015, in house UK54, all room temperatures were between 21-30°C (most rooms between 23-26°C). When external temperatures where at the lowest, between 4:00-5:00 am, internal temperatures were 5-10°C higher. All the other rooms maintained lower temperatures during external peak times. During the 1 July 2015, in house UK55, with exception of the sunspace, all room temperatures were between 25-30°C. When external temperatures where at the lowest, between 4:00-5:00 am, internal temperatures were 10-15°C higher. This remarkable difference should be cause for some concern.

The findings introduced above are partially evidenced by table 5.12, where a graphical inspection shows the high internal temperatures in some rooms and their persistence during 1 July 2015. Note that in houses UK51, UK52 and UK55, most bedroom temperatures were above 26°C all the time.

Table 5.12 - Hourly temperature readings in all houses during 1 July 2015, evidencing hours above 26°C in bedrooms

	°C UK51 living	°C UK51 bed 1	°C UK51 bed 2	°C UK52 living	°C UK52 bed 1	°C UK52 bed 2	°C UK54 living	°C UK54 bed 2	°C UK54 bed 1	°C UK55 living	°C UK55 bed 1	°C UK55 bed 2
00:00:00	25.6	26.3	28.5	25.5	27.2	28.1	23.4	24.5	24.9	27.4	28.9	27.5
01:00:00	25.5	26.3	28.3	25.8	27.1	28.1	23.3	24.3	24.8	27.3	28.6	27.3
02:00:00	25.5	26.2	27.8	25.9	27.1	28.0	23.2	24.0	24.6	27.1	28.5	27.1
03:00:00	25.4	25.9	27.7	25.9	26.9	27.9	23.1	23.7	24.4	26.9	28.2	26.9
04:00:00	25.4	25.7	27.7	25.7	26.9	27.8	23.0	23.4	24.3	26.8	28.0	26.7
05:00:00	25.4	25.4	27.8	25.7	26.8	27.7	22.9	23.1	24.2	26.7	27.8	26.5
06:00:00	25.4	25.8	27.9	23.1	26.7	27.6	22.9	23.2	24.2	26.8	27.6	26.4
07:00:00	25.6	26.0	28.0	23.1	26.4	26.7	22.2	23.1	24.1	26.9	27.6	26.4
08:00:00	26.3	26.9	27.7	24.6	26.2	26.3	22.5	23.2	24.2	27.1	27.6	26.5
09:00:00	26.9	27.5	28.5	25.6	26.3	26.7	23.0	23.4	24.4	27.4	27.7	26.8
10:00:00	27.1	27.6	29.3	26.1	26.6	27.3	23.7	23.7	24.6	27.7	27.9	27.0
11:00:00	27.0	27.6	30.3	26.4	27.2	28.1	24.3	24.1	25.3	28.0	28.1	27.4
12:00:00	26.9	27.7	30.6	26.7	27.7	28.8	24.8	24.6	25.7	28.3	28.2	27.7
13:00:00	27.0	27.8	32.0	27.0	28.0	29.0	26.2	25.3	26.2	28.6	28.5	28.1
14:00:00	27.1	27.9	32.5	27.4	28.4	29.3	26.5	25.6	26.3	28.7	28.8	28.4
15:00:00	27.5	28.1	33.4	28.0	28.6	29.3	26.3	26.0	26.6	28.9	29.2	28.6
16:00:00	27.5	28.2	33.4	28.6	28.7	29.4	26.2	26.4	27.0	28.9	29.5	28.8
17:00:00	27.6	28.5	33.7	29.5	29.3	29.4	25.9	26.2	27.0	29.0	30.1	29.1
18:00:00	27.8	28.7	33.3	30.0	29.8	29.5	25.6	26.1	26.8	29.1	30.0	29.1
19:00:00	27.9	29.1	33.3	30.3	30.0	30.3	25.4	26.0	26.6	29.0	30.0	29.2
20:00:00	28.1	29.2	33.0	30.0	30.1	30.5	25.2	25.9	26.4	28.9	29.7	29.1
21:00:00	28.4	29.2	32.5	29.5	30.1	30.2	25.0	25.8	26.1	28.9	29.4	29.0
22:00:00	28.4	29.2	31.9	29.4	30.1	30.5	24.5	25.5	26.0	28.9	29.2	28.8
23:00:00	28.3	29.1	31.4	29.4	30.1	30.7	24.5	25.4	26.4	28.8	29.1	28.7
hrs above 26°C	16	20	24	14	24	24	4	5	11	24	24	24
hrs above 28°C	4	9	**17**	9	11	**16**	none	none	none	13	**18**	11

KEY:
temperature < 23°C
23°C ≤ temperature < 26°C
26°C ≤ temperature < 28°C
temperature ≥ 28°C

Lag

From a visual inspection of the plotted temperatures in the days before and after the heat wave, it became evident that while external temperatures were lowered from 2 July 2015, the high internal temperatures fell with external temperatures with almost the same slope in all houses (see fig. 5.31 and 5.32).

In house UK52 (lightweight construction), the main bedroom temperatures remained above 25°C for over 3 days after the end of the heat wave. This fact was unexpected, due to the lightweight characteristic of the building fabric and the fact that no thermal mass was exposed. This combination was expected to lower temperatures faster than houses with a thermal mass exposed (as houses UK54 and UK55). A possible explanation for this occurrence lies in the continuously operating MVHR (with heat recovery), with a consequent delay in heat purge on the cooler days, or due to another source of heat gain, possibly within the building fabric. However, it is not possible to establish with certainty the reason for this temperature behaviour, since the design of house UK52 may well incorporate other sources of heat gain (such as no solar control in the bedroom exposed to the south, or the hot water tank). Further investigation would then be required to estimate the relative contribution of different house characteristics to indoor temperatures drop.

In house UK54 (heavyweight construction/natural ventilation) the main bedroom temperatures were below the peak day external temperature, but above the following days. A similar pattern was found in house UK55 which, as a part of the same development, has a heavyweight construction and an MVHR. However, the pattern was repeated with 3-4°C difference higher (see fig. 5.32).

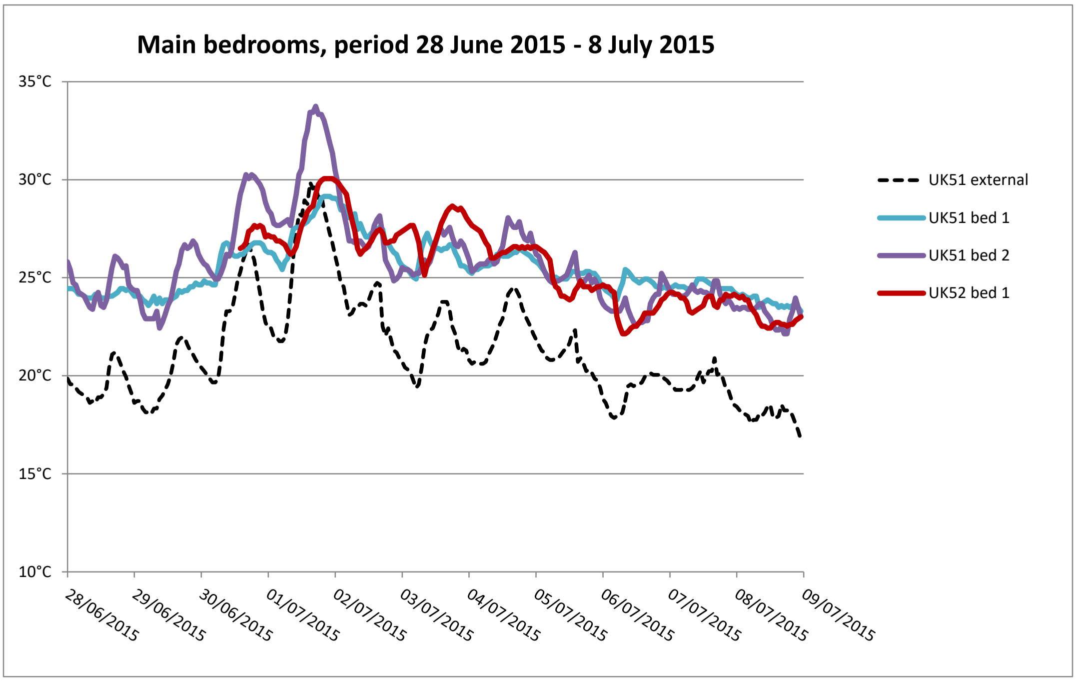


Fig 5.31 Temperature swing for houses UK51 and UK52

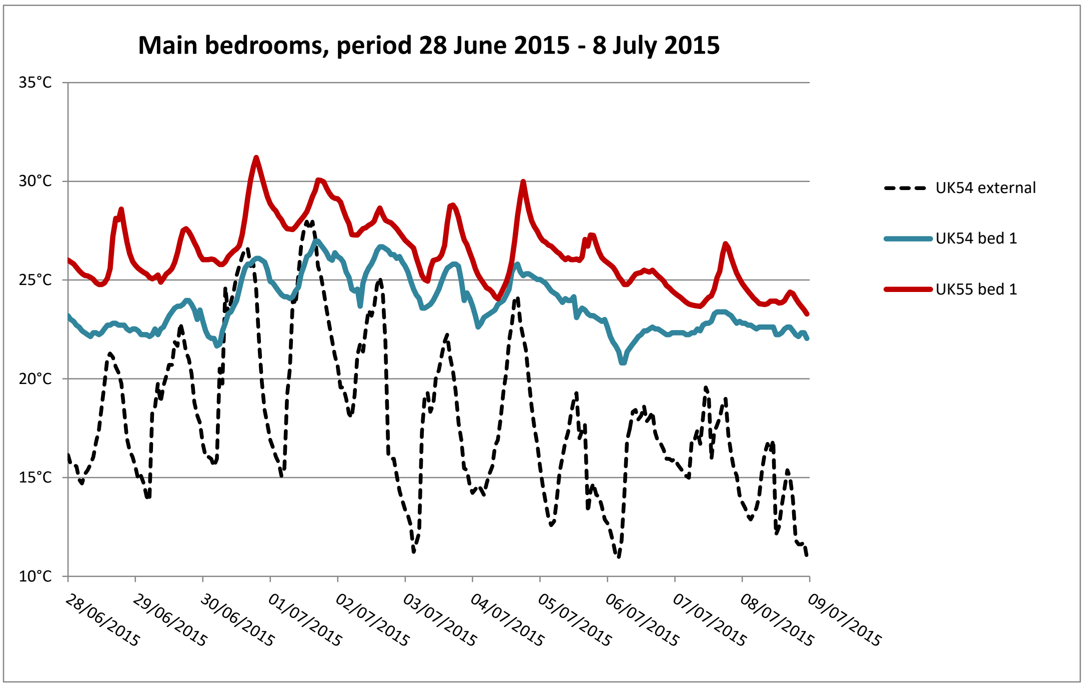


Fig 5.32 Temperature swing for houses UK54 and UK55

Resilience to heat waves: room averages

The data of all inhabitable rooms have been examined to look for cooler rooms within the houses (figure 5.33). Of all the HIHs under study, house UK54 had the lowest average temperature during the heat wave. The coolest room was found to be the north-facing lounge on the first floor in UK54, where during the heat wave recorded temperatures never exceeded 26°C.

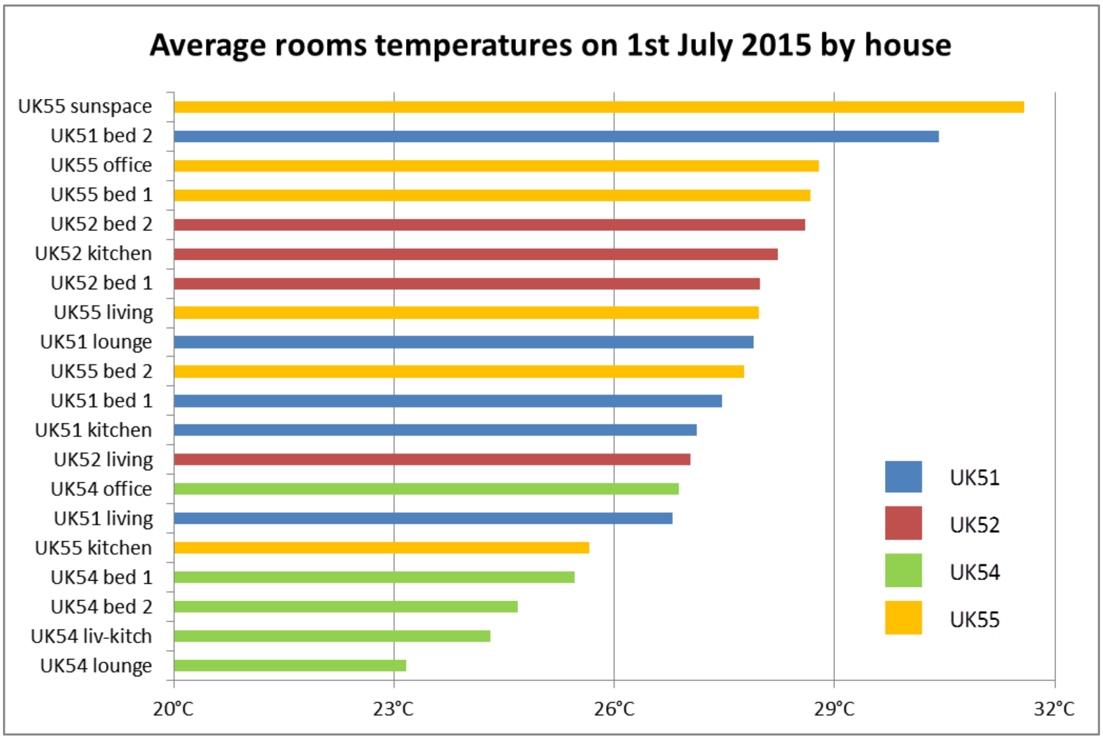


Fig 5.33 Rooms average temperatures during the 1 July 2015

House UK55 was found to perform the worst in general. However in this house it was possible to find the second-most resilient room (the kitchen, which is located in the ground floor, has little or no solar gain, and, importantly, is known to be the only naturally ventilated room in house UK55).

Interestingly, the average temperatures of the bedrooms of house UK52 (lightweight) and UK55 (heavyweight) were similar. Both houses had an MVHR without a summer bypass running at all times, and only the house UK52 occupant incorporated additional ventilation through window opening. However, one would have expected that during a heat wave a lightweight and naturally ventilated house would reduce in temperature more quickly than a MVHR-ventilated heavy weight house. That was not the case, however. The specific reasons that may explain this occurrence cannot be established with certainty. A possible explanation could be found in the bedroom size (house UK52's bedrooms are much smaller than those of house UK55) or due to the site microclimate (UK52 surrounded by asphalt, while house UK55 is on a prevailingly vegetated site). From the above observations, it emerges that natural ventilation is not the only factor to prevent overheating.

Resilience to heat waves: ventilation strategy

Figure 5.34 depicts an interesting effect that the ventilation strategy has on the thermal performance during heat waves. In the four case studies, room temperatures were found to be correlated with ventilation type. While correlation does not mean causation, it should be noted that houses managed via MVHR and MVHR combined with window opening (mixed mode ventilation) showed the highest temperatures (after the non-ventilated sunspace).

On the other hand, the one house with purely natural ventilation recorded by far the lowest temperatures (indeed, to the point that the ‘hottest’ naturally ventilated room recorded lower temperatures that the ‘coolest’ MVHR ventilated room). Whereas one should acknowledge that a number of different factors are involved in such performance, one cannot help noticing that houses where the heat recovery was constantly “on” recorded the highest temperatures. In other words, there seems to be some correlation between risk of overheating during heat wave and a constant reliance on MVHR (or other heat recovery devices). It is worth underlining that none of the MVHR systems incorporated a summer bypass; as such, results here presented cannot extend conclusions to all mechanical ventilation systems. Nor it possible to draw the conclusion that a summer bypass will solve the issue of overheating during heat waves.

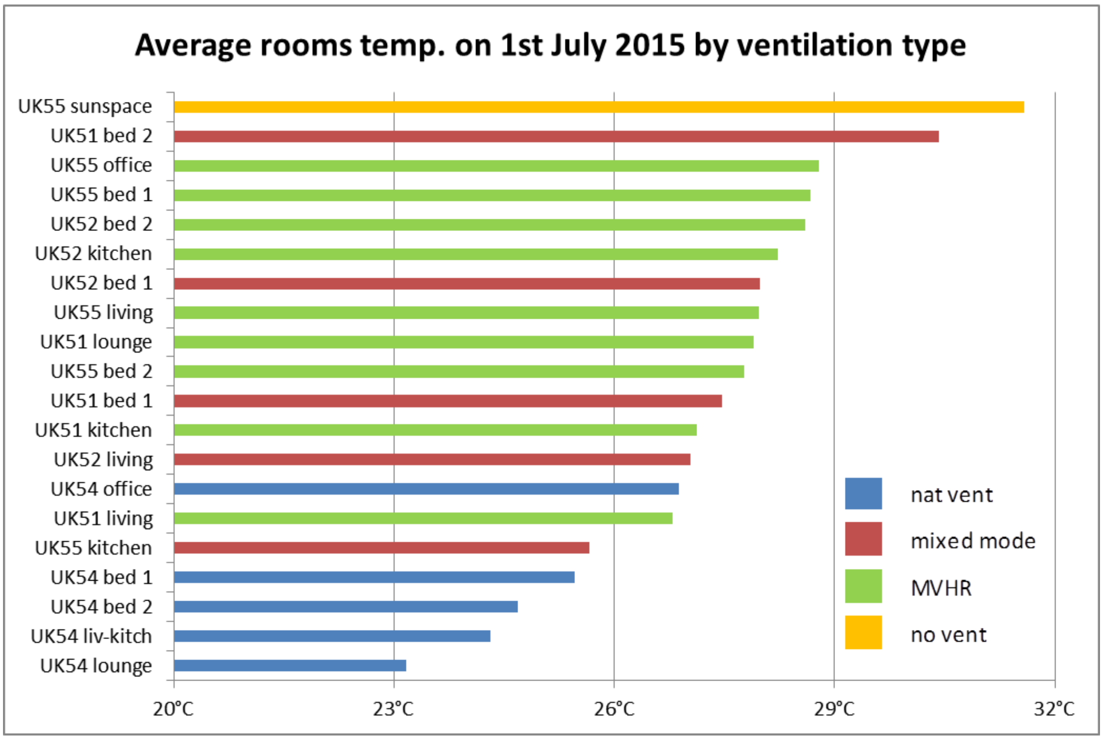


Fig 5.34 Peak room temperatures by ventilation type during the 1 July 2015.
Note that no MVHR installation was provided with summer bypass.

5.2.3.3 DISCUSSION OF HEAT WAVE VULNERABILITY

During the heat wave of summer 2015, some of the rooms became unusable and occupants had to relocate to other types of room. This option is not always available in highly insulated buildings (consider, for instance, flat apartments or overcrowded houses). However, in light of some inherent risks on low-carbon design, designers should consider the provision of variability of thermal spaces (whenever feasible) to design energy-efficient houses that are resilient to heat waves and protect its occupants from extreme heat.

It was also noticed that a lightweight house and a heavyweight house recorded the same average temperatures during the hottest day of the heat wave. This fact is worthy of further investigation, with a view to addressing which factor (climate, microclimate, layout, ventilation, etc.) is decisive to the (risk of) overheating of highly insulated houses.

The fact that house UK54 (naturally ventilated house) performed at its best during summer does not necessarily mean that MVHRs are to be avoided in HIHs. In fact, looking at the other seasons (autumn, winter and spring), it may be noticed that house

UK54 stayed 'cooler' throughout the entire period of the study. Apparently, this is far from ideal, since it might not secure winter comfort (see fig. 5.35 in next pages).

Finally, the study has found that occupants tend to adopt adaptive behaviour in response to their living environments. For instance, all occupants ventilated at least one room. However, as shown by house UK52 (lightweight bungalow Passivhaus), user behaviour alone is not sufficient to lower internal temperatures. For this reason, it may be concluded that the capability of a building environment to adapt to extreme weather events (or to put people in the condition to adapt to those events) constitutes a key asset of such a building environment, and possibly it marks the transition from a *vulnerable* HIH design to a *resilient* HIH design.

5.2.4 YEAR OVERVIEW

The scope of this research consists of looking at overheating, and how overheating correlates with summer discomfort. However, for the sake of completeness and clarity, here the findings presented in the previous sections are complemented with a panoramic of all houses over a whole year. Figure 5.35 shows the median, interquartile range (box) and max/min values room by room and season by season, over the year for each house. The following observations can be made on this basis:

- Summer records high temperatures but also it shows a great variability of extreme temperatures, especially in hotter extremes, where variations of 7°C were found. This 'spikiness' is somehow less evident throughout the rest of year (with the exception of spring).
- During summer, according to TM59 some rooms are deemed to have overheated (cf. section 5.2.2 in this chapter). They are highlighted with a red circle in Fig 5.35. It can be observed that overheating can occur with different extremes and interquartile ranges.
- With the exception of summer, the non-certified Passivhaus UK52 interquartile ranges were similar throughout the heating seasons (again with the sole additional exception of the peak temperatures in spring).
- Autumn, winter and spring are more similar in terms of interquartile ranges. However, peak temperatures are higher in spring, probably due to unmanaged solar heat gains. A reason for this could be fact that occupants do not appropriately adapt their behaviour to avoid early excess heat gains. In this

context, it is worth emphasising that in spring, bedroom 2 in house UK51 was reported by the occupants to suffer problems of overheating during the night (see orange circle in fig. 5.35). This is further analysed in the user perspective section of this chapter.

- The observations for spring are supported by the records of autumn temperatures. In fact, in autumn, peaks temperatures are lower. This may be due to occupants being aware of, and implementing, adaptive behaviour. This is further analysed in the user perspective section of this chapter.
- Lastly, it is interesting to notice that the cooler house UK54, which proved to be the best performing house both in terms of overheating assessment and heat wave resilience, recorded the lowest temperatures in the remaining seasons. This situation may not be ideal for winter comfort. This aspect is further analysed in the user perspective section of this chapter.

Once the temperatures that were recorded all year around are considered, it was found that during summer the houses showed greater variability than in the other seasons. Also, it was found that spring and autumn differ notably, especially regarding the peak temperatures recorded. The most credible hypothesis for this performance is that it was due to the fact that the occupants failed to implement adaptive behaviour, possibly in relation to solar gain control.

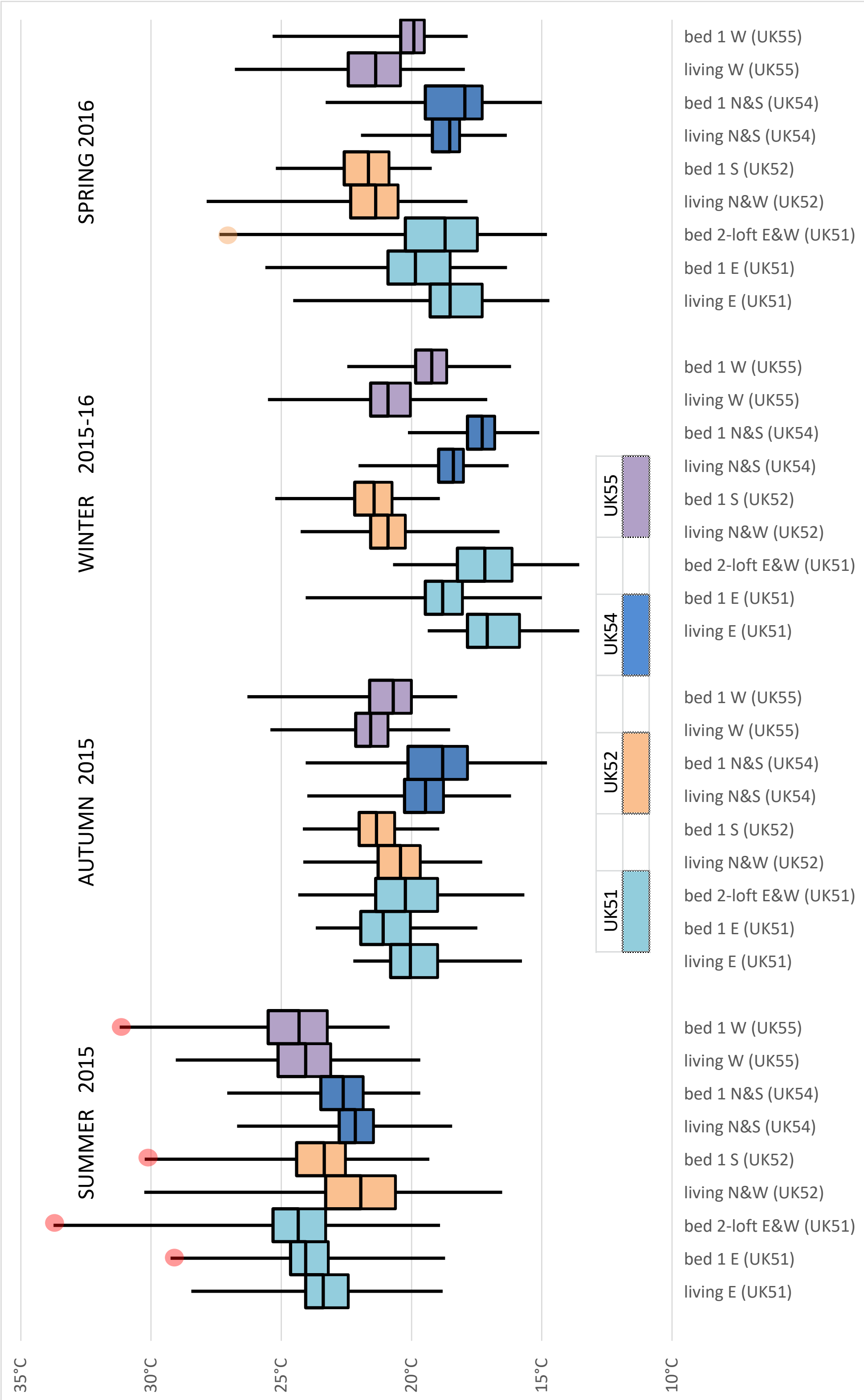


Fig. 5.35 Box and whiskers graph of temperature, for the whole period of analysis, divided by seasons

5.2.5 SUMMARY OF ENVIRONMENTAL MONITORING FINDINGS

The summer and heat wave analysis have provided evidence that uncomfortable temperatures were found in all the houses under review. However, this has occurred with different degrees of severity and for a variety of reasons. During summer, the most commonly affected rooms were the **bedrooms**, which would have been required to stay cooler than living areas, confirming what found in the literature review of Chapters 2 and 3. This situation was exacerbated during the heat wave when some of the rooms became unusable and occupants had to relocate to another type of room. And it was noted that that this option is not always available in highly insulated dwellings.

One of the factors that can be claimed to impact most on the overheating experience appears to be the presence or absence of **natural ventilation**. Similarly to other studies (see [McGill *et al.*, 2017]), it was found that houses operating MVHR during summer reported higher temperatures. In fact, the summer analysis showed that in the houses where natural ventilation is used consistently, temperatures were reduced. Conversely, it seems important to emphasise that mechanical ventilation in dwellings is meant to secure fresh air, not summer cooling. If one wants to minimise the risk of overheating, both occupants and designers need to be aware of, and correctly understand, this difference as well as the need to use additional natural ventilation in warm weather or other form of passive cooling incorporated when ventilation is not a viable solution for cooling.

In addition, it was found that houses with MVHR (none with summer bypass) during summer proved to be more affected by uncomfortably warm temperatures and the unwanted heat gains collected in certain rooms (via lack of ventilation or solar control) may be an exacerbating factor (but certainly not the only factor) that may result in excessively warm temperatures. Here it can be hypothesised that the unavailability of a summer bypass may have contributed by the heat recovery from the MVHR operating constantly during summer[49].

However, the fact that house UK54 (naturally ventilated house) performed at its best during summer does not necessarily mean that MVHR are to be avoided in HIHs,

[49] This is not to say that a summer bypass would not recover extra heat. Informal discussions with BRE experts have anticipated that there are still leakages of heat with the summer bypass. So studies are still needed in the UK in this area.

because winter comfort could be compromised. This can be linked to a study that questions the use of MVHR in mild maritime climates [Sassi, 2013].

On the other hand, the fact that house UK52 - the uncertified Passivhaus bungalow - also left the windows in trickle ventilation during winter poses questions as to whether air movement is constantly needed.

In terms of average **temperatures**, it was shown that 23°C could hide uncomfortably warm temperatures, as shown in the summer analysis of houses UK51 and UK52. Therefore designers must be cautious when interpreting their tested designs because there seems to be need for greater use of detailed simulations at the design stage in order to carefully scrutinise internal temperatures.

It was also noticed that a lightweight house and a heavyweight house recorded the same average temperature during the hottest day of the heat wave. This fact is worthy of further investigation, with a view to addressing which of the factors (climate, microclimate, layout, ventilation, etc.) is decisive in terms of (the risk of) overheating in highly insulated houses.

Overall, the environmental monitoring analysis also showed that the lack of **solar control** in general leads to excessive heat gains and quick response to temperature increase. Solar gains can cause severe overheating in HIHs, which can further be exacerbated by unconventional design solutions, such the sunspace or the converted loft [50]. In fact, from the case studies analysed here, in the summer analysis similar unconventional design solutions proved to be a source of risk. Interestingly, this is especially the case in the UK, where shading has historically been needed or used only rarely.

As for the heat wave analysis, it was shown that high indoor temperatures persisted after the peak day in some houses (even for up to four days). Such persistence encourages one to hypothesise a further degree of risk. Whether reason for this increased risk depends on the super-insulated building fabric, inadequate ventilation or solar gains control was not established. This specific point then requires further investigation, possibly with other methods of data collection, such as building simulation.

[50] Incidentally, this was anticipated by a DTM study, though only in consideration of future climate projections [Rodrigues, Gillott and Tetlow, 2013].

The **assessment of overheating** proved to be intricate. Overheating was found in most houses when the standards set by CIBSE-2006 and CIBSE TM59-2017 were used. But things proved to be different with CIBSE TM52-2013, which, as shown in this section, draws a wider picture when it is applied to the dynamics of internal temperatures within HIHs. In fact, CIBSE TM52-2013 does not only account for the immediate outdoor temperatures but it also gives a sense of the weight of the high temperature. On this basis, it can be said that CIBSE TM52-2013 accounts for more dimensions of overheating. However, the survey undertaken in the overheating assessment has shown that passing the overheating assessment in CIBSE TM52-2013 is easier than in all the other assessments taken into account here.

This is an important finding, since designers with an insufficiently developed professional judgement (for instance, designers with limited experience in relation to HIHs) may end up overlooking the risk of overheating as a result of relying on CIBSE TM52-2013. While this risk is to be confirmed by assessing simulated data (in addition to monitored data), CIBSE TM52 was found to underestimate the level of overheating reported in some occupants' responses.

In addition, the fact that occupancy changed throughout the survey period, particularly with regards to their vulnerability to heat stress, suggests that the elaboration of the concept of '*temporary vulnerable occupants*' and its inclusion into the assessment of overheating should be considered appropriate. This is an important finding: while in this study there were different microclimates within the houses (some rooms with different orientations, locations or ventilation), which provided occupants with the opportunity to move within the house to adapt to high temperatures, in single-sided multi storey apartments this possibility may not be available. Therefore, it could be recommended that there be a revision to building categorisation and a flexible occupancy expectancy inclusion in standards.

5.3 USER PERSPECTIVE (SUBJECTIVE MEASUREMENTS)

This section looks into the user perspective as a part of the longitudinal study. It is based on both quantitative as qualitative data. The aim is to examine how HIHs perform thermally by asking the opinion of the occupants. This means that one must evaluate the occupants' responses of how comfortable they find their houses and examine the role occupants play in the thermal performance of their houses. Importantly, this section will explore how HIHs are used and managed. On this basis, it assesses the occupants' level of understanding of how to maximise thermal comfort.

In this spirit, questionnaires were aimed at collecting a feedback on the effectiveness of new highly insulated designs as well as at collecting data regarding occupants' behaviours, occupants' control, and occupants' thermal comfort sensations in order to capture how perceived thermal comfort and behaviour of the tenant relates to the environmental measurements in their houses.

These subjective measurements were collected via two types of closed-question questionnaires:

- Q1, which was used to record the interaction between the occupants and their houses, such as use, ventilation, adaptive measures, and possibilities for thermal pleasure. These questionnaires were submitted at any house visit (5 questionnaires submitted per case study, total of 20 questionnaires Q1). It included a generous number of open questions in the form of "any other comments on…" in order to let occupants provide any information that they feel relevant. The full questionnaire is included in Appendix C.
- Q2, or thermal sensation questionnaire, was about what people feel and do in order to maintain or modify a thermal state. These self-reported questionnaires were submitted at any convenient time by occupants via an online platform, except for one occupant who supplied written responses (total of thermal subjective responses of 32). The full questionnaire is included in Appendix C.

The figure 5.36 below shows the timeline for the questionnaires' submission and location within the monitoring period.

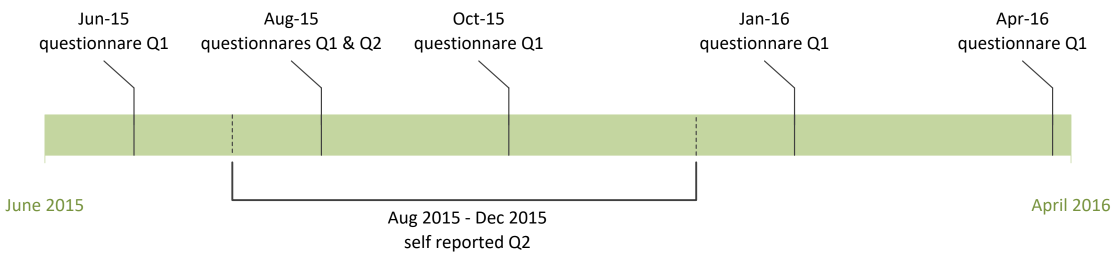


Fig. 5.36 Subjective measurements' timeline.
The period in which temperatures were recorded is shaded

5.3.1 LONGITUDINAL QUESTIONNAIRE

5.3.1.1 BUILDING SYSTEMS USE

Questionnaires allowed us to gain a general view of building systems in each house. While houses UK51 and UK54 did not spend the summer in their houses, it was possible to collect some information about the past winter heating approach.

In fig. 5.37 it can be noted that house UK52 (uncertified Passivhaus) used heating for the lowest number of months. It can also be noted that three out of four houses had the MVHR turned on constantly. This could mean that heat was recovered during summer. It can also be noted that the heating was turned on during more months in the Yorkshire case studies. Interestingly, in both houses where occupants experienced a hot summer, uncomfortably warm temperatures were felt by the occupants to the point that they claimed to have felt the need to cool the rooms.

The necessity to cool rooms was interpreted differently by different occupants. For instance, in house UK52 the need to cool rooms was intended, as per opening the windows; while in house UK55 the need to cool a room was perceived but the occupant believed that the MVHR should have been able to cope with purging high temperatures, and so he kept windows closed despite the high temperatures (see below section 'window opening patterns). It was also found by the occupants' responses that opening the windows was not automatically linked to cooling. So it is possible that cooling was provided inadvertently by opening the windows.

UK51	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
UK52	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
UK54	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
UK55	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December
	January	February	March	April	May	June	July	August	September	October	November	December

heating ON | MVHR ON | uncomfortably warm | need to cool

note: where text is lightr, response was not recorded because occupants had not lived there yet

Fig. 5.37 Heating and cooling needs as reported by occupants

5.3.1.2 WINDOW OPENING PATTERNS

Questionnaire Q1b collected information about occupants' behaviour. Question 10 of Q1b was aimed at collecting information about window opening as a practice to purge high temperatures. The question submitted was the following ranking question: "*During hot weather, how often do you open the windows in order to cool your house?*" (never=0, rarely=1, once a week=2, daily=3, night=4, day&night=5).

A salient finding was the fact that most occupants of the houses surveyed perform window opening day and night (even outside the summer season) and that rooms where natural ventilation was not performed was only a consequence of some restriction (due to an inability to open the windows, inaccessible or street security/odours) rather than the need itself not existing. In more detail, the relevant findings can be summarised as follows.

- In house UK51 (fig. 5.38), windows were open in many rooms throughout the whole year, especially the bedrooms and the first-floor bathroom. This trend changed only for bedroom 1 due to noise from the street. Bedroom 2 (converted loft) was kept open day and night, because it was found to be difficult to keep comfortably cool.

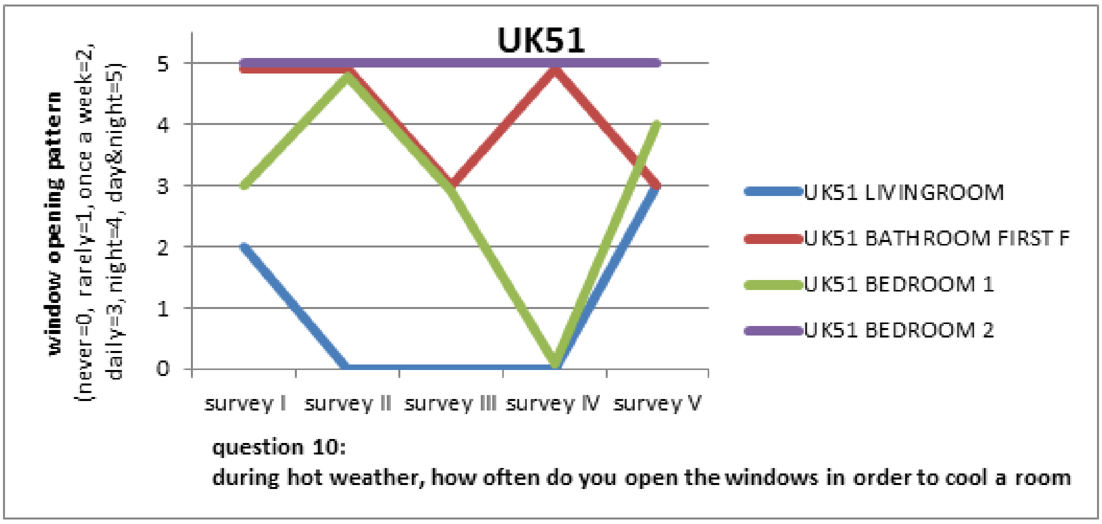


Fig. 5.38 Window opening pattern house UK51

- In house UK52 (fig. 5.39), windows were regularly kept open throughout the entire monitoring period, surprisingly also in winter. The only window that was not regularly opened was in the kitchen, but only because this window was found to be difficult to open (occupant had to use a chair to reach the handle, as the researcher did when trying to open the window).

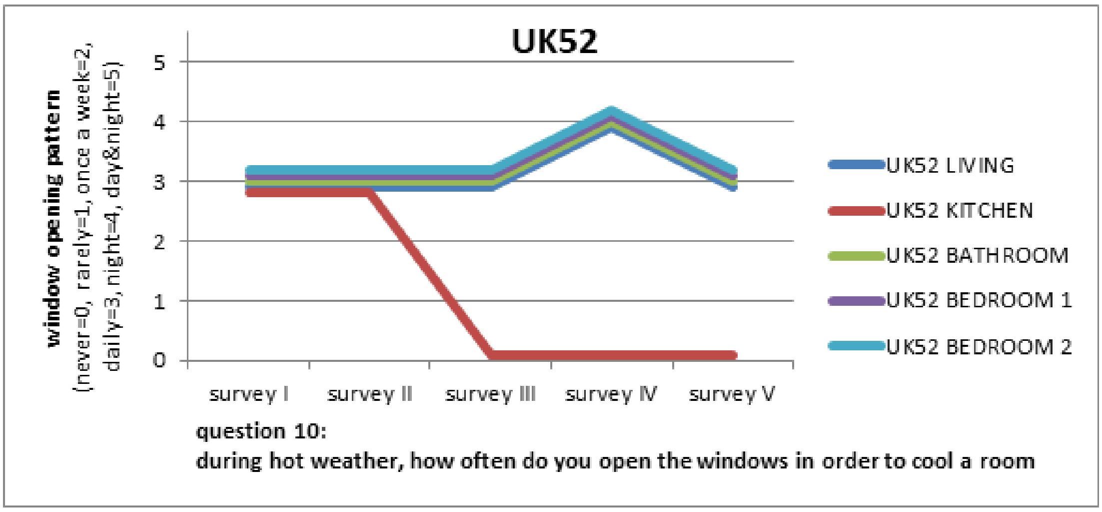


Fig. 5.39 Window opening pattern house UK52

- In house UK54 (fig. 5.40), all windows were opened at least daily, with instances of day&night ventilation. Construction works restricted the opening of the office and bedroom 2 (street facing). Occupants of this house managed the house via natural ventilation only because the MEV provided was turned off (due to the occupants' preference to control ventilation by them). Conversations with the occupants revealed a 'Mediterranean' approach to manage their house, via window opening in the coolest parts of the day. Occupants revealed that they have been visiting Mediterranean countries during the summer for many years, and have thus learned to use adaptive behaviour.

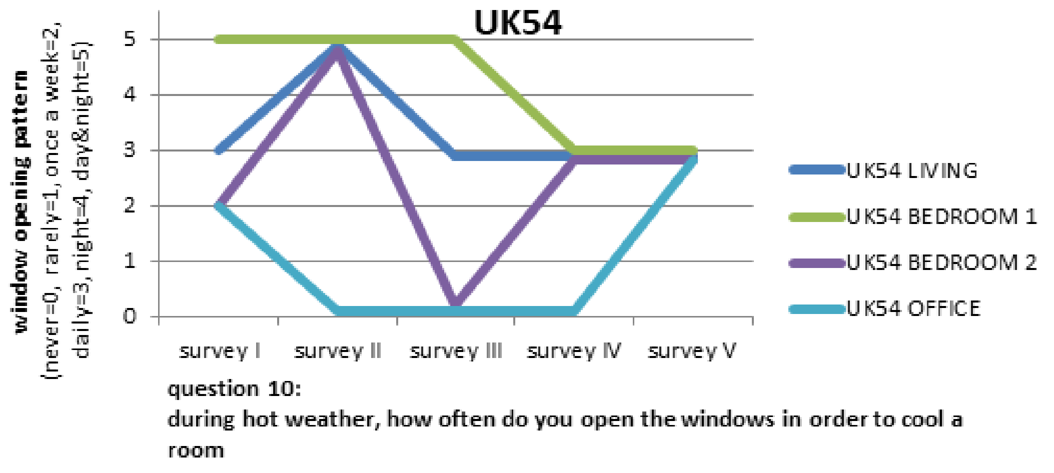


Fig. 5.40 Window opening pattern house UK54

- In house UK55 (fig. 5.41), there was no window opening in the main bedroom despite high temperatures, probably due to the fact that one of the occupants did not notice the warm environment due to health-related issues.

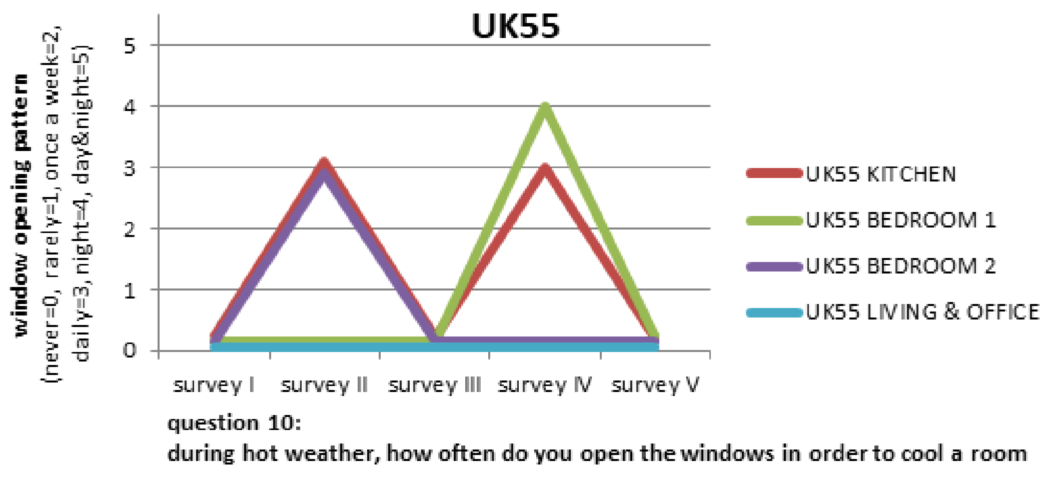


Fig. 5.41 Window opening pattern house UK55

When looking at all bedrooms only (fig. 5.42), it is evident that during the warmer season house UK55-bed1 windows were kept shut. Also, it was evident that house UK51-bed2 was kept open day and night throughout the 11 months of monitoring. Interestingly, these two rooms reported overheating (see overheating assessment in section 5.2 of this chapter) but the fact that house UK51-bed2 reported overheating despite the ventilation management, which brings light to the fact that while house UK55-bed1 would still have adaptive possibilities for lower temperatures, house UK51-bed2 does not.

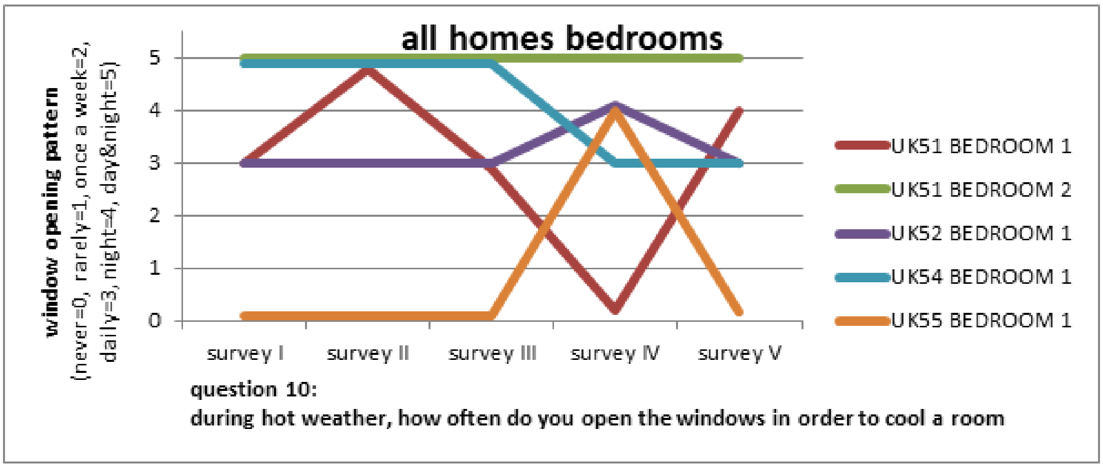


Fig. 5.42 Window opening pattern all bedrooms

5.3.1.3 OVERHEATED ROOMS

Question 13 was submitted to gain feedback on areas of potential overheating within the house. The question submitted was: "*During this time of the year, do you find it difficult to keep comfortably cool in any room?*" Respondents had to circle the times in which a room (room by room) within the house was difficult to keep cool. This question allowed for a first-hand approach to obtain information about each house and the relationship to the comfort provided to their occupants without mentioning the word overheating within the question (table 5.13). This question was completed with an open question for interviewees' comments.

- **House UK51** reported overheating only in bedroom 2 until the last questionnaire. In this room, occupants reported trying to keep the blinds down to reduce temperatures. However, this solution was not sufficient, but later in the year they resolved the issue by opening the windows day and night.
- **House UK52** reported always that the hall was always difficult to keep comfortably cool, though the occupant did not perceive it as something to complain about. The high temperature of the hall was used to "heat up the rest of the house". This may constitute a risk when temperatures are already high, and heating is not needed. It is also noticeable that occupants of house UK52

reported rooms to be uncomfortably warm in the occupied hours of that room, so there is a possibility for such rooms to be too warm during other hours.

- **House UK54** reported no problems besides the office on the first floor. This room has a south-facing Velux window which was kept closed at all times during the first period of the survey (due to building works nearby). Once work was finished and ventilation was restored, no problems were reported. This shows the risk of relying purely on ventilation to purge heat, as at times, and for numerous reasons, ventilation might not be an option.
- **House UK55** was a particular case, since the interviewed occupant seemed not to report problems. However, looking at the loggers recorded temperatures, this house has recorded occurrences of severe overheating. In this case, it was known that the occupant had a neurological condition that might have limited their perception of warmth.

Table 5.13 Reporting of rooms being difficult to cool throughout the longitudinal study

Q1a- question 13:	During this time of the year, do you find it difficult to keep comfortably cool any room?																			
	UK51					UK52					UK54					UK55				
room:	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V	I	II	III	IV	V
LIVING ROOM	no	no	no	no	18:00-22:00	no	09:00-16:00	no	no	14:00-16:00	no	no	no	no	no	no	no	no	no	no
KITCHEN	no	no	no	no	16:00-22:00	no	no	no	no	14:00-16:00						no	no	18:00-20:00	no	no
HALL						00:00-24:00	00:00-24:00	00:00-24:00	00:00-24:00	20:00-22:00	no	no	no	no	no	no	no	no	00:00-24:00	no
BATHROOM GROUND						no	no	no	no	14:00-16:00	no	no	no	no	no	no	no	no	no	no
BATHROOM UPSTAIRS	no	no	no	no	18:00-22:00						no	no	no	no	no	no	no	no	no	no
BEDROOM 1	no	no	no	no	18:00-22:00	no	20:00-08:00	no	24:00-08:00	20:00-22:00	no	no	no	no	no	no	14:00-18:00	no	no	22:00-08:00
BEDROOM 2	18:00-24:00	12:00-20:00	24:00-06:00	no	14:00-18:00	no	20:00-08:00	no	24:00-08:00	20:00-22:00	no	no	no	no	no	no	no	no	no	22:00-08:00
BED 3 OR LOUNGE UPS	no	no	no	no	no						no	no	no	no	no	no	no	no	no	no
OFFICE											11:00-17:00	11:00-17:00	no	no	no	no	08:00-12:00	no	no	no

It was interesting to find that most of the responses correspond with the loggers' temperatures. In detail, the occupants of house UK51 complained about bedroom 2 from the beginning of the survey, which coincided with the overheating assessment.

House UK52 showed difficulties in keeping the hall comfortably cool for the majority of the monitoring time, while the living room and bedrooms only at times of normal occupancy and for some parts of the monitoring period.

House UK54, on the other hand, flagged only the office upstairs. All these three houses saw some correlation with the logger's analysis. On the other hand, the responses from house UK55 changed throughout the monitoring period, and different rooms were mentioned on different occasions. This reveals that the assessment carried out by occupants with health conditions may not be reliable.

Another relevant finding from question 13 concerns house UK52, where the occupants noticed that the hall was being difficult to cool. The hall is not an inhabited space and the overheating assessment would not normally be interested in this space. However, halls or **transitory spaces** (such as corridors) often contain building services which may affect the thermal performance of the building, especially when they release heat. In this case, the domestic hot water tank was located in a cupboard linked to the hall, so releasing extra heat in this area. Interestingly, at a certain point the occupants of house UK55 also indicated that the hall (where the heating systems were located) was too warm. Contributions from the excess heat from these technical rooms are also explored in the heat wave analysis (section 5.2.3 of this chapter).

From a methodological point of view, occupants' responses to question 13 have shown that at times consulting occupants is not sufficient to spot overheating; people might not want to complain or, as for house UK55, might have a limited thermal perception. Therefore, questionnaires to occupants are to be considered only one part of a more comprehensive enquiry.

Moreover, it was found that, while people adapt to find comfort, this possibility is not endless if environments do not provide different means for adaptation. For instance, the fact that house UK51-bed2 was not comfortably cool despite the window being open during the day and many times during the night shows a concerning risk of rooms becoming unusable. In this case, fortunately, the living room provided a temporary shelter during the heat wave, however unsustainable this might have been for the remaining parts of the year.

Finally, another observation relates to the **temporary unavailability of ventilation**, which happened in house UK54-office, exemplifying the risk of relying purely on ventilation to purge heat as at times, and for numerous reasons, ventilation might not be an option. While in this case the disruption was minimal to the occupants, the effects that unavailability of ventilation has on HIHs has to be considered.

5.3.1.4 OCCUPANT CONTROL

Question 17 of Q1b was aimed at collecting information about the perception of control that occupants have over their environments (see fig. 5.43). The ranking question submitted reads: *"How much control do you feel you have over the temperature in this house?"* (1=no control, 7=full control). The open question to comment on the score allowed occupants to justify their scores.

A salient finding was the fact that most occupants of the HIHs performed window opening both day and night (even outside the summer season) and that when natural ventilation was not performed it was due to an inability to open the windows (inaccessible or street security/odours). In detail:

- **House UK51** showed a significant "no control" response over bedroom 2, where occupants reported the need to keep the blinds down to reduce temperatures. This solution was not sufficient for them to have complete control over the temperature. Control over the temperature of bedroom 2 improved throughout the survey but, after the summer, the occupant of bedroom 2 swapped location with the occupant of bedroom 1. This change may have influenced the feeling of control.
- **House UK52** showed a marked change in user perception of control throughout the study period for the same room (the living room).
    - In the first questionnaire, occupant of house UK52 reported "no control" in the living room, claiming that she felt that not having a thermostat in the living room would not give her that option[51].
    - On the second survey, this opinion changed to high scores because "*I can control but because I just kept settings*" [occupant of house UK52, II survey].
    - On the third visit, the occupant' mid score was linked to the fact that she did not know if she was doing things correctly, but she was happy to leave things as they were.

[51] In reality, the living room in UK52 is provided with a thermostat to control the supply air heater. This information was written in the house manual, which was in hands of the occupant. Such lack of awareness, despite having the house manual, may be linked to the large amount of information the occupant had to process in reference to a Passivhaus-like house.

   - In winter (fourth visit) the high scores were justified by the occupant on the basis that she was able to control the temperature by opening the windows.

- **House UK54** reported the highest scores with regards to control over temperature.
- **House UK55** reported the lowest score with regards to control over temperature during the summer.

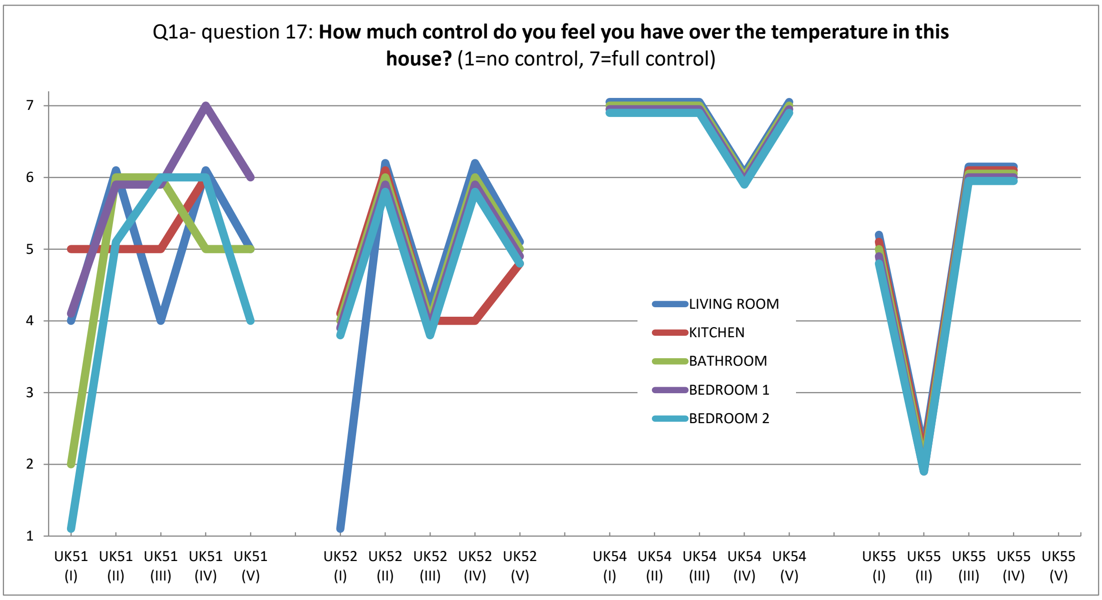


Fig. 5.43 Perception of control over temperatures, all houses

Question 17 revealed to be one of the most multi-dimensional questions when considering the responses to the aspect of control over temperature. When asked to give a ranking of their feelings of control, occupants appeared to have difficulty in deciding on their levels of control over the temperatures in their houses. Once ranking was recorded, the following open question asked them to comment on their ranking. Thanks to this open question, the interpretation of the scores given became much more insightful, allowing for an understanding of the changing perception of control (see house UK52 responses).

- For instance, in some cases a high score (7=full control) was based on the occupant not touching the controls and so being happy with the environment "*I don't understand I leave it like that so I have control*" [occupant of house UK52, II survey]; evidently control in this instance was correlated with contentment over temperatures;

- Another high score for temperature (during winter) was linked to the occupant using a portable electric heater, and therefore was happy to manage temperatures at his ease, even though this was in marked contrast with the assumptions of the Passivhaus-like retrofit of such a house [occupant of house UK51, IV survey];
- Another case was when occupant did not want to give a 'control' score, since in his view there was no need to control the environment that summer, even during the heat wave. In this case, the occupant was known to manage the house via window opening, though he did not appreciate this as being a means of temperature control [occupant of house UK54, II survey]. Also, the same occupant later in the year stated that "*you can't fully control because of the thermal mass, thermal mass does not provide comfort temperatures as quick as other means but I accept it because it performs better*" [occupant UK54, IV survey].

The above considerations would not have been possible without the open question. The answers to this question in particular evolved as the understanding (or confusion) of controls increased throughout the monitoring period. This could allow to link the changing scores of control to occupants changing experience of control over the longitudinal monitoring.

It is the researcher's conviction that ranking questions have helped occupants to form an opinion about their environment. While ranking questions alone might not provide an insightful response (as in the case for temperatures control), they have been effective in enabling occupants to formulate their opinions on environmental control (assumed previously to be none) of their houses. In this process, it is also acknowledged to be a sphere of action research that this longitudinal study has brought, due to the fact that through the researcher inputs (however unintentionally) occupants gain a better understanding of their environments.

5.3.1.5 CHANGES IN OPINIONS

Occupants' responses at the beginning and the end of the summer have been analysed so as to spot differences in opinion throughout the monitoring period. In table 5.14 the responses to the same question submitted in late spring/early summer 2015 and in mid-summer 2015 are highlighted; in other words, at the beginning and at the end of the warmest part of the summer. The goal of this strategy was that of seeking confirmation to the occupants' opinions and behaviours throughout summer, as the general feedback from HIHs was overall positive due to the numerous advantages of these new designs. In other words, it has been considered important to notice if any 'forgiveness factor' was influencing occupants' responses.

Table 5.14 Changes in opinion across summer

	House UK51		House UK52		House UK54		House UK55	
	I	II	I	II	I	II	I	II
When the weather is warm, how often the windows were kept open in order to cool a room?	day&night	day&night	day	day	daily	daily	no	daily only one room
When the weather is warm, how difficult is to keep comfortably cool any room?	only bed 2	only bed 2	no	living rooms (day) & bedrooms (night)	only office	only office	no	all house

survey I: beginning of summer 2015
Survey II: end of summer 2015

When asked: "*How often the windows were kept open in order to cool a room*?" the occupants of houses UK51 and UK54 said that they left the windows open to cool the house day and night. By contrast, the occupant of house UK52 left the windows open during daytime only for security concerns. Lastly, no cooling through window opening was used in house UK55. These opinions where mostly maintained in both the first and second questionnaires.

On the other hand, when asked: "*How difficult is it to keep comfortably cool in a room?*" the responses from early till late summer (i.e., after the heat wave) showed some changes in opinions. The occupant of house UK52 claimed that she did not report any difficulty keeping a room cool in early summer. However, by mid-summer, the occupant did find it difficult to sleep due to excess heat and opted to go to the living room to open a window and – concerned about potential burglary – kept herself awake by reading a book.

Moreover, the occupant of house UK55 stated that they had no difficulty in maintaining room temperatures at a comfortably cool level in the first questionnaire; however, in the second questionnaire the same occupant claimed that they experienced difficulties in maintaining comfortably cool temperatures throughout the whole house during the entire day, to the point that they felt the necessity to go outside in order to gain thermal relief.

This analysis shows that opinions and behaviours change within any given season. Hence, the importance of longitudinal studies in innovative architecture.

5.3.2 THERMAL COMFORT STUDY

The aim of this thermal comfort study is to record and reflect on the subjective experiences of the occupants of the case study HIHs. This task was achieved by comparing the thermal comfort survey of a set of HIHs with the thermal comfort survey of a set of non-HIHs. Both sets of buildings were surveyed at the same time as part of a larger study (see below).

The thermal comfort study presented here forms part of a larger international multi-partner study aimed at understanding the role of air motion in providing thermal comfort in the residential sector [Loveday *et al.*, 2016]. This study was funded by the British Council as a Global Innovation Initiative (GII) project, and generated a dataset of conditions, thermal comfort sensations and occupant behaviours for UK and Indian homes. The analysis presented here utilises a subset of that data together with some of that analysis. The full presentation of the results is currently under preparation as a journal paper. Within this international study there is a group of fifteen British houses, four of which are HIHs. The same method of data collection (i.e., electronic questionnaire submission and hobo loggers indoors and outdoors) was used for all. This process generated a set of data on thermal conditions, sensations and air motion practices.

In this section, the results of the study concerning the four HIHs are presented in the context of the larger group of British houses.

5.3.2.1 BACKGROUND

The thermal comfort **model** engaged is the **PMV model**. PMV, or *predicted mean vote*, is a thermal index related not only to temperature but to a total of six variables (see table 5.15). PMV is typically used as an indicator of indoor comfort [Nicol, Humphreys and Roaf, 2012][52]

The reason for using this model lies in the fact that Passivhaus was developed on the basis of the Fanger's steady-state thermal comfort model[53], which drives the design principle to keep the temperature in the building constant [Passivhaus Institute, 2011]. Two of the case study houses were designed based on Passivhaus principles. The other

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[52] On the contrary, the adaptive thermal comfort model would simply associate thermal sensation responses (actual mean vote AMV) to outdoor temperatures.

[53] Fanger's comfort equation is derived from the concept that for optimal thermal comfort the heat loss of the human body is in equilibrium with its heat production [Passivhaus Institut, 2007]

two were not designed in this manner, though they did have high levels of insulation and air tightness.

It should be initially noted that the adaptive comfort model could have been used in this analysis, in consideration of the fact that in three (out of four) case studies occupants put in place a form of adaptive behaviour (namely, window opening). When the limitations of each thermal comfort model in the analysis of the case studies are taken into account, in HIHs where MVHR operates constantly and the design is based on constant temperature maintenance, the PMV model can be claimed to best fit the case studies. This choice is made on the understanding of each model's limitations and degree of uncertainty.

There are two main components to the data gathering for this analysis:

a. Gain the participants' subjective thermal sensations and thermal acceptability of their thermal environments. This was reflected on the overall actual mean vote (AMV) using subjective thermal votes on the thermal sensation scale; and
b. Obtain the participants' clothing insulation value (CLO) and metabolic rate (MET). This questionnaire was submitted multiple times between the period April-December 2015 (see Appendix C for complete questionnaire vision);

- The spot measurements were recorded from the HOBO loggers (indoors and outdoors). These were then combined with questionnaire Q2 at the times of questionnaire completion.

Subsequently, and prior to data analysis, data cleaning took place. As previously stated, in this survey the general PMV method (and specifically, the *analytic thermal comfort zone method* for compliance) has been applied. Accordingly, only responses with MET within 1 and 2 have been considered [ASHRAE, 2013a]. It is acknowledged that the actual range of metabolic activities in residential housing is much broader. For instance, while sleeping is 0.7 MET, house cleaning lies between 2.0-3.4 MET [ASHRAE, 2013a]. However, questionnaires were submitted online and recorded previous activities before submission were prevailingly sedentary.

This first step of data cleaning of the fifteen British houses surveys provided 509 responses. These responses were divided in two subgroups: (a) highly insulated houses (HIHs) and (b) non-highly insulated houses (non-HIHs).

In addition, and in order to compare results from the two groups—namely, HIHs and non-HIHs—a number of responses were excluded from the analysis to make the two groups directly comparable. The reasons for this are listed below:

- Responses from children (up to 16 years old) were excluded, since in the HIH group there were no children;
- Responses given in the period April 2015 to May 2015 were excluded, since in this period, no response from the HIH group was recorded;
- Responses provided during the heat wave were excluded, since in this period only, responses concerning the group of non-HIH were recorded. This means that there was no opportunity to compare the outcomes relative to the two groups (i.e., associated potential extreme values);
- Responses given by adults younger than 35 years old were excluded. The reason for this deletion is that no adult younger than 35 years old answered questions concerning the group of HIHs.

These further exclusions reduced the number of usable responses to **259.** Of the remaining 259 responses, 227 responses were relative to the non-HIH group and 32 responses were relative to the HIH group. It seems worth noting the proportion of responses excluded from this analysis as shown in fig. 5.44.

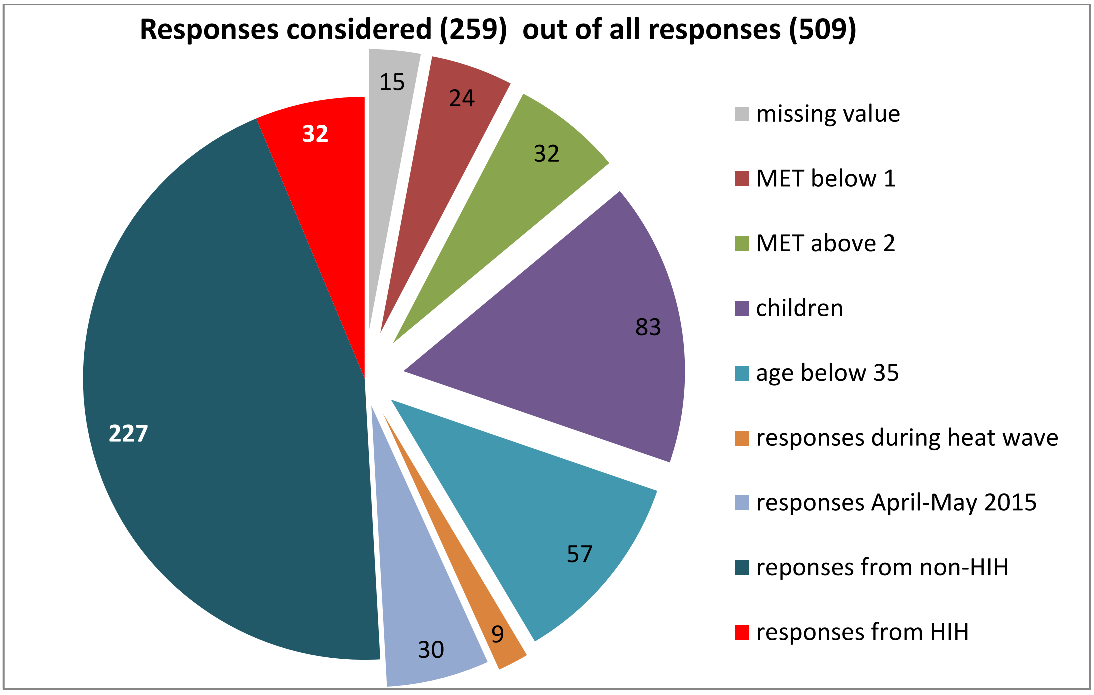

Fig. 5.44 All data collected, and responses considered, in this analysis on the left side of the pie chart

5.3.2.2 RESULTS

Compliance with ASHRAE was sought via PMV. In order to calculate the predicted mean vote (PMV), six parameters were needed. Table 5.15 lists the sources of data for each of the factors. Here, it can be noticed that the air speed value used was assumed to be 0.1 m/s for all houses.

It has to be noted that the HIH group was found to have much lower air speeds when windows were closed and the MVHR was in operation (spot measurements recorded 0.02-0.06 m/s average air speed[54]). However, their occupants have reported keeping at least one window open most of the time. For this reason, the value of 0.1 m/s was found to be more representative of the air speed within all houses.

Table 5.15 Factors addressed to predict thermal comfort

Factors addressed to predict comfort	Source of data
Metabolic rate (MET)	Q2 activity + values from ASHRAE 55
Clothing insulation (CLO)	Q2 garment + values from ASHRAE 55 CLO with Ensemble calculation includes seat CLO [55]
Air temperature (indoor and outdoor)	Spot measurement (HOBO loggers)
Radiant temperature	Assumed (same as air temperature[56])
Air speed	Assumed 0.1 m/s
Humidity	Spot measurement (HOBO loggers)

A number of correlations have been considered and presented in the following paragraphs[57].

AMV and PMV

AMV responses and PMV-derived values for all houses were plotted in relation to **indoor** temperatures (spot) recorded at the time of AMV vote submission. Figure 5.45 shows

[54] Average air speed is the numerical average for the three heights: at ankle level the waist level and the head level, over an interval not less than one and not more than three minutes [ASHRAE, 2013a].

[55] The omission of the thermal effect that chairs have on their occupants has been linked to PMV overestimation [Brager and de Dear, 1998].

[56] "*Lightweight furnishing surfaces are often close to air temperature and consequently the mean radiant temperature in a room is typically close to air temperature*" [Nicol, Humphreys and Roaf, 2012, pag. 14].

[57] The percentage of people dissatisfied (PPD) has not been considered, because "*work based on field studies suggest that PPD does not reliably predict the discomfort cause by deviations from the comfort temperature in real-life circumstances of diverse activity and clothing*" [Nicol, Humphreys and Roaf, 2012, pag. 46].

that there is a marked difference between AMV and PMV: while AMV recorded responses on the whole ASHRAE thermal sensation scale (i.e., from +2 hot to -1 cold), the corresponding PMV results ranged between +1 (slightly warm) and -3 (cold). The first observation one can make, therefore, is that all AMV responses report a warmer environment than the one that could be predicted.

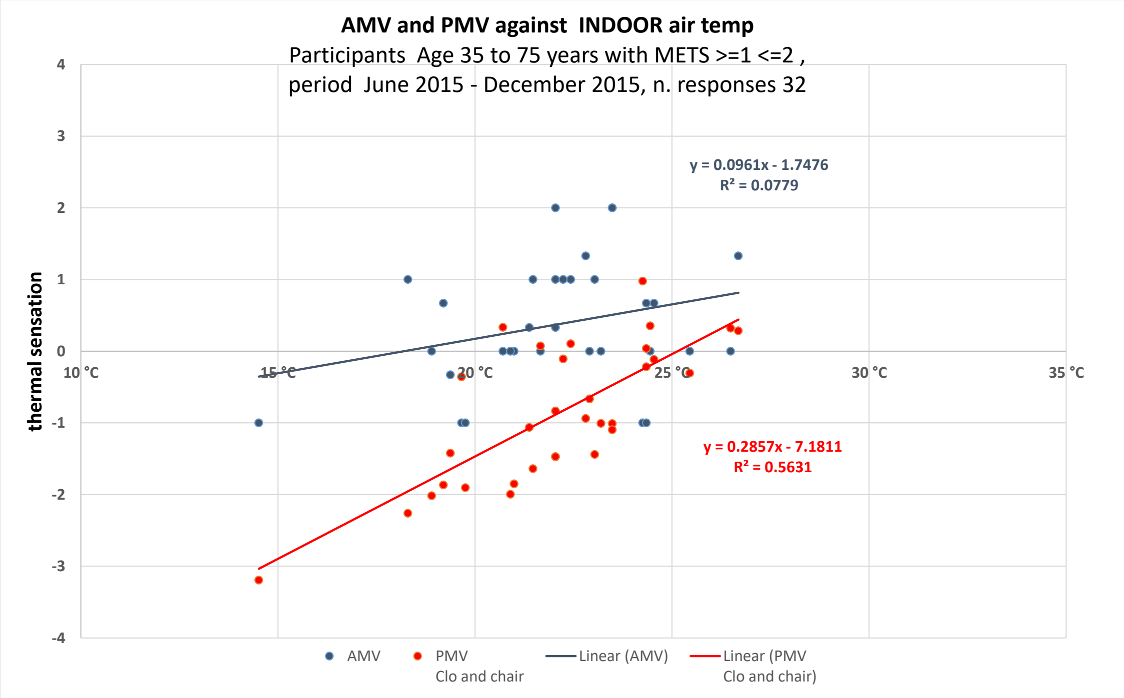

Fig. 5.45 AMV and PMV against indoor air temperatures for highly insulated houses

This could be of relevance in the design of HIHs in England. The fact that the calculated PMV is considerably lower suggests that if PMV were to be used in the thermal design of those houses, in reality people would experience a warmer environment than predicted. This potential underestimation of warmth could lead to PMV potentially underpredicting overheating. Although inconclusive, this finding is in line with other UK field studies where it has been found that PMV generally estimated the thermal sensation lower than the actual thermal sensation [Beizaee *et al.*, 2012], providing indication that PMV prediction is not encountering the other processes of adaptation that occur in real life.

AMV ranges

The range of recorded internal temperatures was between 14-28°C. Such a range was similar in both the considered subgroups (non-HIHs and HIHs). Within these temperatures, non-HIH respondent's AMV values covered the whole ASHRAE scale, from -3 (cold) until +3 (hot). The HIH respondent's AMV values covered a much shorter range of thermal sensations within the ASHRAE scale, from -1 (slightly cool) until +2 (warm) (see fig. 5.46).

In non-HIHs, respondent's sensation of "hot" (+3 on the ASHRAE scale) was recorded with internal temperatures between 19-28°C, and "warm" (+2 on the ASHRAE scale) was recorded with internal temperatures between 16-25°C.

In HIH, respondent's sensation of "hot" (+3 on the ASHRAE scale) was not recorded, while a thermal sensation of "warm" (+2 in ASHRAE scale) was recorded with internal temperatures between 22-24°C.

On this basis, it can be claimed that a different range of values on the thermal sensations scale is shown for each of the subgroups. Moreover, HIHs were found to perform better than non-HIHs in terms of comfort when assessed with the analytic thermal comfort zone method.

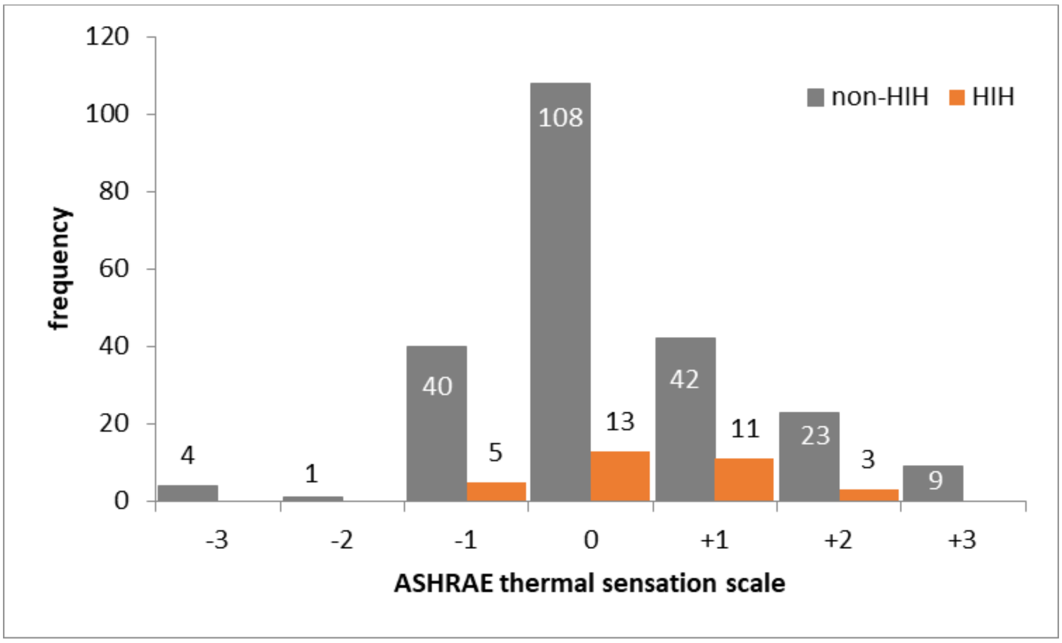

Fig. 5.46 AMV Histograms for all houses: non-highly insulated houses (grey) and highly insulated houses (orange)

AMV frequency distributions

Looking at the histogram in figure 5.46, it can be appreciated that the majority of reported thermal sensations (AMV) are neutral: in the HIH subgroup the range of thermal sensation lies mostly in neutral (0) and slightly warm (+1), whereas in the non-HIH subgroup there are instances spanning across the whole thermal sensation scale with concentrated responses between slightly cool (-1) and slightly warm (+1). In other words, it can be appreciated that between the two groups the proportions are similar, though with a shorter range (-1 until +2) in the HIH group. It is acknowledged that these results are based on a small sample; therefore, the results cannot be considered fully conclusive.

The responses from the HIH group do not suggest a thermal sensation that is "hot" on the ASHRAE thermal sensation scale; by contrast, the non-HIHs reported instances of "hot" thermal sensation votes.

Moreover, the histogram in figure 5.46 shows that in the majority of cases (both in the non-HIH group and in the HIH group) thermal sensation was indicated as being 'neutral'. A notable difference can be found in the HIH group, where the proportion of 'slightly warm' responses is higher (a proportion similar to the 'neutral' sensation) than that recorded for the non-HIH group.

AMV and temperatures correlation

As shown in figure 5.47 responses from both groups (non-HIH and HIH) indicate no correlation between AMV and indoor temperatures, and between AMV and outdoor temperatures. The red arrow in fig. 5.47 is further investigated because it shows a "slightly cold" thermal sensation vote with indoor temperatures around 25°C. This is performed by presenting each house separately, as in figures 5.48, 5.49 and 5.50.

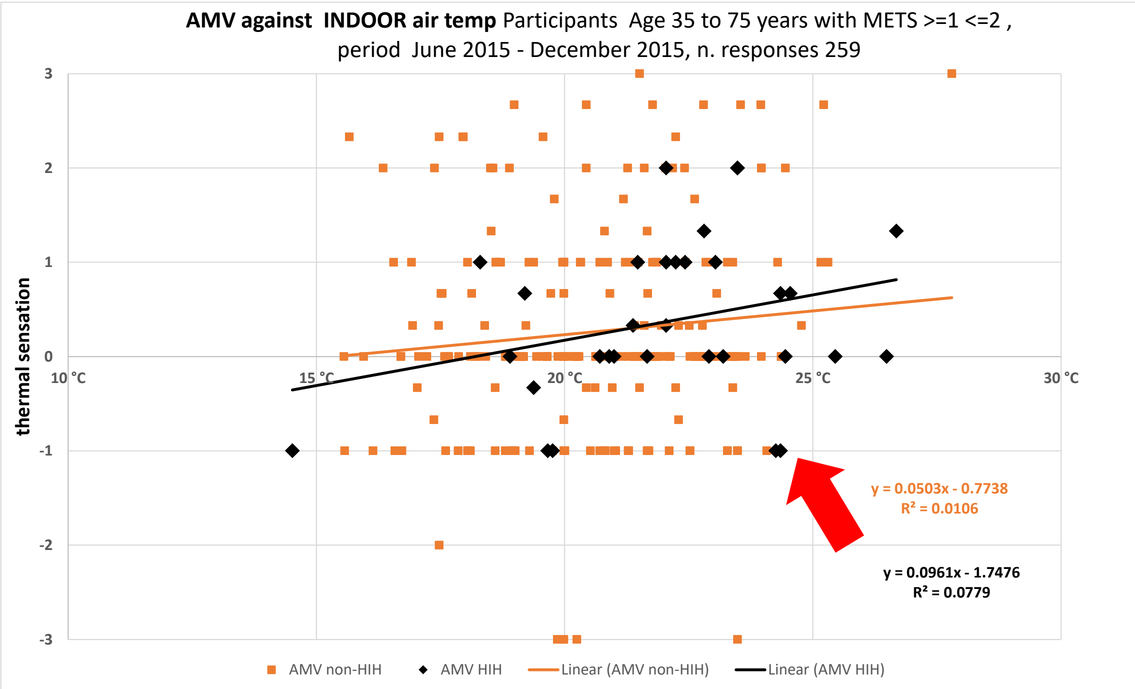

Fig. 5.47 Scatter plot of AMV against indoor temperatures, HIHs in black.

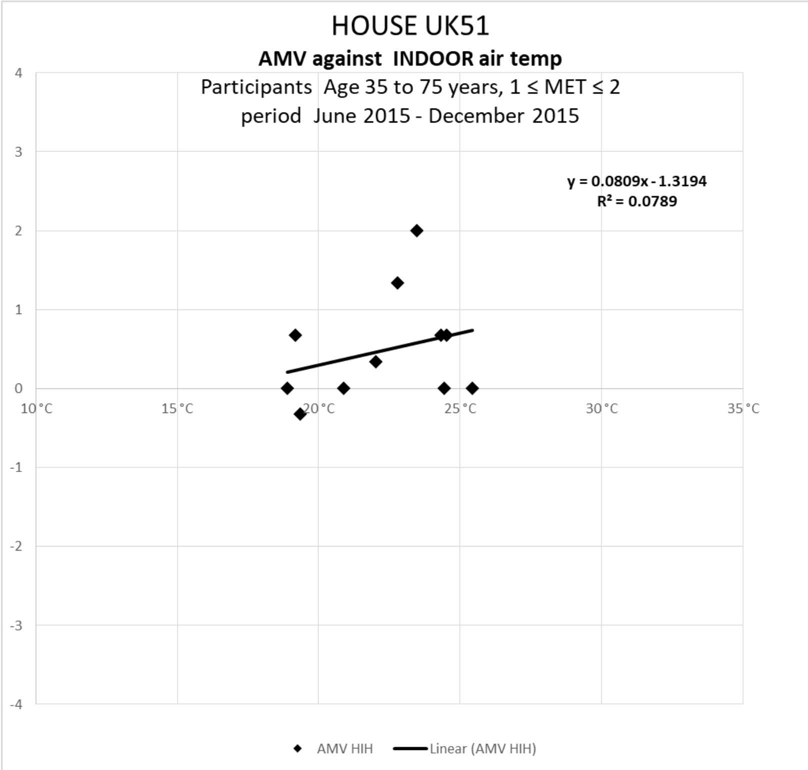

Fig. 5.48 Scatter plot of AMV against indoor temperatures, house UK51

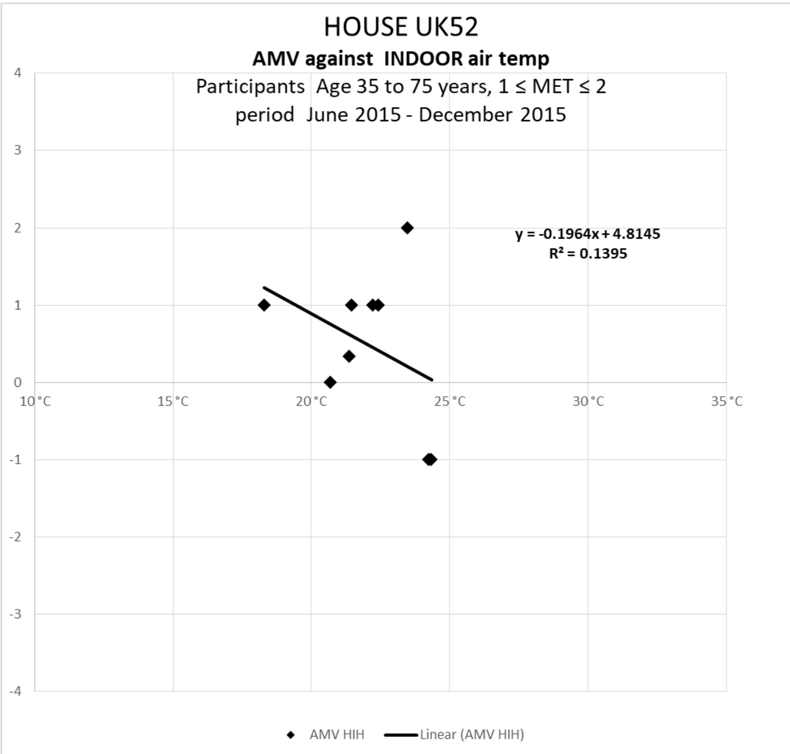

Fig. 5.49 Scatter plot of AMV against indoor temperatures, house UK52

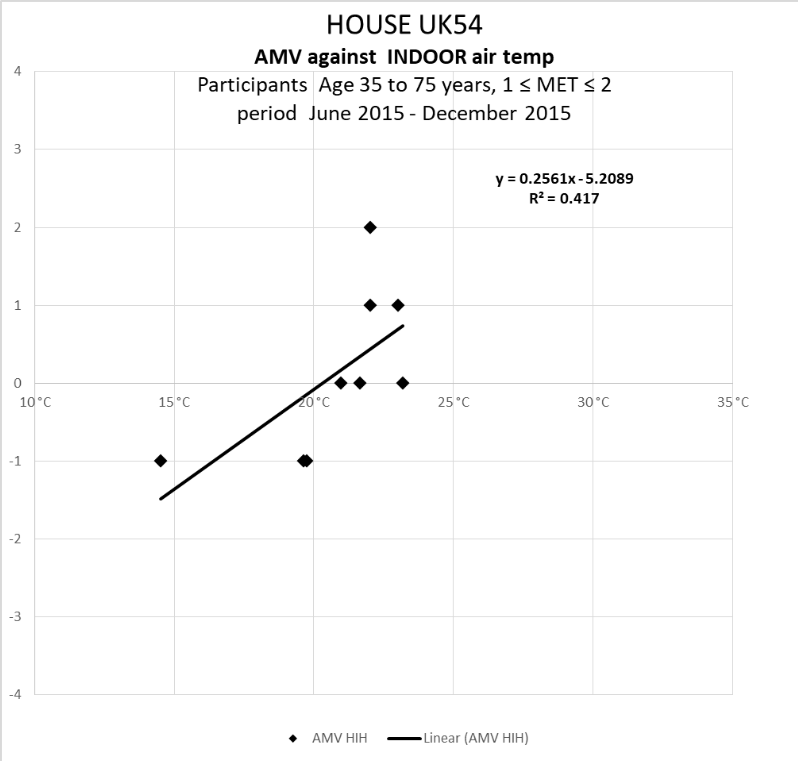

Fig. 5.50 Scatter plot of AMV against indoor temperatures, house UK54

The sensation of "slightly cold" with 25°C was found in House UK52. While this vote may be found hard to believe at such temperature, during the survey the occupant had the two windows slightly open to perform cross ventilation in the living room (from where she was submitting her vote). Performing cross ventilation may have influenced the occupant's thermal sensation. In figure 5.51 it is possible to appreciate the air movement recordings with the Dantec Comfort Sense that may support this finding.

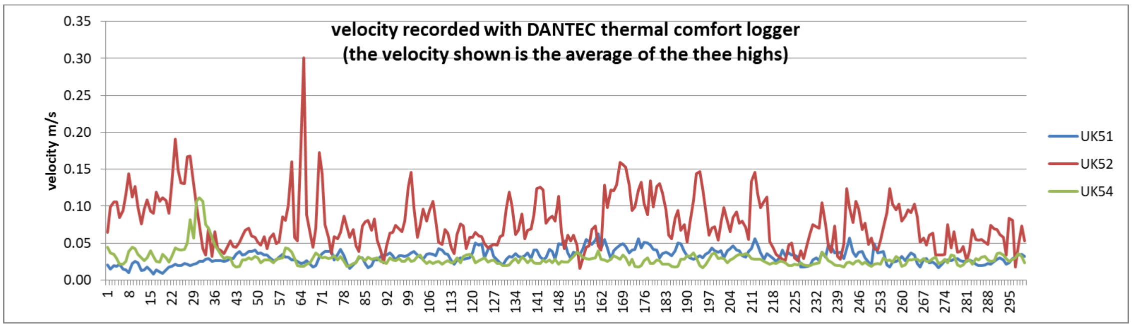

Fig. 5.51 Air movement recorded during the thermal comfort survey in each house.

CLO range

The range of all recorded CLO that took place at the same time in which responses were submitted are distributed between 0.19 CLO and 1.10 CLO. The HIH group represented a shorter range than the non-HIH group, since the former is comprised of values between 0.35 CLO and 0.74 CLO. This difference in range is especially evident in cooler seasons (figure 5.52).

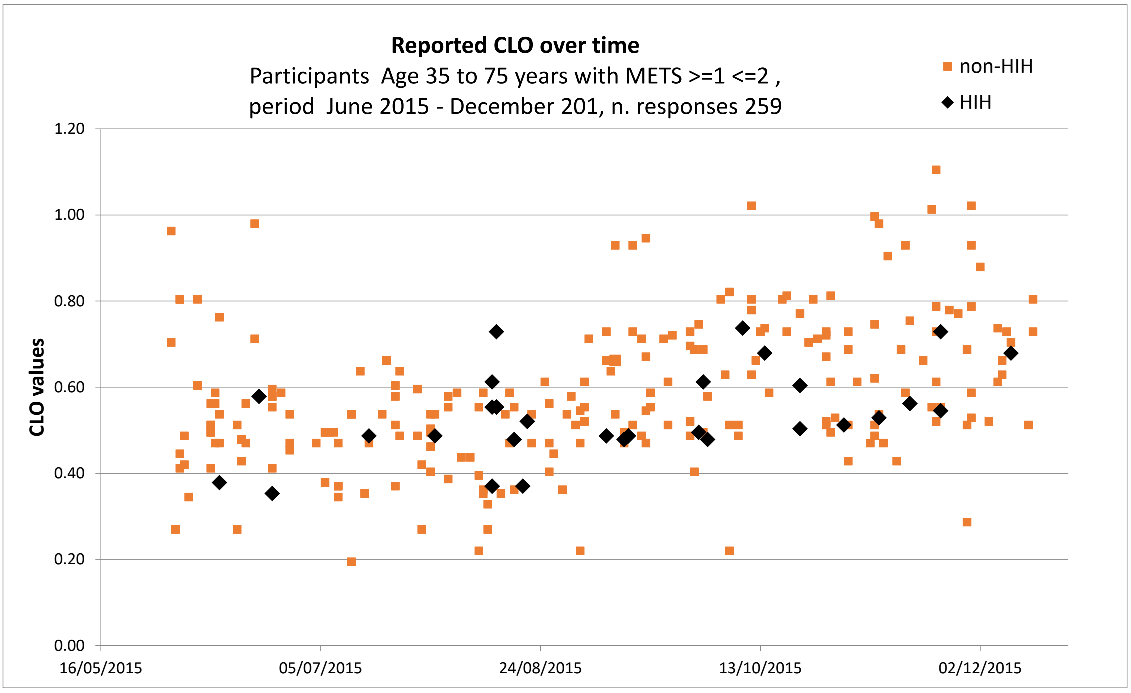

Fig. 5.52 Scatter plot of CLO against AMV over time

In fig. 5.53 it can be appreciated that there is no apparent correlation between AMV and CLO for either the non-HIH or HIH responses. However, if one looks at the thermal sensation votes in points 0, 1 and 2, it can be noted the lower CLO values reported by respondents from HIHs. This may be an indication in the HIH group respondents are less inclined to adapt their clothing to the indoor environment. This is true especially as far the addition of CLO values in terms of adaption to winter temperatures is concerned.

However, the sample used in this study is too small to justify generalisation. Nonetheless, one may be tempted to claim that the recorded results may mean that living in HIHs discourages clothing adaptation and so in the long term may negatively impact the energy consumption in HIHs.

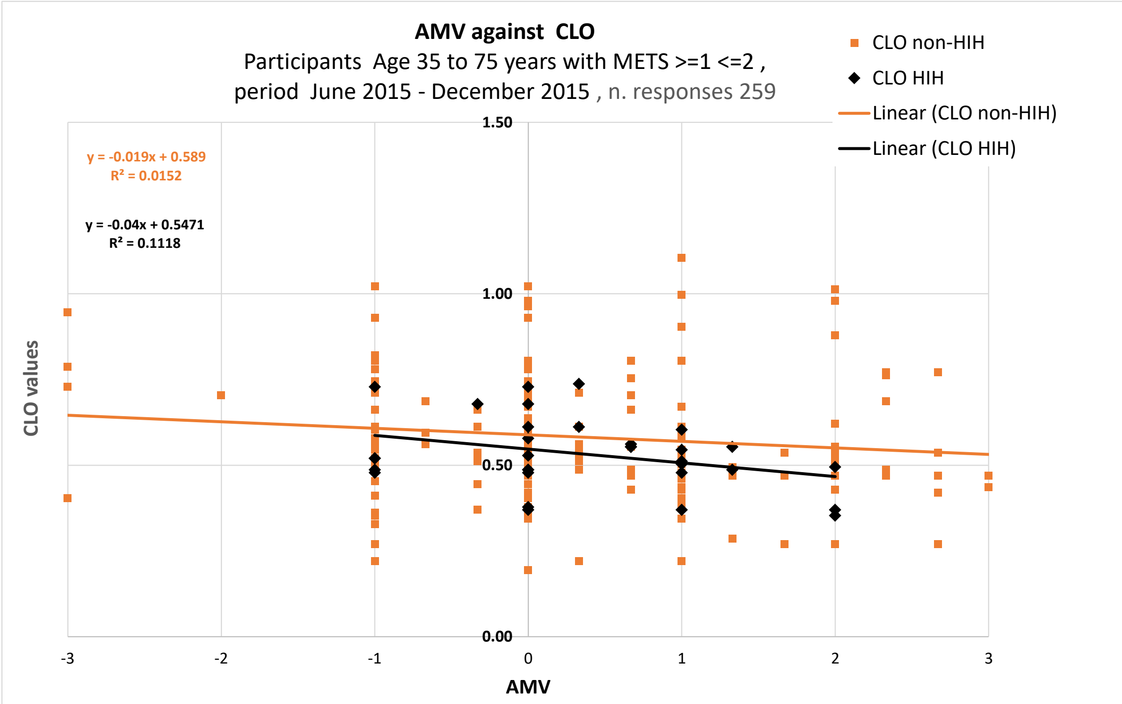

Fig. 5.53 Scatter plot of CLO against AMV

CLO and temperatures

In fig. 5.54 and 5.55, it is possible to appreciate that in non-HIHs, respondents remove clothes as internal temperatures get warmer; the correlation is weak. Plus, when external temperatures are considered the relationship becomes even weaker.

In HIHs, no correlation was found between CLO and indoor temperatures, while there seems to be a weak correlation between CLO and external temperatures.

The fact that people in HIHs adapt their clothes in relation to external temperatures could be an indication that occupants use natural ventilation as a means of adaptive behaviour instead of clothing. This hypothesis seems to be confirmed by the strong correlation found between indoor/outdoor temperatures in the HIHs in particular (see fig. 5.57 in following pages).

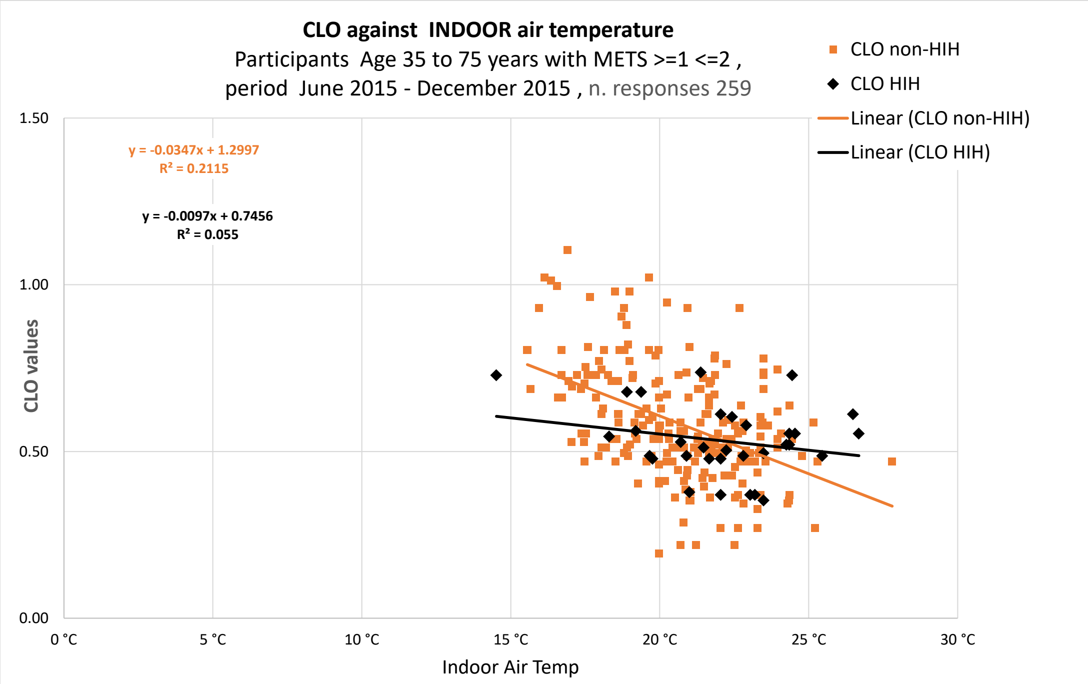

Fig. 5.54 Scatter plot: CLO against indoor temperature

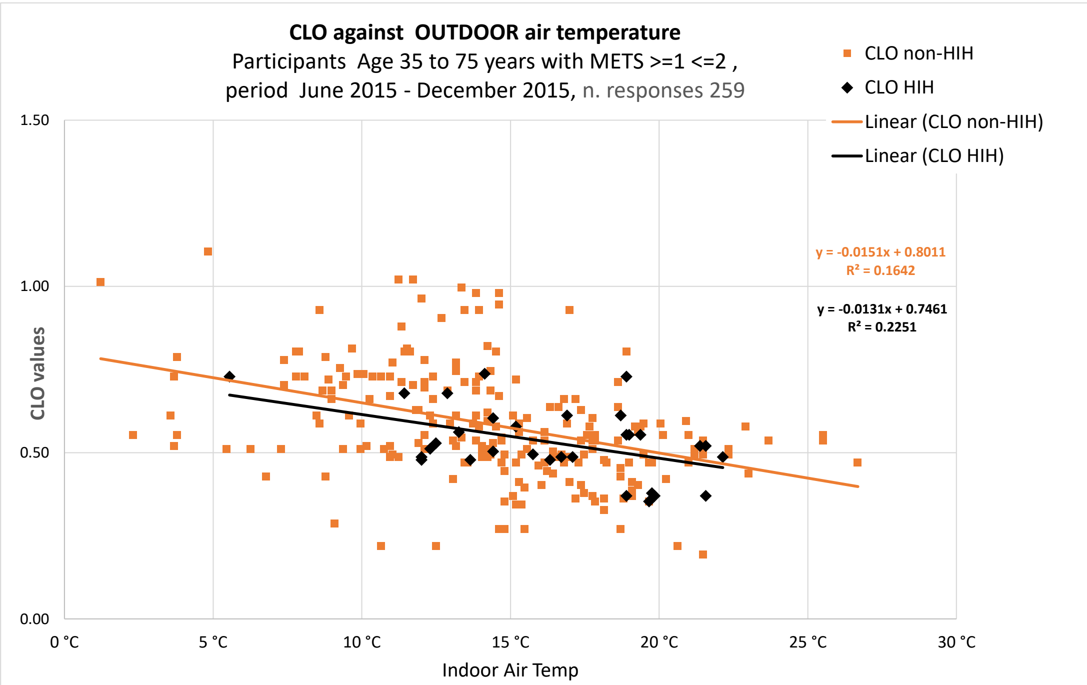

Fig. 5.55 Scatter plot: CLO against outdoor temperature

Indoor/outdoor temperatures

The recorded range of internal temperatures is distributed between 14-28°C. While in non-HIHs a very weak correlation was found between indoor temperatures and outdoor temperatures (fig. 5.56).

In HIHs there is a strong correlation between indoor temperatures and outdoor temperatures (fig. 5.57).

This difference can be taken to support the assumption, introduced in the previous section, regarding the possibly of more frequent use of natural ventilation as a means of adaptive behaviour in the HIHs group. This more frequent use is of some significance, particularly in consideration of the fact that in 3 out of 4 houses, the MVHR was operated at all times.

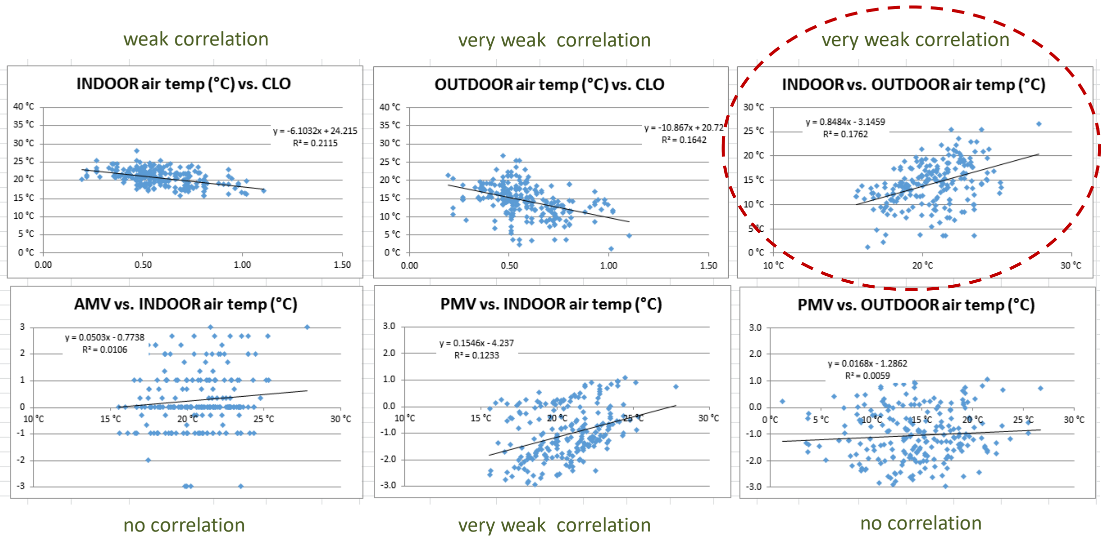

Fig. 5.56 Scatter plots for non-highly insulated houses responses

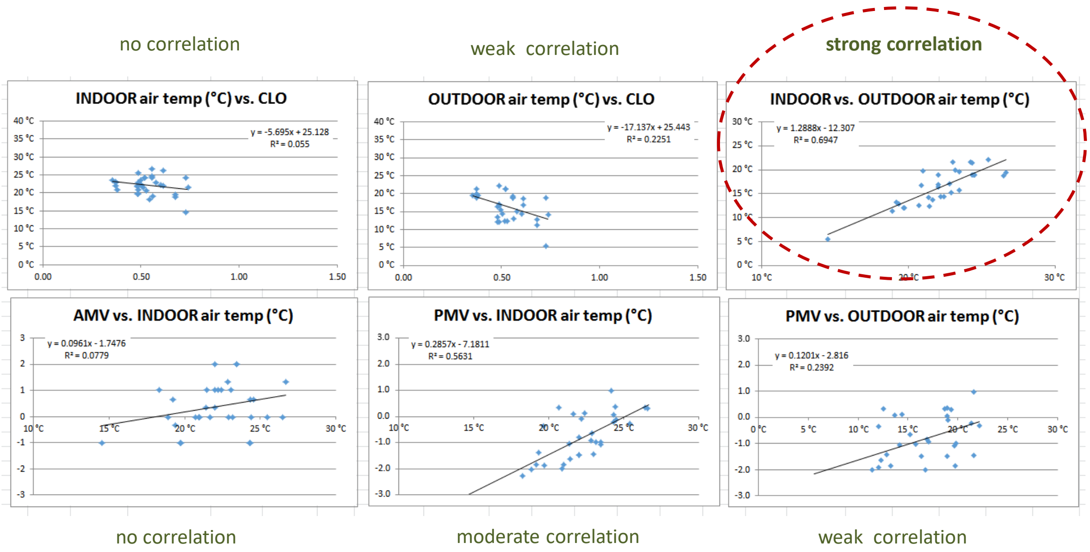

Fig. 5.57 Scatter plots for highly insulated houses responses

5.3.2.3 DISCUSSION OF THE THERMAL COMFORT SURVEY

The thermal comfort survey undertaken in the preceding sections showed **no conclusive** evidence of overheating (not even a recorded "hot"-point 3 on the ASHRAE thermal scale). At the same time, even within the small sample considered in this work, the survey has disclosed a number of risk factors pertaining to HIH. Those risk factors can be summarised as follows.

First, HIHs performed better in terms of ASHRAE compliance: in HIHs, the range thermal perception is less wide—neither too 'hot' nor too 'cold'. This limited variation should be considered positive in terms of the thermal comfort provided. However, when compared to non-HIHs, in HIHs the AMV responses were concentrated on the **warm** side of the ASHRAE scale. This marks a significant change in the thermal perception in HIHs.

In terms of temperature, it was observed that in all houses the air temperature of 24°C was linked to different thermal perceptions, ranging from "warm" sensation to "slightly cool". On one hand, air temperature is the dominant environmental factor[58], and as such, establishing a threshold of 'hot discomfort' constitutes a viable goal. On the other hand, the thermal perception is also related to other factors, as the 24°C observation suggests. This supports the view that thermal comfort is hardly a matter of just temperature. Thermal comfort is rather a matter of thermal experience as a whole. Designers should be aware of this dimension of thermal comfort when they test their designs and the importance of incorporating means to provide such thermal experiences.

To reinforce this point, thermal adaptation in the built environment has been attributed to three different processes: (a) physiological acclimatisation, (b) behavioural adjustment and (c) psychological expectation. In the literature, the last two are claimed to be of much greater influence [de Dear and Brager, 1998]. However, when a thermally comfortable design is reduced to (only) a temperature expectation, it has the potential to reduce opportunities for (low-carbon) thermal adaptation.

In addition, the survey provides initial indication that **PMV underestimates** actual comfort levels of HIHs. That is, in reality, the occupants' actual comfort levels were higher than PMV (especially towards the warm end of the scale). This should be taken as having

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[58] After all, air temperature is the dominant environmental factor, as it determines convective heat dissipation "*air movement accelerates convection, but it also changes the skin and clothing surface heat transfer coefficient (reduces surface resistance), as well as increases evaporation from the skin, thus produces a physiological cooling effect*" [Szokolay, 2008, pag. 17].

implications for the thermal design of houses, since the underestimation of PMV might result in some unnecessary over-specification of the building fabric during the design of HIHs. However, the sample of HIHs is too small.

Moreover, the survey also found that in **HIHs the range of CLO** is smaller than that for non-HIHs. This may suggest that occupants decided to rely on other forms of adaptive behaviour, such as window opening. This is another notable finding, because, if the occupants' comfort mainly depends on window opening, careful design considerations should be taken in order to ensure that this means of adaptation is actually available and, for instance, does not interfere with the operation of MVHR (especially during winter), as instead it was the case in one of the houses.

The thermal comfort survey showed that the thermal experience in HIHs had a shorter spread over the thermal sensation scale (when compared to the non-HIH group), suggesting a shorter window for thermal sensations in HIHs. On the one hand, this could be considered a positive outcome of low-carbon design; on the other, the low values of CLO and their correlation with outdoor temperatures could be showing that occupants are already adapting to cope with warm temperatures. This fact deprives occupants of forms of adaptation as indoor temperatures get warmer.

To restate this point, the constant use of window opening as a means of ensuring comfort could be linked to an increase in energy use (the constantly running MVHR may have localised heaters as in the case of house UK52). This could trivialise efforts to reduce carbon emissions intended in the first place. Also is important to remark that the reliance on such means for comfort (i.e. constant use of window opening to provide comfort) could be problematic in certain areas (i.e., UHI, noisy area, etc.) and may induce to further carbon emissions (air conditioning) or heat stress.

Finally, one should not underestimate the fact that temperatures are predicted to rise over the next decades due to climate change and increased urbanisation. The tendency towards rising temperatures over time means that the demand for cooling in HIH can reasonably be expected to rise. For this reason, one can speculate that HIHs, as they are built today in the UK, are vulnerable to overheating despite the fact that their enhanced insulation has a positive counterbalancing influence.

Apparently, the findings of the thermal comfort survey in relation of the phenomenon of overheating in HIHs are far from conclusive. In fact, in consideration of the limited amount of data available, here it is not possible to generalise the results of the survey and related reflections. Nonetheless, the existence of a number of additional risk factors in HIHs is hardly deniable.

5.3.3 SUMMARY OF USER PERSPECTIVE FINDINGS

This section examined how HIHs are experienced by its occupants, how comfortable HIHs are found by them and to what extent user behaviour play a role in such perception.

The reliance on window opening evidenced by the longitudinal questionnaires have provided an initial indication of the use of **air movement** as main means for achieving comfort; it is not known if this is rooted in a hedonic component of comfort (and by so related to the pursue of pleasure[59]) or a need to lower internal temperatures. This implies that adaptive measures enacted by occupants might not be enough to provide comfort. This is an important finding because HIHs designs are to be equipped with an array of adaptive opportunities to avoid discomfort.

To stress this point, the thermal comfort survey has shown **people report smaller CLO values** in HIHs, therefore clothing as an adaptive measure has already been used and other forms of environmental-related adaptive measures are needed. While one of these is ventilation, one of the case studies has shown that this is sufficient in itself (UK51-bed 2), with the effect that the room had to be vacated during the heat wave. While vacating a room has been possible in UK51, in other designs (such as single aspect flats) this may not be available.

The form of control from the occupants over the **ventilation** appears to be unpredictable and complex: while ventilation might be a poor source of comfort when

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[59] Hedonism in thermal comfort refers to a theory of comfort that moves away from the conventional (PMV) and adaptive thermal comfort research. In both the PMV and the adaptive approach the objective to minimise thermal discomfort; they consider thermal neutrality as mean for comfort, and by so if a thermal environment is unnoticed, the comfort is achieved. Hedonism in thermal comfort refers to a paradigm theorised in the seventies in Thermal delight which hypothesise the pursue of thermal diversity rather than thermal monotony, linking lifestyles and physical environment [Heschong, 1979]. The psychological and socio-cultural components are central to this theory. Though, such a paradigm of thermal comfort has been kept underexplored thorough these years.
Some authors are underlining the fact that the psychological aspects of comfort are potentially the most significant dimension in thermal comfort, though resenting from the lack of a framework that links behaviour, well-being and thermal comfort [Anderson and French, 2010], which may allow to move beyond the sphere of physiological acclimatisation.

outside temperatures are high, it has been found to be linked to the occupants' comfort[60]. Linking this to the design of HIHs, it seems appropriate to claim that no one solution to ventilation type fits all approach is appropriate when it comes to low-carbon design. In this case, for instance, house UK51 would have benefitted from localised extract ventilation. While this point seems crucial, it is also important to emphasise that, from the results provided, there is no guarantee that one solution can fit an entire year's performance, as the winter results of house UK54 have shown.

It appears appropriate to conclude that while **adaptive behaviour is key** to occupancy of HIHs, however it is crucial that occupants are given additional **options for adaptation**. Such opportunities are to be given from the design stage and should be of many and varied types (according to the contextual design possibilities).

Also, it should be noted that the HIHs that have been surveyed in this study have cross ventilation and hence are capable of effective purge ventilation (theoretically). This circumstance has most likely reduced the chance of overheating significantly. However, not all the HIHs built in the UK are equipped with this feature. For instance, a multi-storey building do not necessarily allow for cross ventilation [Nooraei, Littlewood and Evans, 2013], which makes these HIH typologies more vulnerable to overheating when compared to the buildings surveyed in this work.

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[60] Research into air movement to achieve comfort in the UK is currently undergoing [Loveday *et al.*, 2016]

5.4 CHAPTER SUMMARY

As found in the published studies presented in Chapter 2, there is neither a universal definition of overheating, nor an objective-value-free method for the assessment of overheating. These facts are supported by the findings from the environmental monitoring, which would not have been interpretable without reference to the user perspective discussed in this chapter. The findings introduced and discussed in this chapter, then, support the conclusion that the phenomenon of overheating in HIHs in England should be approached from a not purely quantitative approach.

More specific main findings of the chapter can be thus summarised.

Warmer environments

The environmental monitoring showed that excessively warm temperatures were found to be persistent in some of the cases presented. With the provision of adaptive opportunities within HIHs' designs, overheating can hence move from a temporary condition to a chronic condition. From a user perspective, it can be said that HIHs provide warmer environments. This fact was not necessarily reported as a problem by occupants.

The complexity of HIHs is exemplified by the fact that the analysis of the recorded temperatures for the whole year showed that the best performing house during summer does not necessarily perform at its best in winter. In fact, the best summer performing house showed the lowest temperatures in winter.

The thermal comfort survey indicated that HIHs are warmer indoor environments. In this context, the provision of adaptive opportunities - normally aimed at enhancing the thermal experience of occupants - appear to be an essential aspect that should be addressed by designers in order to avoid potential thermal stress from warm indoor temperatures.

Ventilation

Moreover, assessments do not necessarily reflect the risks accompanying low-carbon design. In the cases presented, the reasons for not opening windows are numerous: from building work nearby to a fear of burglary. This reinforces the idea that designers should not design buildings with just one means of adaptation available, since such means may become momentarily unavailable. For instance, in HIHs the provision of natural ventilation alone is not sufficient to guarantee a reduced risk of overheating, and designs should, therefore, include other means to avoid the build-up of heat inside the thermal envelope (i.e., provision of external shading in HIHs).

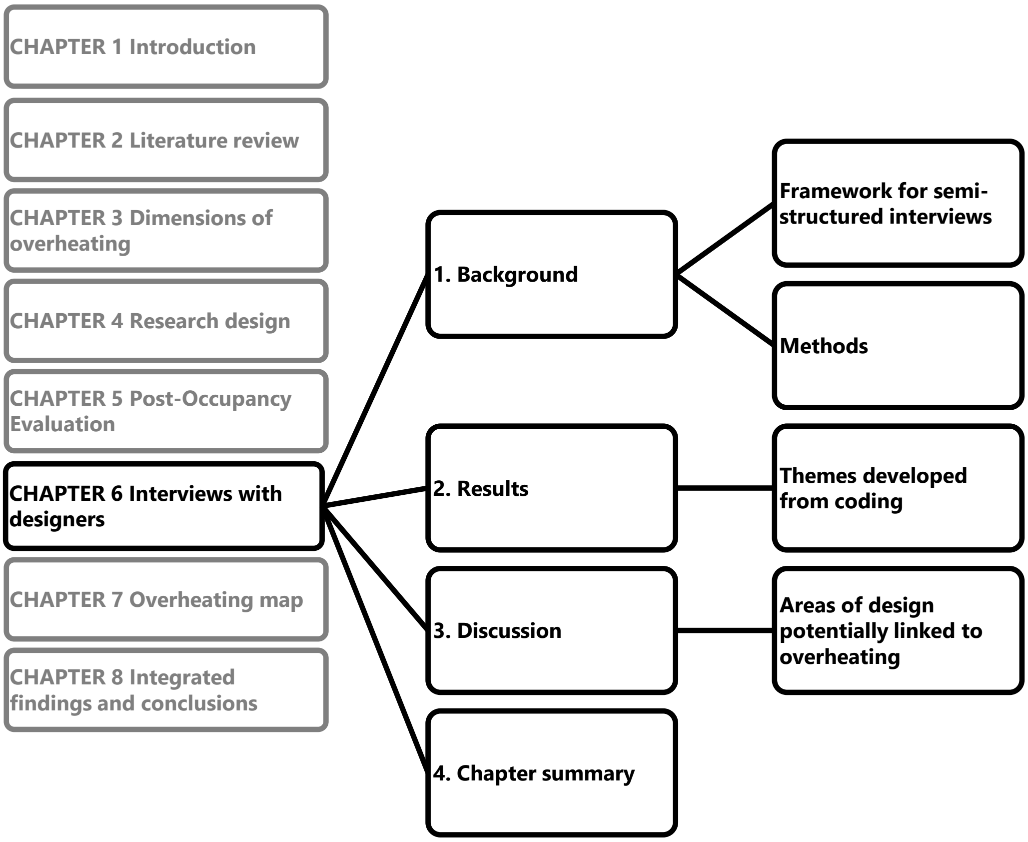
Ventilation was shown to be an essential component of adaptive behaviour, though it is not always accessible. Mechanical ventilation was revealed to be a complex factor, and its interaction with layout design can have dramatic impacts on comfort.

Innovation

From the post-occupancy evaluation, it became clear that when considering HIHs, the current 'new' way of designing houses in the UK has perhaps not yet matured sufficiently to gain an understanding of innovative designs. In fact, it has to be considered that designers today might not have the experience of living in such environments. This means that compliance to an overheating assessment or governmental compliance, on the one hand, and an understanding of the thermal environment of HIHs, on the other, might not be sufficient to minimise the risk of overheating in HIHs. Exceptional measures, both in terms of design as per standards guidance change are necessary, such as more restrictive assessments, the concept of vulnerable groups of occupants being considered in the standards, knowledge development, and post-occupancy evaluation, to ensure avoidance of temporary or permanently detrimental environmental conditions for occupants of HIHs.

The proposed study has some limits as its finding cannot be generalised due to the small sample of houses considered here. On the other hand, the analysis of four houses, so different in typology and performance, gives a fair sense of the complexity of the thermal performance of HIHs and clues as to potential exploration in future research and design precautions that can be embedded by designers.

CHAPTER 6: INTERVIEWS WITH DESIGNERS



Synopsis

This chapter is largely concerned with the *prediction* aspects of thermally comfortable HIHs as it intends to investigate the contribution of the design process of the case studies to their thermal performance and its impact on the occurrence of overheating in the case studies. This chapter is thus devoted to critically analyse the interviews to designers and to single out the dimensions of design that are potentially associated with the *production of overheating*[61].

Due to the nature of the design process, qualitative research, in the form of semi-structured interviews to architects and designers, was used in order to complement data from the POEs.

[61] The nomenclature '*production of overheating*' is used to refer to overheating as an unintended consequence of HIHs design; and by so, to distinguish it from overheating as a consequence of climate change.

In this chapter, first a framework is introduced to guide both the collation of data (interviewees' responses) and the critical analysis of the designers' interviews; secondly, a content analysis is performed to reflect on the design of HIHs, as it is conceived and practiced today in UK.

Two short caveats should be added before proceeding: to begin with, the analysis undertaken in the chapter will be exclusively concerned with the qualitative component; to continue, the outcomes of this chapter contribute to map (or model) the production of overheating – map that will be introduced and discussed in Chapter 7.

6.1 BACKGROUND

In the literature the use of interviews with designers constitutes a consolidated methodology. Such interviews are used in the present research to investigate the impact that the design of selected case studies has on the thermal performance of specific HIHs and so on their overheating. Semi-structured interviews to architects and designers are here employed to investigate how designers handle the new design requirements established by the governmental carbon reduction agenda in the light of their knowledge and the project requirements.

Due to the nature of the design process, in this work qualitative research is used to complement predominantly quantitative methods. In this context, it is acknowledged that while qualitative methods can follow a well-established set of rules, such as coding [Bryman, 2015], there exists an intrinsically subjective (or at least less-than-objective) dimension in qualitative data analysis. This dimension necessitates a conceptual framework, which will be formulated in section 6.1.1. This conceptual **framework** has been used to frame the questions to the designers of the HIHs under consideration.

It is important to preliminarily note that the relevant conceptual framework is derived not only from the literature review but also from the researcher's personal and professional experience. Other relevant elements affecting the framework are the researcher's speculative thinking (as it is shaped by her architectural background), the current non-academic debate, and a number of unpublished papers that have been circulated among academics during the time in which this research project was undertaken (the relevance of those sources is discussed in Chapter 4). In particular, the non-academic debate undertaken by members of the construction industry, governmental parties, housing associations, architects, Passivhaus architects and occupants of 'overheated' houses provides anecdotal insights into overheating. Those insights are in turn based on practical experiences, which have so contributed to channel the present research project.

In creating the conceptual framework for the research questions, some of the factors that are understood to influence the thermal performance of houses have been reviewed. They are listed below (in order of importance).

To begin with, **climate** should be considered a major factor influencing the thermal performance of buildings. Climate-base considerations have driven building design since the very outset of architectural work, although this integration in design was tacit. This dimension of architecture is made evident by vernacular and traditional design of buildings [Dahl, 2009], in which all meteorological factors are regarded as 'not subject to human interventions' [Givoni, 1998]. In contemporary architectural practice, only in the recent decades designers have explicitly integrated weather data into design by means the deployment of building simulation [Herrera *et al.*, 2017]. Prior to this, design was based on the locally known technical advice and requirements shaped by *what is known to work* for that climate and context.

To continue, in addition to climate considerations other environmental conditions are taken into account and refined by taking **localised conditions** into account. These include the context (urban, rural, urban heat island, urban cold island, wind exposure, etc.) [Ritchie and Thomas, 2013]. Some effects of those (such as site layout, microclimate and orientation of the building) can be manipulated in the design stage, though not necessarily under the direct control of the design team (since decisions relating to the site layout, microclimate and orientation of the buildings are normally split between decision takers - client and design team- and planning requirements).

Further down the hierarchy, there are the factors that are commonly attributed to **building** design, such as house layout, typology, materials, and building services. The house layout, materials and building services depend on the interactions between the client and design team (including consultants); and reflect the building regulation requirements. Low-carbon design heavily relies on the interaction between layout, typology, materials and building services when adopting a fabric energy efficiency approach.

The final aspect influencing the thermal performance of buildings is **occupancy**, which can have a different degree of impact. To some extent designers can influence the behaviour of occupants with their designs. But occupancy-related elements are not completely under the control of designers, if not for other reasons because occupancy is likely to change through the life of buildings. Likewise importantly, designers tend to make assumptions on how these buildings will be used and managed, based on either the designers' experienced-based assumptions or design guidance on a typical household. However, when it comes to innovative designs, it should be considered that these assumptions are (a) not necessarily correct, (b) not necessarily followed by occupants, or (c) followed by certain occupants but not others [Stevenson, Carmona-Andreu and Hancock, 2013].[62]

Despite the fact that the scope of design predominantly depends on each project's specifics, such as the context, procurement route, etc., all the above mentioned factors, either tacitly or explicitly, have an impact on the performance of a (thermally performing) building. Consequently, there is no exact location where the 'realm' of design operates. The diagram drawn in figure 6.1 attempts to nuance the areas of potential design manipulation[63]. These are also areas of potential overheating 'production'.

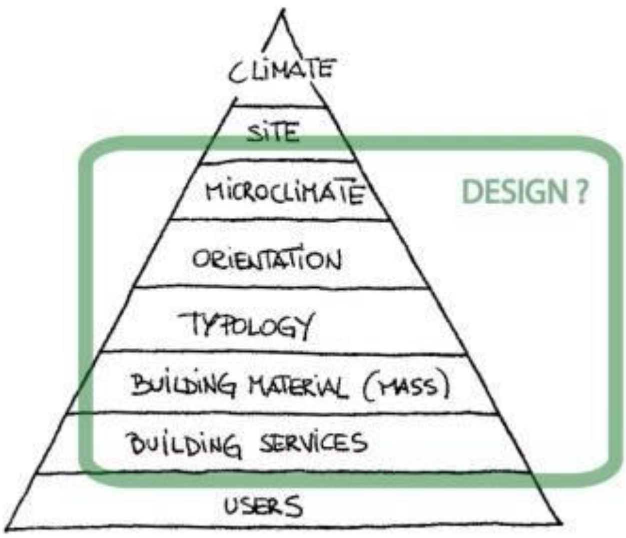


Fig. 6.1 Factors concurring in the thermal performance of buildings and design control

[62] Incidentally, this aspect shows the importance of gaining knowledge in the relationship Environment-Behaviour as a whole, to inform the architectural profession, as introduced by Takahashi [2000].

[63] The microclimate (or site or landscape) can be treated to reduce the effects of solar radiation, wind, temperature, and humidity on a particular site and by consequence to the buildings in it [Brown and Gillespie, 1995].

6.1.1 FRAMEWORK FOR SEMI STRUCTURED INTERVIEWS TO DESIGNERS

The literature review provided in Chapter 2 showed that in UK overheating in houses can be caused by the cumulative effects of (a) external heat gains (such as sun and UHI), (b) internal heat gains (such as occupancy effects, appliances' heat outputs) and (c) inadequate ventilation [Dengel and Swainson, 2012; NHBC, 2012b]. The impact on such cumulative factors is exacerbated by high levels of insulation [Orme, Palmer and Irving, 2003; Energy Saving Trust, 2005; DCLG, 2012]. In fact, in relation to overheating, HIHs provide a *context* in which gains and ventilation act differently when compared to non-HIHs.

The factors mentioned above have been integrated in the diagram presented in figure 6.2, where both factors of building design (left side of the diagram) and the cumulative factors of overheating (right side of the diagram) have been integrated to allow identifying (a) the basic themes used in the guide interview, and (b) to link these interviews questions to the areas of potential risk of overheating in the design stage (such diagram will be used later to produce the integrated findings from all areas of enquiry in Chapter 8).

This diagram is not considered as a fixed interpretation of the integration between design-related factors and overheating-related factors; instead it constitutes an opportunity to link areas of design to potential overheating factors and to taking into account the intrinsic uncertainties in understanding occurrences of overheating in HIHs.

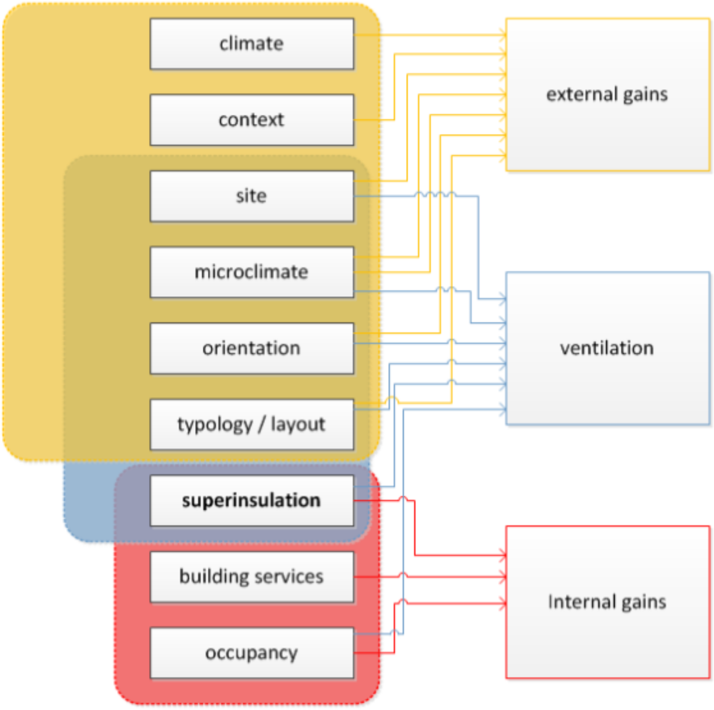


Fig. 6.2 Diagram of cumulative effects to overheating (right-hand side) in relation to building thermal performance factors (left-hand side) (repeated from Chapter 3). The three groupings on the left-hand side express the relationship thermal-design/overheating factors.

6.1.2 METHODS

The factors just illustrated are presumed to be understood and weighted differently in different projects. Therefore, there is scope to explore their knowledge and control within the design process. The questions of the semi-structured interviews to the designers of the building studied in this work central to this research project are listed below:

- Do designers have the knowledge to avoid overheating?
- How do designers assume their designs to perform? What do they know?

Other questions asked during the interviews (see Appendix E) specifically looked at how designers went about their designs of HIHs. The rationale of those questions consisted in trying and establishing how to prevent overheating in the design phase and what can be improved in that phase Those questions were then directed to obtain information about:

- What tools were used to design the case study houses,
- What standards were considered,
- What designers did in respect to comfort and whether they perceive or take into account any discomfort issue (such as winter comfort, summer comfort, particular time of the day discomfort),

- Whether designers considered the cumulative effects of external gains, internal gains, and ventilation cumulatively
- Whether designers considered overheating as an issue
- What the designers' view of their HIH projects was
- What the main focus of their studies houses was.

A total of five interviews were conducted with the designers of the case study houses: two interviews for house UK51, two interviews for house UK52, and one interview for a house that has not been part of the monitoring process in the present research (and so is not, strictly speaking, a case study, and yet can be considered of significance).

The addition of the latter was decided once it become clear that it was not possible interview the designers of houses UK54 and UK55, who never replied to the interview requests. During the interview of one of the designers of UK52, the interviewee mentioned the existence of a new project. This led the researcher to contact the architect of another HIHs development in which the consultant of UK52 was also involved. The list of all the interviewees is reported below:

- From house UK51 (case study 1), interviews with both a designer and a consultant.
- From house UK52 (case study 2), interviews with both a designer and a consultant.
- From a project linked to the consultant of case study 2, interview with the architect.

Table 6.1 - Interviewees list (repeated from Chapter 4)

	Coded name	role in case study	background
From case study 1	**D1-UK51**	Project initiator	designer and planner
From case study 1	**D2-UK51**	Specification consultatnt	building surveyor
From case study 2	**D3-UK52**	Passivhaus consultant	physicist
From case study 2	**D4-UK52**	Design architect	architect
Linked to case study 2	**D5**	Project manager	architect

Where possible, interviews were held after POEs had initiated. This means that the interviewer had some feedback about the houses to discuss with the designers, in case they wished to. The link between designer and case study house is listed in table 6.1.

After being transcribed, interview data have been managed through the software NVivo11. The data then underwent a content analysis that identified and confirmed a number of themes relating to the production of overheating. This analysis forms the backbone of the discussion contained in the next chapter (Chapter 7: Overheating Map).

6.2 RESULTS

The transcripts were reviewed in the light of the framework presented in figure 6.2. The analysis also accounts for issues brought forward by the designers themselves while telling the story of how their designs took shape.

To analyse the data, a technique called *coding* has been performed. Coding is a key for of qualitative data analysis and it entails two main stages: (i) a first line-by-line breaking down the transcribed data into 'codes', called *open coding*, and (ii) a second stage in which the researcher formulated main categories (or themes), which is referred as *axial coding* [Bryman, 2015]. In other words, while *open coding* breaks the interview into pieces (i.e. the coded themes), the subsequent *axial coding* reassembles such data by searching for connections between the categories emerged [Strauss and Corbin as cited by Bryman, 2015, p.574].

(i) Open coding

The data underwent a first breaking down through a line-by-line open coding, where tentative labels where formulated. The result was numerous amount of codes (see Appendix F "Open coding" to gain a sense of the proliferation of codes generated) which is normal at the first stage of coding [Bryman, 2015].

To aid the analysis, codes where combined to a higher order of abstract codes, where data were not just coded to an overheating-related factor (such as solar gain and MVHR), but also in the perspective of the designers' knowledge and opinion about these and the changes in the design practice, i.e. if they expressed a conflicted feeling about airtightness or understanding of MVHR. Hence within the open coding, theses abstract codes were:

- codes relating to **factors** of overheating (solar gains, inadequate ventilation etc.), as emerged in literature and relating to the building physics aspects of overheating;

- codes relating to the **process** in which HIH are conceived (superinsulation design, Passivhaus design, building regulations, etc.)
- codes relating to a generalised **critique** expressed by the interviewee (to the Passivhaus design, or building regulations, etc.)
- codes relating to anything **else** raised up by the interviewee.

This first breaking down of data (open coding) can be seen in figure 6.3a. It is recognised that open coding poses the risk of losing both the context of what it is said and the narrative flow, due to the fragmentation of data [Bryman, 2015]. These problems are tackled through the subsequent step, axial coding.

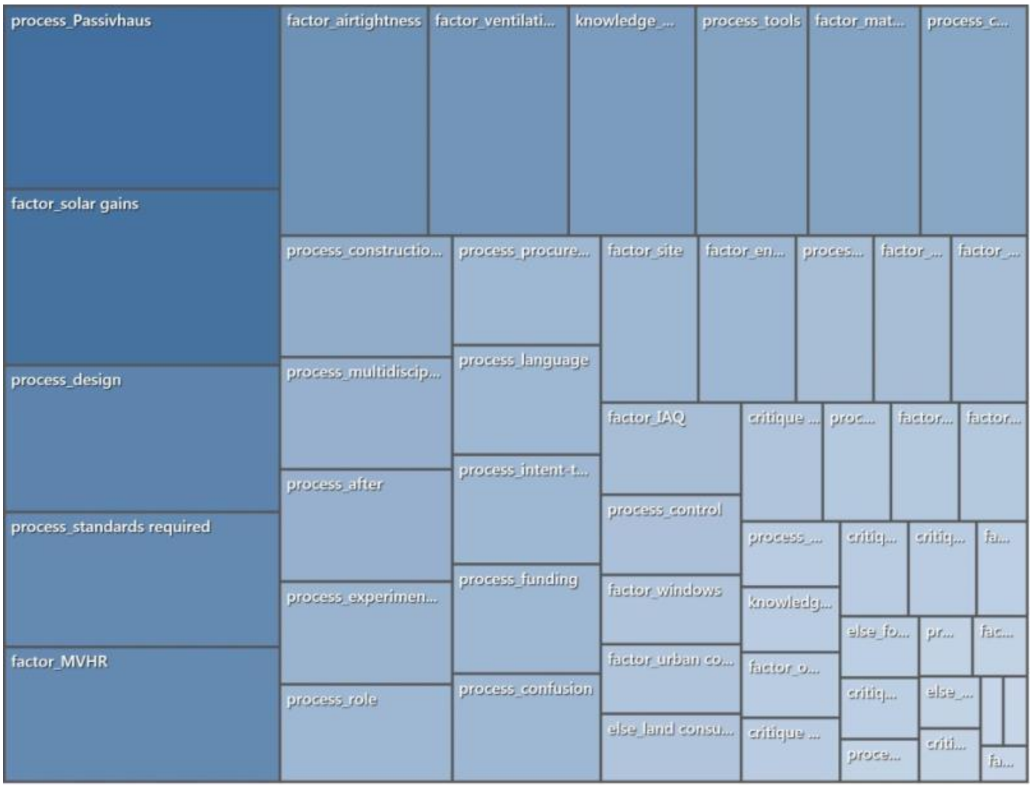
(ii) Axial coding

Then data has been reviewed to consider more general ideas in relation to the first open coding, connecting coded data to concepts relating to overheating that have emerged from interviews. This is called **axial coding**. Axial coding acts as a mechanism to bring coherence to the coded data, by looking at what those data have in common so that they can be combined into more generic themes [Bryman, 2015].

In this process, connections between codes are created with the guidance of the elaborated framework developed in fig. 6.2. Such framework has guided the researcher's interpretation, while at the same time keeping a flexible attitude towards any rigid categorisation.

It is acknowledged that axial coding requires a degree of interpretation from the researcher [Bryman, 2015], but has also been added by assigning a degree of weight of codes (via repetition), which was aided managing the transcribed data within Nvivo software. In figure 6.3b the process just described can be appreciated.

a.



b.

Fig. 6.3 The distillation of themes process from open coding (a) to axial coding (b)

The gradual grouping of codes has led to a gradual distillation of themes from open coding to axial coding. The themes identified by the analysis are presented in table 6.2. An example of such distillation of themes from open coding is provided with the theme 1 - *implementation of solar gain control*. Here, codes (listed in appendix F) such as the provision of solar gain control (code name: "factor_solar gains") is linked to the use of housing layout to control solar gains (code name: "factor_typologyLayout"), as a result of no budget allocation for external shading (code name: "process_funding"). As a result, this first theme is the result of the grouping of a number of distinct codes (such as solar gain control, site layout, designers' experience, architectural language) that have found an (axial) relationship with aspects of knowledge, expectation, or even budget issues.

The same process used in relationship to theme 1 has been applied to other codes too. This reiterated procedure has produced the other themes listed in table 6.2

Table 6.2 - Key themes distilled from the interviews

	theme
1	Implementation of solar gain control
2	Ventilation and MVHR: novelty and misconceptions
3	'Fabric first' approach: insulation and airtightness
4	Initial requirements: brief, standards and aspirations
5	Design aspects
6	Emerging issues linked to HIHs

To further clarify the table just introduced, a *theme* can be defined as a category identified by the analysis, which possibly relates to the research questions, as listed above, and builds on codes identified in transcripts [Bryman, 2015]. The reconstruction of the key themes has allowed organising and interpreting the data.

This method was found particularly suitable because it allowed an *interpretative approach*, where a repetition of a word is insufficient as a criterion for it to be labelled as a theme and where the meaning behind words or phrases are the focus [Bryman, 2015]. While using this framework, it was allowed for themes to emerge in a non-fixed and prescriptive manner (using the framework as guidance only).

In the following sections, each theme is discussed and presented with examples of comments made by the interviewees.

6.2.1 THEME 1: IMPLEMENTATION OF SOLAR GAIN CONTROL

This theme encompasses the designers' attitudes towards solar gain control in HIHs. In the UK sensitivity to solar gain control has developed only in recent decades as the solar radiation has historical been modest. Not surprisingly all the case studies have no solar control (apart from the sporadic use of internal curtains or Velux internal blind).

6.2.1.1 UNDERSTANDING OF SOLAR GAINS CONTROL IN THE CONTEXT OF PASSIVE DESIGN

The first consideration emerging from the interviews is that solar gains are considered by designers a positive and necessary contribution in the thermal balance of passive houses. As one interview puts it:

> "We were trying to get living rooms facing south or S or SW or SE, we were trying to achieve that.... It will be more pleasant also" [D4-UK52, May 2016].

Related, designers referred to site layout in order to maximise its gains and avoid overshadowing:

> *"All the roofs at a certain pitch, with a steep pitch facing south to get the optimum solar gain for that façade"* [D5, March 2017].

In this context, it should be added that at least Passivhaus trained consultants are aware not only of the positive effects of solar gains, but also the negative effects that excess solar gains have on the thermal balance of HIHs. This emerges from the following statement, for instance:

> *"These days I will be much more inclined to recommend fixed solar shading and rely less and less on the window opening"* [D3-UK52, May 2016].

Despite this awareness, when the historic building stock (i.e. traditional terrace houses) is retrofitted, the negative effects of excess gains tend be overlooked. As acknowledged by one of the designers:

> *"When you have got a terrace house in the middle of a terrace street solar gain thorough window is very limited"* [D4-UK52, May 2016].

In addition, tools like SAP seem to be perceived as recommending merely curtains as devices securing solar protection:

> "*SAP have a thing where you have your curtains*" [D4-UK52, May 2016].

6.2.1.2 COSTS OF SOLAR GAINS

Orientation of the buildings is the most passive and cost effective way to control solar gains in houses. However, this variable is often not controllable:

> *"Sometimes you have to have north facing; it is just a fact of life"* [D4-UK52, May 2016].

Notably, even when the variable is controllable, the risk is correctly identified and an understanding of the effects of excessive gains in HIHs is fully grasped by those in charge with the relevant decision, budget may still not allocated to implement an effective strategy of solar control. This point was emphasised in the interview with consultant D3-UK52, for instance:

> *"What I will try and recommend the more and more is fixed solar shading. But again I can recommend it but it comes down costs at the end of the day whether it is included or not"* [D3-UK52, May 2016].

Also in consideration of the additional risks, such as the effects of climate change, there is a persistent reluctance to dedicate budget costs to external fixed shading, as it emerges from the statement that follows:

> "(The contractor) *took the view that the solar shading is not needed now, it's needed in the future, when the climate is warmed up"* [D3-UK52, May 2016] in reference to the other (not the case study) project.

In this context it can be also appreciated that postponing a strategy developed 'today' to a 'future' retrofit may result in loss of information when the time for retrofit comes.

6.2.1.3 CULTURAL BARRIERS

In addition, architectural design can be a barrier to solar gain control in the UK when designs contemplate a vernacular language. In this regard I refer the reader to the following statements:

> *"One of the criteria was to make it actually look like a normal house"* [D4-UK52, May 2016];
>
> *"Was thought at the very early stages but I think that it didn't fit with the vernacular which they were thinking to achieve with this houses… so I don't think that the solar shading architecturally aesthetically will have fit in this scheme, with a very traditional looking scheme with a fake chimney"* [D3-UK52, May 2016].

6.2.1.4 FUTURE TENDENCIES

For all the above reasons, the conception of external shading must be developed from the very first stages of the design concept**:**

> *"Certainly if you get involved with the scheme earlier on, then it's possible to get it the designed in from the very early design stages and it is not seen as an add-on then"* [D3-UK52, May 2016].

Here, it is recognised that layout and orientation do not always work in one's favour; so other techniques are in place, such as extended eaves:

> *"We put solar shading at the top of these by building extended eaves, so we already got being protected by solar gain"* [D5, March 2017].

Finally, while climate change is recognised as threat, it is managed by designers as a remote risk:

> *"We evaluated the homes using future climate scenarios and were found them to be in need of additional solar shading from the current state at some point in the future, I can't remember when, in 20 years or 50 years something like that … But [the contractor] took the view that the solar shading is not needed now, it's needed in the future, when the climate is warmed up … [the contractor] took the view that it was pointless to install the external shutters and now because they will come to the end of the life the serviceable life time"* [D3-UK52, May 2016] in reference to the other (not the case study) project.

6.2.2 THEME 2: VENTILATION AND MVHR: NOVELTY AND MISCONCEPTIONS

In this section the focus of the analysis shifts to cooling tools in general, and ventilation and MVHR in particular. In this context, the (mis-)conception of cooling, as they are widespread among designers are accounted for.

6.2.2.1 VENTILATION BY MEANS OF MVHR

A first, honest, misconception of the purpose of ventilation, as this is achieved by means of MVHR, concerns the issue as to whether they provide cooling via its air change rate[64]. While the continuous operation of the MVHR system provides for background ventilation

[64] None of the case studies in the present research have summer bypass nor comfort cooling.

(i.e. for pollutant or water vapour removal), it does not cope with purge ventilation[65]. This statement is not universally accepted in practice, though. In fact some designers believe that the mechanical ventilation can also cope with high temperatures via rapid ventilation. This attitude is attested by the following statement collected in the interview process:

> *"There was a MVHR obviously to cool the building to heat the building and cool the building, during cold spells and warm spells"* [D4-UK52, May 2016].

Other designers are, however, aware that cooling does not occur through MVHR operation. For instance, two of the designers claimed that:

> *"(MVHR) has very slow ventilation rates, is not going to do much (cooling)"* [D3-UK52, May 2016].
>
> "(the MVHR) *it's got a boost on it but the truth was that you have to go for opening the windows for rapid ventilation"* [D5, March 2017].

6.2.2.2 LOCATION OF THE MVHR UNITS

There appears to be several rationales for the MVHR location within the house. One of those rationales relates to the optimum efficiency, as it is clarified by the statement below:

> *"Getting a dedicated cupboard for the unit and making sure that the unit is on an external wall to keep the intake and exhaust duct length very short because that improves the efficiency in the system* [D3-UK52, May 2016].

Another rationale relates to facilitating access for maintenance to the MVHR units when servicing them as filters need cleaning or replacement:

> *"You got another cupboard with the boiler and the MVHR outside. We wanted to put that stuff in a cupboard with external access to make it easier to access and service it"* [D3-UK52] in reference to the other (not the case study) project.

At the same time, this interviewee listened carefully to the researcher's account of the problems with temperature stratification (as they occurred in another case study, UK51), and changed his view:

[65] Purge ventilation consists in a much higher rate of ventilation, normally provided by window opening (manually) or via localised fans (mechanically) [HM Government, 2013a].

> *"I guess is that it might be a good idea to extract from the top floor room where the heat is going to be collecting and then obviously that gets push around the heat recovery ventilation system"* [D3-UK52, May 2016].

The above comments bring into light the fact that there is no 'best practice' when it comes to the location of the MVHR units.

6.2.2.3 VENTILATION BY MEANS OF WINDOW OPENING

The reliance on window opening as a form of cooling proved to be tainted by fewer misconceptions. It can even be said that this practice is understood clearly by most of the designers, as evidenced by the following statements:

> *"We thought to deal with overheating by opening and closing the windows"* [D1-UK51, April 2016];
>
> *"In terms of overheating, we put in a window regime* (in PHPP) *which involves during the cooler hours of the night, two windows open at the opposite sides of the bungalow to allow for cross ventilation and open for one hour … what PHPP was telling me is that it was okay with some window operating"* [D3-UK52, May 2016].

At the same time, window opening can be claimed to be at least underestimated by technical consultants. In fact, when the Passivhaus consultant of house UK52 was told that its occupant leaves the windows open (in trickle) all the time, even in winter, his comment was:

> *"She likes fresh air, it is interesting that that is something the MVHR should be providing for. There maybe that is something she is used to do, the MVHR should provide it but maybe it is something she is used to do it"* [D3-UK52, May 2016].

While it cannot be ascertained whether the occupant performed constant windows opening for the purpose of comfort or as a mere habit, it is hardly deniable not only that the Passivhaus consultant of house UK52 pointed at that as a preference-based behaviour (rather than reducing temperatures). However, such unexpected proportion of window ventilation should be regarded as an issue that requires attention during the design phase, for it has the effect to trivialise the efforts aimed at securing heat recovery (energy efficiency and airtightness measures) pursued via MVHR.

6.2.2.4 FUTURE TENDENCIES

Interestingly, the uncertainty surrounding window opening, together with location constrains, has led one of the Passivhaus consultant to rely less in window opening in future designs:

> *"These days I will be much more inclined to recommend fixed solar shading and rely less and less on the window opening"* [D3-UK52, May 2016] in reference to the other (not the case study) project.

6.2.2.5 INNOVATION AND EMBEDDED KNOWLEDGE

The extent of innovation in HIHs has proved to challenge the experience of UK professionals. This fact is exemplified by the difficulty that designers have experienced in relation to the scale and connectivity that a HIH's 'kit' embeds. This statement is supported by the following quote reporting a conversation that an interviewee had with his technical team:

> *"We did the thermal store 'we are going to size the solar thermal store on the basis of your space heating demand' … and we said 'well hang on a second, we think that our heating demand is going to be so low that the only reason you need the solar thermal is for domestic hot water'… How big this thermal store was going to be"? A really naïve obvious question like is it 200 litres, 500 litres? And was that they never worked on a project as super insulated property, a Passivhaus."* [D1-UK51, April 2016].

Another interviewee said that s/he experienced similar difficulties for the same case study:

> *"Nobody looks at how they will all integrate together in one big lump. And I think that is probably one big learning that needs to come out of that…It's like the MVHR, their ducting system was too big and it would have took a lot from the insulation out of the wall"* [D2-UK51, April 2016].

This shows a (missing) aspect of holistic design in HIHs – aspect that would be necessary to balance the complexity brought by innovation.

A third interview pointed out another issue, which is related to the learning curve of installing and maintaining these units:

> *"The roof pod had the inlet for MVHR system and the intake and out vent should have been separate by 3 meters. We have them far too close together, so you could*

have cool air going out and being sucked back or hot air going and being sucked back in, so it doesn't fit the best practice" [D1-UK51, April 2016].

This statement is revealing of another misunderstanding with the heat recovery: inlet and outlet have similar temperatures but, importantly, this proximity between them results in stale air be going into the inlet.

Finally, there are issues relating to the maintenance of the MVHR units. It was witnessed by the researcher that the maintenance company forgot to turn on the MVHR unit after servicing it in house UK52. Noticing no noise, the researcher observed the switch in 'off' position, and called the housing association to notify the mistake.

6.2.3 THEME 3: 'FABRIC FIRST' APPROACH: INSULATION AND AIRTIGHTNESS

Insulation is recognised as the most important factor in energy efficient design. However, efficiency is also linked to the control of air leakage.

6.2.3.1 WINTER FOCUS

The 'fabric first' approach to energy efficiency in houses is generally viewed as a way to 'keep the warmth in'. Consequently, most of the focus of the 'fabric first' approach is devoted to achieve 'winter comfort'. As such, much effort is made to provide a building fabric with the lowest overall U-values and airtightness solutions, and to produce drawings specification that go into tender before involving the contractor. This means that specifications go into tender, as attested by the following statements:

"I say to them "do this calculation before they go to tender and write a document, give the contractor a clue on how was going to achieve this" [D4-UK52, May 2016];

"Some of these contractors it's all the money and "can we get away with putting 100 mm in the floor rather than 150 or 125". And I say "for God sake put 150 and then you'll be alright"... And the number of times you are literally on the limit" [D4-UK52, May 2016].

6.2.3.2 NOT ONLY INSULATION

The fact that fabric insulation efficiency comes hand in hand with air infiltration control should not be downplayed. The control of air infiltration, which is referred to as *low air permeability* (UK Building Regulations) or as high levels or *airtightness* (Passivhaus), has increasingly been changed in recent years. As a result, the designers' experience is challenged by this innovation in regulations and calculations in the market offer:

> *"All comes down to airtightness at the end of the day"* [D4-UK52, May 2016];
>
> *"We dealt with that kind of red line around the whole thing"* [D1-UK51, April 2016].

6.2.3.3 REGULATIONS CATCHING UP

Several aspects of regulations have kept changing quickly in the last years. As a consequence, the construction sector finds it difficult to catch up with those swift changes, as one of the designers explicitly pointed out:

> *"They are getting more and more airtight; they are getting now condensation problems"* [D4-UK52, May 2016].

In this context, a problem concerning the way in which the law-makers have regulated purpose-provided ventilation and air leakage control should be noticed. In England purpose-provided ventilation guidance is regulated in Part F of the Building Regulations ('Ventilation'), where it is established that for calculation purposes, one should assume no, or zero, air permeability. By contrast, air leakage control (or control of infiltration via airtightness measures) is regulated in Part L of the Building Regulations ('Conservation of Fuel and Power'). Now, in the Building Regulations those two dimensions – purpose-provided ventilation and air leakage control – are dealt with as they were disaggregated (this is the reason why they are regulated in different parts of those regulations). By contrast, in practice they are closely connected and interlinked. This problem is emphasised by the following quotes:

> *"So what they actually said was 'if you achieve 5 or worst then you have the standards, if you achieve 5 or better, you have to put more trickle ventilation under part F'"* [D4-UK52, May 2016];
>
> *"It seems a bit pervasive that we are driving to get airtight buildings and at the same time they change the regulation to get more air into the building"* [D4-UK52, May 2016].

The fact that the concept of airtightness is new to the construction industry is also a cause of concern for the building constructors:

> *"We know that the airtightness was going to be an issue, we didn't know that asphyxiation of the residents was going to be a big issue"* (laughing) [D1-UK51, April 2016].

6.2.3.4 ISSUES WITH AIRTIGHTNESS

Airtightness presents a number of difficulties for designers and builders. One of the most obvious difficulties has to do with the possibility to implement an airtightness strategy in a refurbishment project, as claimed by one interviewee:

> *"The airtightness barriers that was more… because of the way the building was put together and there were so many anomalies in the building that was more of a learning curve once it has been installed"* [D2-UK51, April 2016].

Another difficulty concerns the MVHR units. In fact, a senior and experienced architect reported:

> *"To get Passivhaus you got to achieve below 1*[66] (ACH) *is actually complicated by the fact that they had two different methods … it was the figures, the xm3/ … it was a different reading, a different criteria … and they didn't make life easy cause the figure they had in their calculation didn't bear any relationship to the ACH in Building Regulations"* [D4-UK52, May 2016] [67].

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[66] The Passivhaus requirement of airtightness fixes a maximum of 0.6 ACH at50 Pascal) verified with an onsite pressure test (in both pressurized and depressurized states) [Passivhaus Institut, 2015]

[67] This issue is indeed quite complicated and it is easy to bring confusion among trained people which are dealing with projects in the UK with international standards. To clarify, the airtightness of a building is often expressed in terms of the leakage airflow rate through the building's envelope at a given reference pressure (usually 50 Pascal). Airtightness can be expressed in different ways, commonly referred as (a) air permeability area and (b) air changes per hour volume [ATTMA, 2010]

a) In UK, it is calculated by dividing the leakage airflow rate (obtained by performing the blower door test) by envelope area, noted as $\mathbf{Q_{50}}$ units expressed in $\mathbf{m^3/(h{\cdot}m^2)}$. The requirement from part L is to limit air permeability area to max. 10 $m^3/(h{\cdot}m^2)$.
b) In other countries, and the Passivhaus standards it is calculated by dividing the leakage airflow rate (obtained by performing the blower door test) by heated building volume, noted as $\mathbf{N_{50}}$, units expressed in $\mathbf{h^{-1}}$

The main difference is that air permeability considers the envelope area (m^2) and ACH the volume. Using ACH means that it is not possible to take into consideration the effects of shape and size. [Johnston *et al.*, 2004].

In addition, it should be noted that the value obtained for air permeability is fine for comparing the airtightness of different buildings. However it is important to underline that the *leakage flow rate* ($m^3/(h{\cdot}m^2)$) is measured with blower door test, while the *ventilation heat loss rate* (ACH) is measured with tracer gas test. It is possible to get the ACH figure by dividing air permeability by

A further difficulty has to do with the challenge of contextualising airtightness within the construction process. In this context, another architect mentions the careful quality control that their Passivhaus-like houses went through:

> *So once you laid the ground floor membrane, it was ready for insulation and it will be signed of, and the door was locked away from anybody being able to go to that space, Until the next step it was ready…So the point was that if you didn't put the quality control in, you weren't going to achieve that lower* (D5, March 2017).

Finally, even the effectiveness of the airtightness measures was perceived as a problem. Specifically, the life cycle of the airtightness membrane: was considered problematic:

> *"I know that there are issues about the performance of the insulation airtightness fading overtime, that it probably won't be as good in 10-15 years down the line … But actually if it is, it creates more a problem because it is climate change so isn't resilient enough to cope"* [D1-UK51, April 2016];

> *"I am a little bit worried about airtight buildings; I think airtightness might not be the way forward"* [D4-UK52, May 2016].

6.2.3.5 FUTURE TENDENCIES

Among designers, modern methods of construction are perceived as a reliable option to achieve greater airtightness, as attested by the quote reported below:

> *"It has to achieve a certain air leakage rate. And they say how you can do this, you can't use masonry, it leaks like a sieve! …. and standard timber frame leaks like a sieve. They went down to this composite panel system, where the panels where factory made, so they were airtight and to make the factory manufacture poses obviously a controlled process."* [D4-UK52, May 2016];

> *"My experience of using modern methods of construction in a factory is that you can do something that is as cheaper than a standard construction if you are performing to Code level 5 or Code level 6. The cost benefit is that is was cheaper in a factory because of the quality control in factory and with airtightness particularly"* [D1-UK51, April 2016].

20, which gives an approximation of the ventilation rate at normal atmospheric pressures [Nicholls, 2008].

However, in practice design systems that perform better in terms of airtightness are often excluded on the grounds of cost:

> *"We thought it will be much easier to implement the airtightness details and from a thermal bridging perspective if we use the complete system but [the builder of UK52] chose not to on the basis of costs"* [D3-UK52/UK56, May 2016].

6.2.4 THEME 4: INITIAL REQUIREMENTS: BRIEF, STANDARDS AND ASPIRATIONS

6.2.4.1 REFURBISHING THE OLD STOCK

One of the case studies (UK51) was a traditional terrace house. In this case, designers had the ambition of retrofitting a traditional building to Passivhaus-like standards. This provided an opportunity to explore the potential of off-site manufacturing and modem methods of construction as well as to determine how the retrofitting industry was affected. In the words of one the designers, the intention was to achieve

> A *"code for sustainable homes, which was abolished two years ago, level 5 and 6 and 36kWh/m2 per annum ... which is higher than Passivhaus, but zero carbon because all of that had to be met by low or zero carbon technologies"* [D1-UK51, April 2016];
>
> *I thought that probably was a step too far, and I think that when they did it, they thought that too [laughs]* [D2-UK51, April 2016].

When one of the consultants was asked if he had any concerns with overheating, he replied that:

> *"The only thing that worried me was damp and any moisture getting trapped somewhere ... a big 150mm of insulation, big lump of insulation. If that get damp in the wall nobody will ever know ... you have hidden an old building behind something that is so airtight, so thermally efficient, that that worries me more than anything"* [D2-UK51, April 2016].

Retrospectively, this interviewee reflected on the suitability of aspiring to such standards. This was expressed not only in terms of difficulty but also in terms of land occupation. This raises further questions about sustainable housing design:

> *"Don't do the Passivhaus, or don't try to do Passivhaus in a terrace house unless is a new built. It was challenging, it was interesting and exciting, we lifted a roof pod*

and it look very good in the news, but is not the right house to do it on ... I think it ended up with a small house probably being too small" [D2-UK51, April 2016].

6.2.4.2 CODE AND PASSIVHAUS

Something that kept emerging in the interviews was 'the Code', which is also something of actual interest to the client. One of the distinctive strengths of the rationale of Passivhaus project is its goal of delivering the lowest possible levels of carbon emissions whilst also avoiding the costs of renewables:

> *"Housing associations, and they want their Code 4 houses, but if you say let's put PV panels on the roof, well "why we need that? but you only need get more points so just change something else"* [D2-UK51, April 2016];
>
> *"At the time were interested at meeting Code 4 without any renewables energy and they wanted to explore the options for that, and we presented Passivhaus as being one of those options"* [D3-UK52, May 2016].

On this basis, it can be predicted that the Passivhaus tool (PHPP) may keep, if not even increase, its popularity and use.

6.2.4.3 EVOLUTION OF STANDARDS AND REGULATIONS

With the withdraw of the Code for Sustainable Homes in 2015, an interviewee —an architect with 35 years of professional experience—depicts the Building Regulations as the main magnet of all standards:

> *"The Code 4 had disappeared, the Building Regulations had taken over; Secured by Design had disappeared, Part Q has taken over of the Building Regulations, Life time homes had disappeared, because Part M of the Building Regulations had taken over... So all these standards were replaced by the Building Regulations"* [D4-UK52, May 2016][68].

[68] **Approved Document M** from the Building Regulations deals with the access to and use of buildings in dwellings and buildings other than dwellings, and provides a baseline for accessibility in the built environment. **Approved Document Q** instead is concerned with security in dwellings and provisions that must be made to resist unauthorised access to any dwelling; and any part of a building from which access can be gained to a flat within the building [MHCLG, 2015a, 2015b].

6.2.5 THEME 5: DESIGN ASPECTS

6.2.5.1 BLINDED DESIGN

None of the interviewees have had any real experience in designing HIHs before they were involved in the projects that features as case studies in this research. Likewise importantly, they never experienced living in HIHs:

> *"Really the project of house UK52 was my first new built passive house scheme"* [D3-UK52, May 2016];
>
> *"Never worked on Passivhaus project before … nobody has worked to this level of performance in the UK"* [D1-UK51, April 2016].
>
> *"I have not lived in one, have you done interviews with people that live in them?"* [D5, March 2017].

These inexperienced designers hence relied on Passivhaus consultants and learnt from their training and knowledge:

> *[the Passivhaus consultant], well they certainly were instructed in specification of the heating system and the MVHR so that all there they knew really* [D4-UK52, May 2016];
>
> *[The Passivhaus consultant] was consulted …in hitting the targets, managing air control air leakage together with detail assessment of all installation and electric's body heats … how much … has to be extracted when it goes to the MVHR* [D5, March 2017].

Notably, the Passivhaus consultant's advice impacted not only in the sizing of HVACs but potentially on the house layout too, as indicted in the following statement:

> *"They didn't want the boiler in the kitchen because obviously would create a heat loss"* [D4-UK52, May 2016].

6.2.5.2 TOOLS

Tools appear to be mostly engaged when taking decisions aimed to achieve a target. In the projects considered in this study the relevant target was that of achieving CO2 emissions reductions from energy savings from winter comfort. The need to avoid overheating risk was also taken into account, as this quotation indicates:

> *"So from our perspective the model was telling us that the model was manageable with window opening and that is what we have been communicating the amount*

of window opening, so that would have been the end of the conversation really" [D3-UK52/UK56, May 2016];

"Well the SAP calculations does tell you if you are complying with overheating or not" [D4-UK52, May 2016].

During the interviews, the appropriateness of a trusted and well developed tool such as PHPP has been called into question, as some designers raised doubts about the appropriateness of relying on PHPP in the UK context. For instance, one of the designers recognised the limitations (at least in climate data) of PHPP[69] for a project in Leicester:

"TSB [Technology Strategy Board who funded project] asked to use PHPP … but also we tried to triangulate with SAP …" [D1-UK51, April 2016].

In the same vein, another interviewee observed that, according to PHPP, occupants manage their comfort:

"PHPP assumes that we people want to maintain a constant comfortable temperature throughout the year, so it is not really based on occupancy in a sense" [D3-UK52, May 2016].

However, this assumption is not shared by other designers, who expressed a much deeper view of the family structure in social housing, where the physics of PHPP was applied:

"The first question that PHPP asks is the level of occupancy: it was so airtight so the internal heat gains are get by the people. And one of the families had a child, and he had a child from different relationships, and he was away an awful lot, so the occupancy was something between 3 and 6. So the first question of PHPP is about how many people live in the building and we couldn't answer that. We knew who was going to be there but we couldn't put in the software and say its 3 4 5 6. It was a ridiculous question" [D1-UK51, April 2016].

Finally, another interviewee claimed that, when common sense is needed to grasp the intrinsic limitations of tools, requirements of compliance to a target (leading to a prescriptive-tick boxing design attitude) and the process thinking that accompanies it may get in the way of managing the normal uncertainties of a project:

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[69] EnerPHit, the established Passivhaus Standard for refurbishment of existing buildings using Passive House components, was not available at the time of refurbishment.

"That is what I think real world comes to place, that we just need to use common sense, we knew what the software was trying to do, buy we need to guess the best information we can" [D1-UK51, April 2016].

6.2.5.3 ARCHITECTURAL LANGUAGE

As shown in the discussion of the theme concerning solar gain control, the architectural language in housing in the UK seems still to aspire at unrealistic standards:

"One of the criteria was to make it actually look like a normal house, that looks like any other house…It doesn't get rendered pallets or big windows or louvres…" [D4-UK52, May 2016].

Nonetheless, architects seem to leave their clients free to choose their own preferred architectural give the option of language to. This could interfere with a design thought to be energy efficient, though:

"That is what we asked "do you want a contemporary approach to this or you want it to look like standard houses", and they wanted a fairly traditional approach" [D4-UK52, May 2016].

Where it was possible, Passivhaus designers opted for technological solutions by thus at the same time disregarding vernacular options (see 'solar implementation' section). However, this attitude may increase the risk of overheating, as noticed in the quote below:

"There is no (solar) protection at all, but there is a configuration: if you look at the plan you will find only this one and this one window facing out … it was only on featured elevations because of architectural language. But, yes, maybe there is some additional risk" [D5, March 2017].

6.2.6 THEME 6: EMERGING ISSUES LINKED TO HIHS

6.2.6.1 LAND CONSUMPTION

One of the most evident consequences of HIHs is the thicker fabric, and hence the increase in land consumption (if new) or the reduction of internal space (if retrofitting).

"I think it ended up with a small house probably being too small" [D2-UK51, April 2016].

While this fact by itself can be claimed to call into question the suitability of 'sustainable' houses, another statement collected in the interview process shows the extent of the conflicts between passive design and development density:

> *"It has to be low density because we couldn't get the separation between the units, because one was overshadowing the other unit for the midterm sun the autumn and spring midterm low sun … you have to look at how you can get to come out (the sun) of the rooftops"* [D5, March 2017].

6.3 DISCUSSION

The issues found in this part of the research project can be related to the diagram in figure 6.2. The interviews of designers revealed that most of the problems relate to (a) external gains and (b) inadequate ventilation.

The fact that most interviewees were at their first experience with HIHs can be claimed to have significantly impacted on their capacity to acknowledge the risk of overheating. Because of their relative inexperience, they had the tendency to overlook not only the combined effects leading to overheating but the also the potential risk for increased energy consumption and, even worst, for threat to health.

6.3.1 EXTERNAL HEAT GAINS

With regards to external heat gains, it can be argued that there is a limitation in the knowledge of designers. The research found that most designers consider external gains to be a positive contribution of heat in the context of passive design. As such, site layouts are designed to allow for as much solar contribution as possible. While this feature is not wrong in itself, in the case studies at hand it led designers to underestimate the effects of excessive solar gains in HIHs.

In addition, from the research it emerged that SAP plays no decisive role in preventing this oversight. In fact as, most designers are at their first HIH projects, unless preventive measures are put in place, there is a risk that the control of solar gains is neglected.

Moreover, the effects of excessive solar gains have been understated in the retrofitted terrace house (namely house UK51). The morphology due to the close proximity of English terraces tends to be considered incompatible with solar gains. However, the situation proved to be different in house UK51, where the converted loft showed excessively high temperatures. The fact that *traditionally* terraced houses do not have problems associated with excessive solar gains may thus be claimed to have mislead the designers into thinking that traditional houses are *by construction* immune to those problems and so to have led then not consider the risks associated with solar gain.

The research also showed that there is reluctance to allocate project funds to control solar gain. In the case of new HIHs, where consultants simulated the risk of overheating in a climate change scenario, developers delayed action until the future refurbishment of such houses.

During the interviews the possibility was considered to embed new projects of solar control optimised designs from the earlies stages of projects. This strategy would require one to rely on architectural languages (such as thick walls, big reveals, and external shading) that may depart from the traditional approaches still embraced by architects today and are incompatible with the ‘new’ language required by in the design of HIHs.

In consideration of the possibility of such tension, architects should have the authority to advice clients to take a different approach, if not to exclude altogether the recourse to the traditional approach. This way, the design of HIHs would be an opportunity for developing a new design language that takes into account, and creatively incorporates, today’s needs.

Finally, the conversations that took place during the interviews proved to be opportunities to consider whether in HIHs there is a need for a *solar optimised fabric design* combining both contemporary requirements of energy production (i.e. building fabric optimised for solar panels) and thermal comfort (i.e. building fabric optimised for solar control). Such optimisation could be achieved by means of a plethora of alternative solutions. Nonetheless, their application appeared to be disjointed in the case studies presented in this research work.

6.3.2 INADEQUATE VENTILATION

With regards to inadequate ventilation the interviews showed the existence of lacunae in the knowledge of (1) MVHR as a technology, (2) the concept of airtightness, and (3) the need of window opening in HIHs by its occupants.

6.3.2.1 MVHR AND WINDOWS

Designers proved to tend to underestimate the need for window opening by the occupants. The underestimated use of windows in HIHs may lead to compromise the efforts of energy efficiency. In fact, while designers and builders are required to implement outstanding control of air leakage, in some of the cases studied in this research project (UK51 and UK52) occupants relied on constant window opening to regulate their indoor environment.

On these occasions, MVHR operation was maintained. This would not have been a problem if the energy expenditure (and consequent emissions) had been the limited expenditure associated with the fact that the MVHR's fan worked constantly. However, MVHR units are not always just a fan with a heat recovery chamber: they may incorporate heaters and, in some recent cases, comfort cooling, whose performance in terms of comfort and energy requirements in the context on HIHs is under researched[70].

6.3.2.2 AIRTIGHTNESS CONCEPT

The lacunae in embedded knowledge of airtightness are due not only to the novelty of the concept of airtightness but also to the different metrics and diverse paradigms of means of ventilation. While the Passivhaus-related term 'airtightness' is connected to the need of sealing from air leakage, the 'air permeability' measured in air change per house has an immediate connection to fresh air provisioning. Both terms concur in 'infiltration control and management'. But airtightness may be perceived as a negative word (as the asphyxiating concerns ironically rose by D1-UK51). This may in turn lead to misjudgements on the management of the ventilation in HIHs.

6.3.3 ENERGY EFFICIENCY IS NOT EVERYTHING - THE ROLE OF DESIGN

The current ability of designers of HIHs is challenged by the knowledge problems just introduced. Those problems negatively impact on the capacity designers currently have

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[70] Even though terms are marketed in a confusing way, **comfort cooling** is different from air conditioning, the latter means full control (of air temperature and humidity) though often used to mean just cooling. Comfort cooling controls only temperature [Designing Buildings Wiki, 2018]
It is marketed as having a lower capital cost than AC and that it drops temperatures by 8-12ºC on airflow from outlets) and as an integrated in the MVHR system (using existing ducting). It requires a condensing unit (references are not explicit as to whether it is an external or internal condensing unit) [Insulation Warehouse, no date; Systemair, 2018]
Recently used in residential to cope with street noise when ventilation is needed to reduce overheating [Conlan and Harvie-clark, 2018], their efficiency in terms of energy consumption when compared to air conditioning systems has been questioned [The Independent, 2006].

to deliver HIHs. Such ability is put at risk by other factors too. In particular, delivering low energy and thermally comfortable houses is made more difficult by the frequently changing requirements for energy efficiency in combination with long standing systems, processes of design, and social expectations.

A good example of this difficulty is provided by the role of façades. Building façades requires more than just delivering 'thermal' building fabrics, since in buildings façades cannot be reduced to their thermal role. Façades incorporate qualities other than the reduction of heat transfer: they form part of the urban landscape and, as such, they play a role in the social dimension of people. This was exemplified by the recreation of a 'village atmosphere' to promote the family dynamic, as narrated by D5 [D5, March 2017], and by the aesthetically valuable proportion of size windows assigned to a side façade in a kind of 'formal' dialogue with an important road adjacent to it [D4-UK52, May 2016].

These other dimensions of design too have to be acknowledged and consequently dealt with. In this context of innovation, the act of *design*[71] in ought to respond to a design problem with an optimal solution to a number of (possibly conflicting) variegated requirements, not easy[72] to balance.

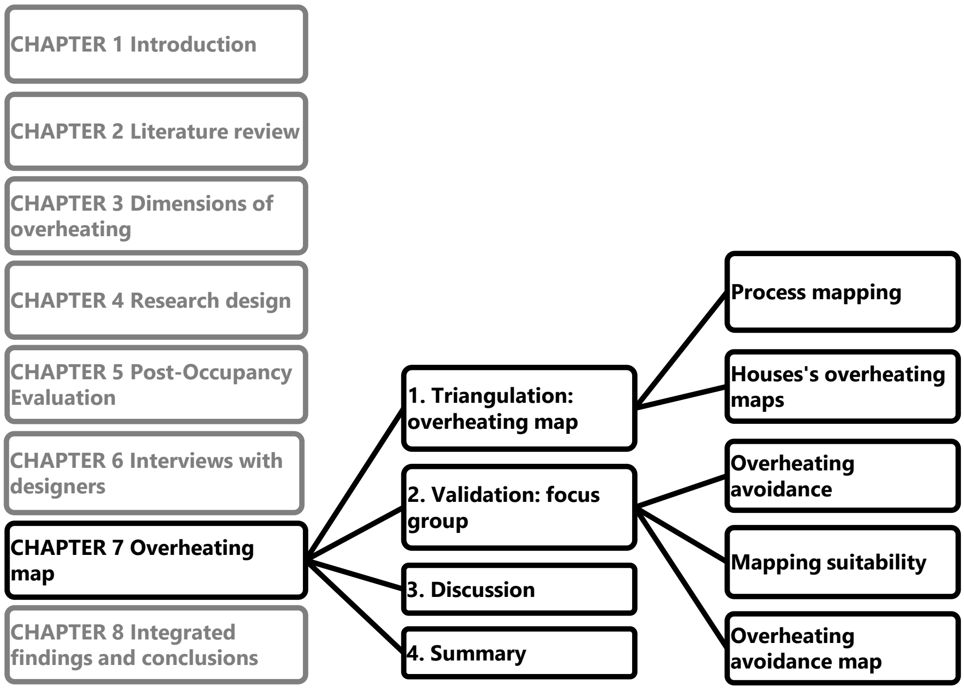
[71] Design has been defined in Chapter 3 by the author as "*the act that (intentionally or unintentionally) initiates change in man-made things to deliver the optimum solution to the sum of the true needs of particular set of circumstances*".
[72] Not instinctively immediate to designers.

6.4 CHAPTER SUMMARY

This chapter was aimed at investigating the contribution of the design process of the case studies to the thermal performance, inclusive of the overheating, of those buildings. The themes that emerged from the conversations with designers and architects concerned not only the environmental factors that pertain to overheating (as per the framework introduced in section 6.1.1), but also the ambitious low-carbon agenda set out by public bodies in combination with the limited knowledge of the practice of the design of HIHs. That is to say, in HIHs current knowledge is challenged by innovation and (perhaps) by a more traditional social expectation of inhabiting such buildings.

This chapter also showed that overheating can be seen as a risk triggered by the process of transition towards an energy efficient environment and low-carbon design. Therefore, overheating calls for a solution from the same context in which it originates as a problem: *design*. The practice of designing HIHs thus need incorporate specific extra measures, because today low-carbon design is in the process of knowledge developing: experience and innovation are still limited and partial, at least in the UK, where the practice of designing and constructing energy efficiency buildings does not have (yet) a long history.

CHAPTER 7: OVERHEATING MAP



Synopsis

This chapter rely on the “dialogue paradigms” introduced in Chapter 4 to describe the reality in which overheating occurs. The leading idea structuring the treatment of overheating offered here, then, is that only a combination of methods and reliance on both quantitative and qualitative data, which then need to be triangulated, can secure a solid understanding of overheating in HIHs. Building on these premises, in this chapter overheating is modelled by means of a structured methodology (process mapping) capable of graphically representing the functional relationships in the different stages of the building process and their influence on overheating risk. The result of this modelling exercise is a map of the *production of overheating*[73], as it occurs in HIHs in the UK. In sum, thus, this chapter completes the picture of both overheating performance and prediction of HIHs by thus addressing the second fundamental research question structuring this research work, namely: *How can the process of designing HIHs be improved to reduce the risks of overheating?*

[73] The nomenclature '*production of overheating*' is used to refer to overheating as an unintended consequence of HIH design, and by so, to distinguish it from overheating as a consequence of climate change.

7.1 TRIANGULATION: OVERHEATING MAP

The real-world knowledge described in previous chapters is integrated in this chapter in the attempt to arrive at an explanation of overheating production. Integration of data, as explained by Bryman [2015], can take place in different forms. In its simplest form, integration takes the form of a triangulation and refers to the process of cross checking findings derived from both quantitative research and qualitative research. Triangulation is not the only procedure that combines quantitative and qualitative research. An alternative process, which is called explanation, prioritises one of the research methods applied to the subject matter and use it to explain the findings generated by the other method(s). An even more elaborated form of integration of quantitative and qualitative research requires the use of different research questions [Bryman, 2015]. In the triangulation carried out here the integration by reference to different research questions will play an important role. For the two fundamental research questions structuring this project (namely **I.** *Do HIHs provide an uncomfortable indoor environment for their occupants?*, and **II.** *If so, how can the process of designing HIHs be improved to reduce the risks of overheating?*) will be combined in the attempt to understand under which circumstance HIHs overheat and what can be changed in the design of HIHs to avoid the risk of overheating.

In this research process, there is thus an element of progression, as the qualitative data coming from the interviews help explain the findings obtained from the post-occupancy evaluation via a methodology of process modelling (called IDEFØ), in turn validated[74] via a focus group (fig. 7.1). Importantly , the mapping process (IDEFØ) restructures the findings of this research in an *integrated whole*, as opposed to a mere bulk of different inputs.

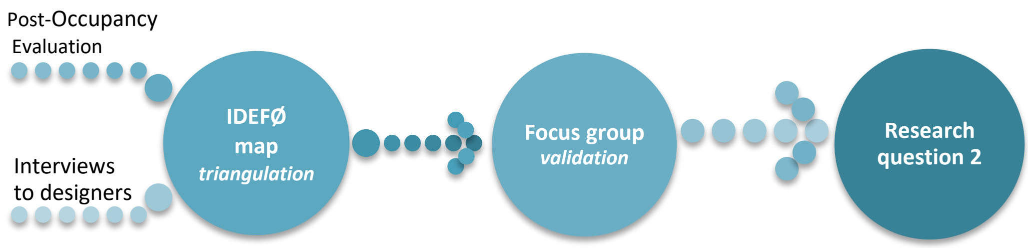


Fig. 7.1 Chapter 7 process: sequential triangulation and validation

[74] Construct validity is achieved through a strategy of multiple measures of the same construct [Yin, 1993].

7.1.1 PROCESS MAPPING

The occurrence of overheating in HIHs has proved to be an intricate phenomenon, the complexity of which needed to be modelled, so that both the physical and the non-physical aspects that govern it could be represented. In the present study, the quantitative research provided an account of a phenomenon whilst the qualitative research provided a sense of the process in which that phenomenon occurs by qualifying it.

In order to model the occurrence of overheating in HIHs , a transdisciplinary approach to the problem has been adopted. As indicated in Chapter 4, such approach crosses over architecture and systems engineering. Systems engineering is a discipline that provides methodologies by which one is able to model organisms, organisations and structures. Some of these methodologies rely on traditional methods such as data flow diagrams, whereas others rely on methods specifically developed in recent years for process mapping.

As such and in order to model the risk of overheating in HIHs, a specific function modelling method has been adopted. Such method, which is known as IDEFØ, [75] is part of a family of modelling languages – the so-called Integrated Definition Methods - which covers a range of uses (function modelling, information modelling, process description modelling, etc.). IDEFØ is a structured analysis methodology that is capable to graphically represent the functional relationships in the different stages of the building process and their influence on overheating risk. In this study, IDEFØ has been used to facilitate the legibility of the POE conducted, as it illustrated the interactions between activities in terms of inputs and outputs [Hassanain and Iftikhar, 2015].

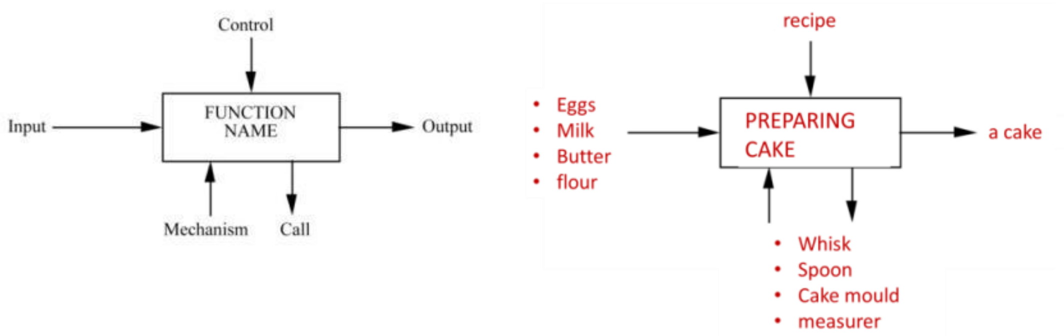
The advantage of IDEFØ lies in its capacity to model the decisions, actions, and activities of a system. So, the decisions, actions and activities that have characterised the case studies have been modelled through IDEFØ by using the stages of the building process as context. As a result, the reliance on IDEFØ has enabled the researcher to triangulate the data collected from the physical reality (from POE, the data of which have both quantitative and qualitative nature) and data collected from the interviews with designers, by so linking prediction and performance, which are the main areas of enquiry of this research.

[75] This technique it is also known as *structured analysis and design technique* (SADT).

7.1.1.1 BACKGROUND INFORMATION ON IDEFØ

IDEFØ is a function modelling methodology and functional modelling language that addresses information models and database design issues [Ang *et al.*, 1997]. Released in 1993, IDEFØ is useful in "*establishing the scope of an analysis, especially for a functional analysis. As a communication tool, IDEFØ enhances domain expert involvement and consensus decision-making through simplified graphical devices. As an analysis tool, IDEFØ assists the modeller in identifying what functions are performed, what is needed to perform those functions, what the current system does right, and what the current system does wrong*" [Knowledge Based Systems, no date].

IDEFØ, which is characterised by its simple graphics and precision [Pieterse, 2006], has a specific semantics relying on boxes and arrows. An activity box specifies the process represented. On the **left**-hand side of this box, incoming arrows represent the inputs of the action. These inputs can be, for instance, data or consumables needed for that activity. On the **upper** part, the incoming arrows represent data necessary for the action, commands or conditions which influence the execution of the activity but that are not consumed. On the **bottom** of the box, incoming arrows stand for the means used for the action: the components or tools used to perform that activity. Outgoing arrows show a link to another activity box and by so expressing a dependency of the activity of this box to another one. On the **right**-hand side of the box, the outgoing arrows represent the outputs of the actions or products produced by that activity (fig. 7.2).



a. b.

Fig. 7.2 IDEFØ: arrow positions and roles (a) and example (b) [NIST, 1993]

Arrows on an IDEFØ diagram can also represent a sequence (fig. 7.3) when the subject being modelled is sufficiently detailed to treat specific changes made to specific data items [NIST, 1993].

Another useful feature of IDEFØ is that it can represent nested stages within a function box, from a more general (parent) diagram to a more detailed (child) diagrams(s), by decomposing a top-level function into sub-function boxes. Likewise, each box may be both a parent box (detailed by a child diagram) and a child box (see fig. 7.4), because every parent box can be part of a higher hierarchy diagram [NIST, 1993]. This unfolding and potentially never-ending series of parent/child boxes is extremely versatile, especially when representing complex processes.

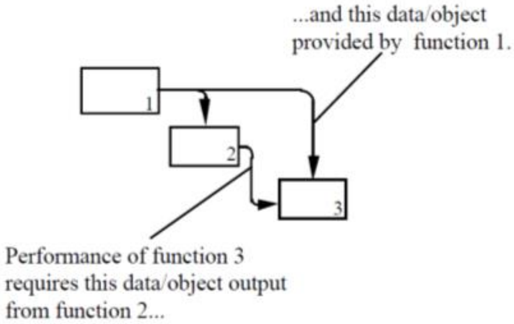


Fig. 7.3 IDEFØ: arrows in a sequence [NIST, 1993]

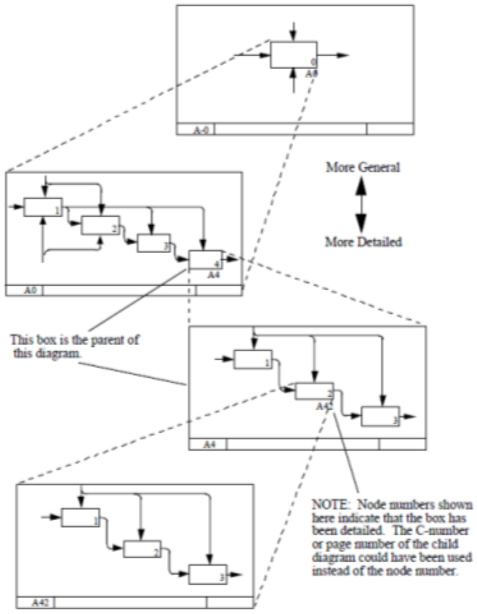


Fig. 7.4 IDEFØ: parent and child boxes [NIST, 1993]

In this study, this technique for process mapping is combined with the stages of the building process. This way, both (process mapping and framework) form the canvas on which the factors influencing the production of overheating in HIHs are located.

7.1.1.2 THE BUILD PROCESS

While in this study IDEFØ provides the method for modelling overheating, a framework representing the process also needs to be adopted. From conception to use, each building follows the stages of the building process. In the UK, this process has been formalised within the RIBA Plan of Works, as a shared framework, or model, for the building design and construction process. Such a model splits the building design and construction process into a number of key project stages and identifies a number of core tasks with associated team members' responsibilities [RIBA, no date c]. The RIBA Plan of

Works is effectively both a process map and a management tool, which was initially used for identifying liabilities [Designing Buildings, no date].

First conceived in 1963, the Plan of Works has continuously evolved to incorporate the complexity of projects, changing regulation, multiple procurement routes and a variety of roles and multidisciplinary teams through a flexible process where stages such as planning permission and procurement are moveable to embed requirements relating to sustainability and Building Information Modelling (BIM) [RIBA, no date b]. For instance, the UK RIBA 2007 presents the main stages of a design framework with the addition of a pre-construction stage for pre-tender documentation production, while UK RIBA 2013 focuses on the documentation to be produced at each stage and responsibilities of roles, and is thus more applicable to complex buildings [RIBA, no date a].

Due to the nature and growing interest in low-carbon design, which can nowadays be considered to be a complex project, it seemed appropriate to apply a more generic abstraction of the RIBA Plan of Works. This abstraction was regarded as necessary to formulate the IDEFØ map of overheating in HIHs, as found in the case studies this thesis has been concerned with was also felt necessary in order to:

a. simplify the mapping of the data collected;
b. make this research applicable to other countries' building design and construction processes and other countries' research into their built environment;
c. and, even more importantly, to cope with some of the vagueness of the collected data.

In arriving at the required abstraction two frameworks for the build processes have been considered: (a) the Spanish framework, which is focused on the stages prior to construction; and (b) the Italian framework, which is focused on the three main stages of the building life cycle. In both these cases, all stages can easily be compared to the RIBA stages (see fig. 7.5).

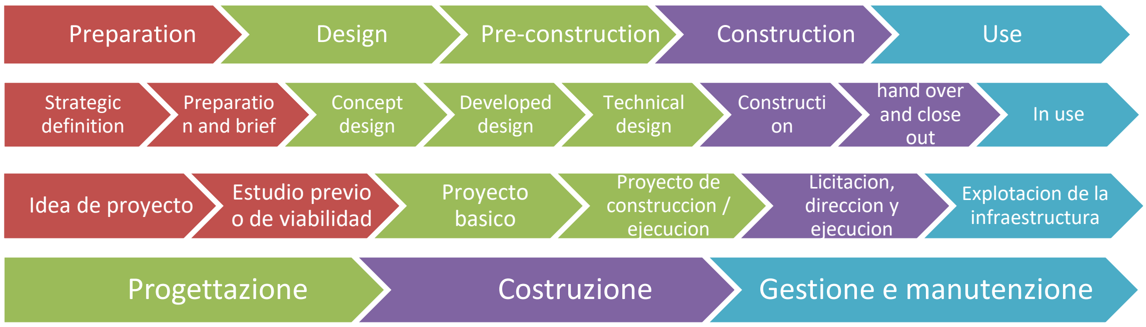


Fig. 7.5 The build process in various contexts: from the top, the UK RIBA 2007, UK RIBA 2013, the Spanish "Proyecto de Obra" and, at the bottom, the Italian "Progetto edilizio" [RIBA, no date c; Wikipedia, 2007; Giovenale, 2012]

For the purposes of the present research, the current version of the RIBA Plan of Works (2013) has been simplified from eight stages into four basic stages. These are indicated in fig. 7.6 below (in brackets one will find the main, although not necessarily the only, actor): 1. BRIEF (client), 2. DESIGN (designer/architect), 3. CONSTRUCTION (construction company) and 4. IN-USE (occupants), as shown.

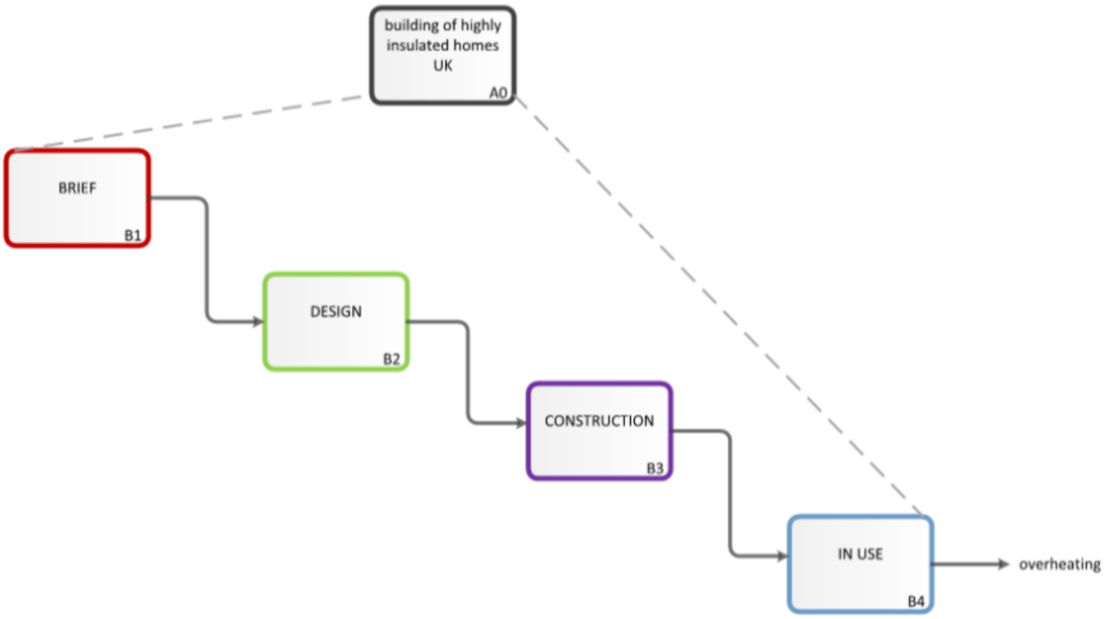


Fig. 7.6 IDEFØ framework to map overheating from the data collected.
The parent level (box process A0) contains a series child boxes (boxes named B1, B2, B3 and B4). Dashed lines are to indicate this parent-child relationship between the established parent level and its (zoomed) child boxes.

7.1.2 OVERHEATING MAPS OF CASE STUDY HOUSES

The framework presented in fig. 7.6 forms the basis on which to elaborate an overheating map for the case study houses based on disparate forms of data (qualitative and quantitative), as they emerge from the previous two chapters (Chapter 5-POE and Chapter 6-Interviews). The data has then been interpreted to formulate and position the 'arrows' with information relevant to the production of overheating[76].

Producing these maps has entailed some degree of subjectivity, as one needs to interpret the data, once they have been collected, and breaking them down into the IDEFØ map. And the processes of interpreting and reorganising are not completely objective procedures, since the input of the interpreter plays a role too. The subjectivity involved in handling (even objective) data is widely regarded as a natural component of (almost) any type of research though [Strauss & Corbin, as cited by Rabiee, 2004, p. 657]. So, there is nothing arbitrary in the mapping process relied on in this research.

In addition, the triangulation exercise carried out here is based on the constructivist assumption that there is no value-free objectivity and so research projects are also shaped by the reflexivity and stated epistemological assumptions of those who carried those projects out (as referred in Chapter 4 section 4.2).

By following this approach, two maps were produced, one for house UK51 and one for house UK52. The maps indicate the occurrences of overheating in accordance to TM59 (see fig. 7.7 and 7.8). In these cases, coloured text is intended to represent information coming from different actors in the design process. A red arrow is instead intended to highlight some of the reflections of the design team with regards to future projects. The other two case studies, namely UK54 and UK55, were not mapped because it has not been possible to interview the members of the design team to date.

By looking at the *IN-USE* stage of the overheating map of the Victorian retrofitted house UK51 (fig. 7.7), it can be appreciated that such house is uncomfortably warm in some rooms in summer, autumn and spring. A lesson learnt by interviewing one of the consultants is that retrofitting Victorian houses to Passivhaus standard as a low-carbon strategy should be avoided, due to loss of space associated with that typology of house. Another indication that emerged during the interviews is that both external shading and controlled glazing G values should be used. Interestingly, this map also highlights not

[76] Other studies have use IDEFØ to map data from POE only [Hassanain and Iftikhar, 2015].

only that the *DESIGN* stage made use of PHPP as a tool, but also that the thermal model was triangulated by the designers with other tools. This shows that despite careful considerations, the outcome of the thermal performance of UK51 was at time and in some rooms unsuccessful for summer comfort.

By looking at the *IN-USE* stage of the overheating map of the uncertified Passivhaus UK52 (fig. 7.8), it can be noticed that such house UK52 is uncomfortably warm in summer only. In this case the overheating risk analysis was performed on the assumption of a window-opening schedule: "*two windows open at the opposite sides of the bungalow to allow for cross ventilation and open for one hour… And with this level of ventilation, the frequency of overheating is 0.2%*"[77] [D3-UK52, May 2016]. The POE has instead shown that residents do not open the windows at night for security concerns. This indicates that the assumptions designers make on the behaviour of occupants may be unrealistic at times and this fact may mislead overheating assessments.

Both the cases under consideration were informed during the *DESIGN* stage, and careful thermal considerations were taken at this stage, and underwent SAP assessments. However the factors leading to overheating were not fully identified, to the effect that:

- In house UK51 no external shading was provided (see input to *DESIGN* stage), because it was considered that internal curtains would be sufficient (as it is in any traditional Victorian house). This expectation was, perhaps wrongly, extended to the converted loft, which had Velux windows.
- In house UK52 the Passivhaus consultant had to transform into Passivhaus a development that was designed to be traditional. Consequently, no external shading was provided. For this reason, avoidance of overheating had to rely purely in a ventilation strategy, which however was not performed by the occupants.

As shown in these examples, the complexity of the production of overheating in HIHs can be described only when the *system* where overheating occurs is described. It can also be noted that future designs may benefit from these maps, which have the potential to substantially improve the design of HIHs.

[77] Note that 10% of frequency of overheating is the criteria threshold.

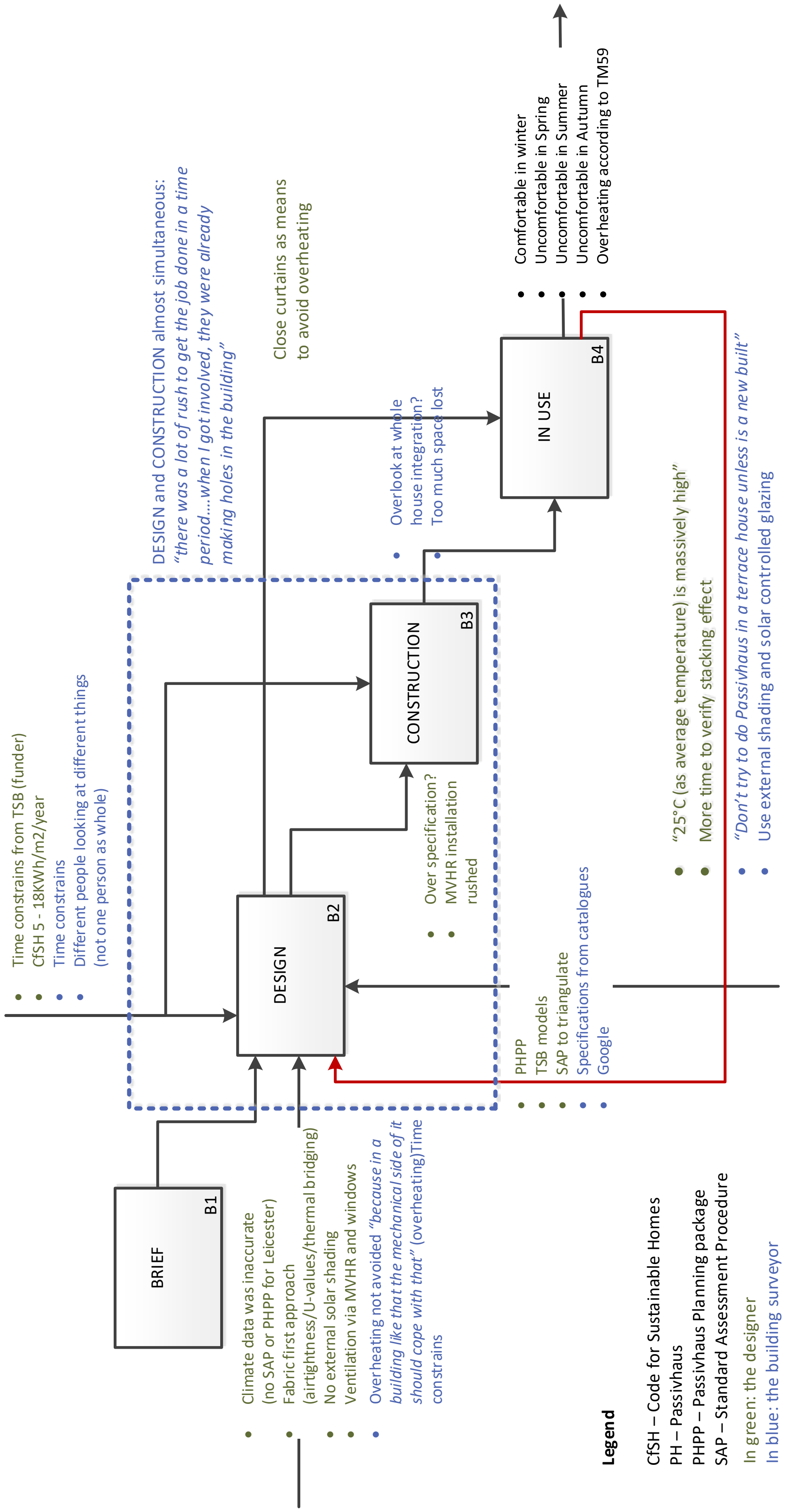
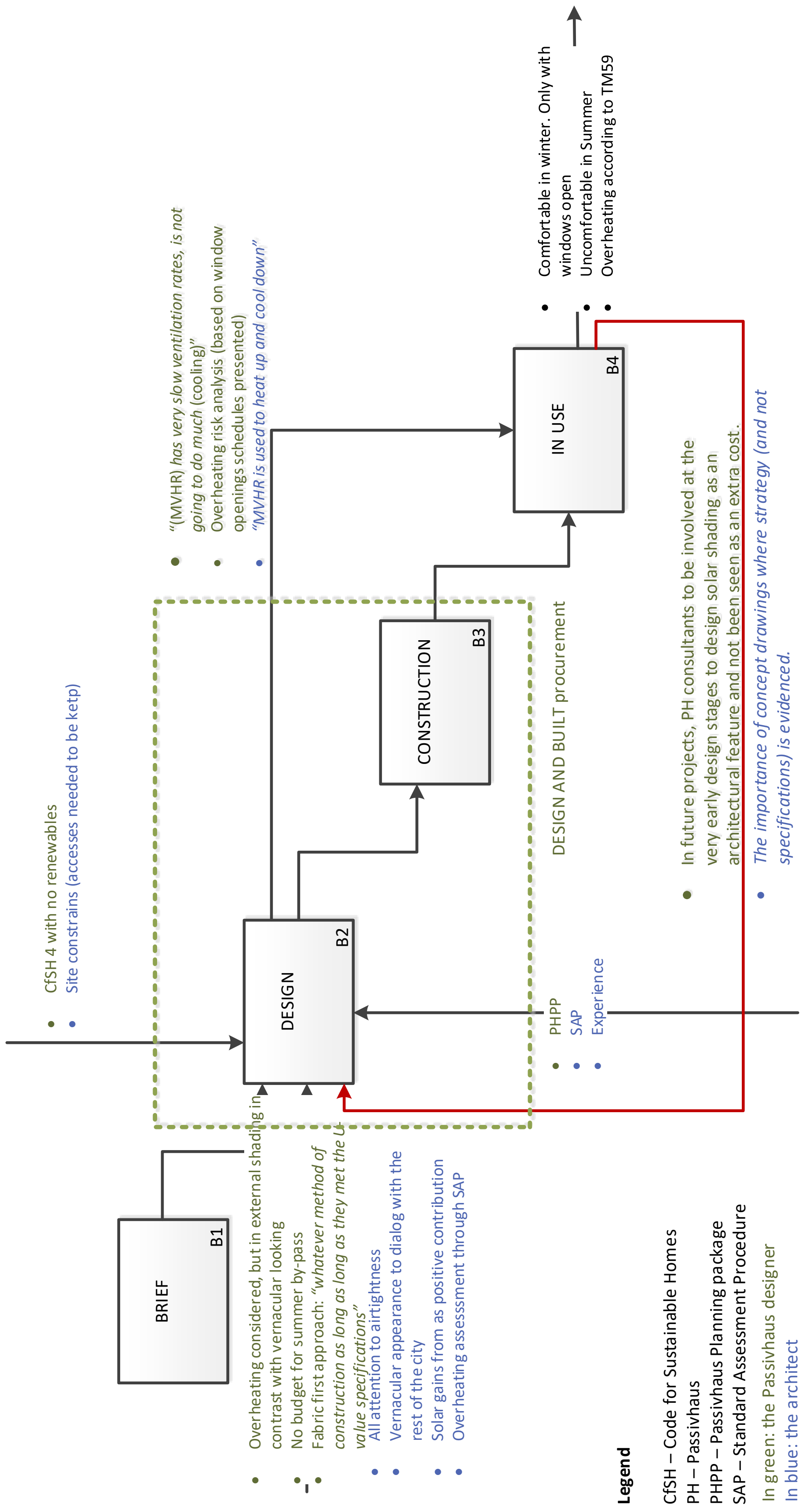


Fig. 7.7 Overheating map of house UK51



ig. 7.8 Overheating map of house UK52

7.2 *VALIDATION*: FOCUS GROUP

The word *validity* has different meanings and aspects according to the nature of the research. Mixed methods research by its own nature incorporates the validity criteria embedded in the distinct quantitative and qualitative components. As such, it means that mixed methods research incorporates the criteria of validity in use in both quantitative research (such as objectivity) and qualitative research (such as reflexivity), see Chapter 4 Section 5 "Validity". While for mixed methods research, there are still undergoing discussions on what constitutes *validity* delineated [Dellinger and Leech, 2007], it is accepted that *meaning* is not a function of the type of data collected but rather a result of the *interpretation* of such data [Dellinger and Leech, 2007].

To provide a legitimate meaning to the different "constructs" of the reality of overheating (quantitative and qualitative), in this research such constructs have been triangulated into a process map (IDEF map in Section 7.1) via a procedure of holistic interpretation of the performances of the different HIHs.

Such *interpretation* has been provided by the researcher, who has relied on her own epistemological assumptions, as treated by numerous authors [Pyett, 2003] and as they have been set out in Chapter 4. However, while triangulation alone may provide validity to the multiple methods and sources (see Section 4.5.2 of this thesis), it does not validate the construct of the reality of overheating represented in the IDEF maps.

For this reason, the researcher has integrated the process leading to establish the meaning of the findings with a discussion involving a group of experts. This idea is justified by the thesis, defended by Dellinger and Leech that construct validation[78] is the continuous process of negotiation of meaning accomplished through argument (as dialogue), criticism and objection [2007]. In the context of this research the relevant argumentative and dialogical process has then taken the form of a focus group. In the latter an expert audience has critically engaged and partially revised the original triangulation exercise (IDEF map). That way, the main findings of the research have been subjected to "negotiation" with a view of achieving interpretative rigor.

[78] Construct validity is defined as "*an overall evaluative judgement of the extent to which empirical evidence and or theoretical rationale support the adequacy and appropriateness of the interpretation*" [Dellinger and Leech, 2007, p. 316].

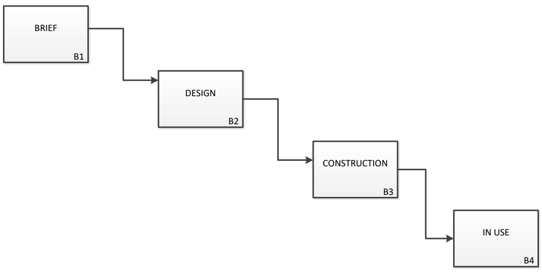
To achieve this, the two maps reported in the previous section have been validated by means of gaining feedback about their usability. Feedback was facilitated by conducting a focus group session, where a brief background of both (a) occurrence of overheating in HIHs and (b) a process mapping methodology were presented to a specialised audience consisting of experts in sustainable building design. Participants were designers and engineers, working both industry and in academia.

In order to gain feedback by means of focus groups, Bryman recommends a controlled group size, from six to ten members [Bryman, 2015]. To control both participation and to allow for management of responses, in this instance seven participants were invited (see table 7.1).

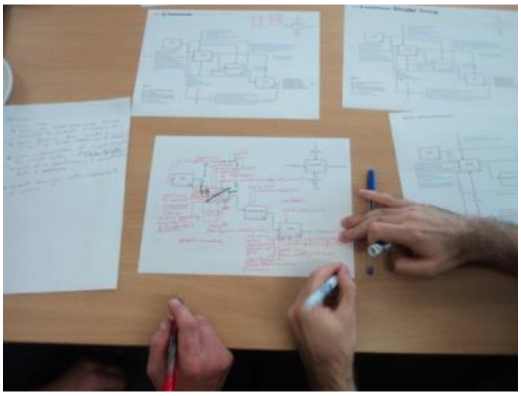
Table 7.1 - Focus group participants (repeated from Chapter 4)

Coded name	background		architecture	engineering	Housing association
FGP1	designer	academia and industry	1		
FGP2	architect	industry	1		
FGP3	engineer	academia		1	
FGP4	engineer	industry		1	
FGP5	housing provider	industry			1
FGP6	engineer	academia		1	
FGP7	engineer	academia		1	

During the focus group, a brief background to the process mapping methodology was presented by the researcher. The audience was then divided into groups of two people each. Each group was invited to reflect and elaborate on the maps presented (fig. 7.7 and 7.8) in order to propose a more generic 'overheating map'. Accordingly, the first part of the workshop focussed on ways by which to avoid overheating, mapped in a blank IDEFØ map template (fig. 7.9) and distinguished into the four key stages.



a.



b.

Fig. 7.9 Blank IDEFØ map for focus group (a) focus group pairs 'IDEFØ' exercise (b)

Subsequently, the audience commented on their maps and on the usability and appropriateness of the process map methodology used (IDEFØ map) in a plenary, open discussion. During the plenary session, a group synergy, in terms of positive interaction, was achieved, as anticipated by many authors [Rabiee, 2004; Bryman, 2015]. This synergy allowed the participants to arrive at a shared interpretation of the IDEFØ map, namely, to achieve the so-called *joint construction of meaning*, as articulated by Bryman [2015, p.501].

Data gathered during the discussion was transcribed and a thematic analysis was performed. In this respect, it is worth emphasising that because the focus group was not of an exploratory nature (in fact, it was framed by the findings described in Chapter 6), content analysis was found not to be necessary.

The plenary discussion provided suggestions for improving the overheating map concept originally presented.

The main findings of the focus group are presented in the following paragraphs. This validation and related suggestions enabled the researcher to turn the original map into a possible 'overheating aiding tool'.

7.2.1 OVERHEATING AVOIDANCE

7.2.1.1 BRIEF STAGE

With regards to the first stage in the map—the BRIEF (fig. 7.10.a)—during the plenary discussion, it was suggested that the DESIGN phase should feed back into the BRIEF stage, to the effect that the client may be invited to reconsider the requirements in light of the implications of the design of HIHs buildings (fig. 7.10.b). In this context, participant FGP5 observed that:

> *"We thought that the DESIGN should feedback the BRIEF... Making sure that the person who is asking for the property actually understands the consequences of what they are asking for, and that they understand the consequences and cost of what they might need to add to the design".*

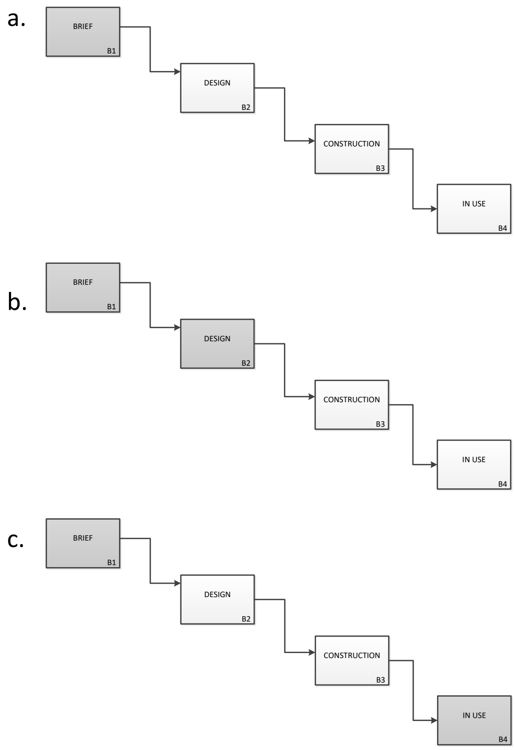


Fig. 7.10 BRIEF stage (a) and links to other stages, emerging during the focus group

Another participant (FGP7) observed that there was a need to have an understanding of what affects comfort in order to be able to specify what the design should achieve. This observation does not only imply that clients and facilitators should understand the implications that their demands have on comfort; it also implies that BRIEF requirements should be informed by the POE, which presently is not compulsory (fig. 7.10.c).

7.2.1.2 DESIGN STAGE

A greater amount of time of the focus group was devoted to discussing the DESIGN stage (fig. 7.11.a). At first, the group discussed which guidance, or tool, or/methodology, was needed to avoid overheating. The debate then moved to the relevance of having proper guidance (a suitable tool for measuring overheating) and, in particular, a specific tool that focusses on overheating (participants FGP4 and FGP5). A participant (FGP6) noted that an overreliance on calculating tools may impair judgement.

In this context, it was observed that one single tool to assess overheating may not be sufficient. As participant FGP6 put it "*one of the problems is ON trusting too much these tools*".

Likewise, some participants reflected on the kind of accuracy that is required when using these tools. In this context, it was widely agreed that it would be wise not to rely on just one particular tool, but rather to perform tool triangulations. As participant FG7 put it:

> *"if you use more than one method of assessment, if you get discrepancies between them, there is an opportunity to ask the question which of these is right, which is closer to being right, and what are the differences … is actually understanding what results you are getting back and why you are getting them".*

In other terms, every tool inevitably incorporates a degree of subjectivity (approximation and error), so it is important to exercise one's judgement when interpreting the results of the analysis (no matter which tool has produced it).

For this reason, it seems to be the case that different forms of approximation are needed to predict the performance of HIHs, or at the very least to anticipate (and guess) the risks of overheating, at least insofar as it may be possible.

Moreover, in relation to comfort, the group highlighted that designs should be simple for users to understand and maintain. In fact, a thermal strategy is often found to be not so intuitive by occupants. Accordingly, it was proposed to avoid designing for thermal strategies that cannot be easily understood and followed by occupants, who may not necessarily be aware of the principles of building physics and not shape their way of living on those principles.

The audience's shared opinion also linked the DESIGN stage with IN-USE, where the output from the design stage (a HIHs design) becomes a tool by means of which occupants

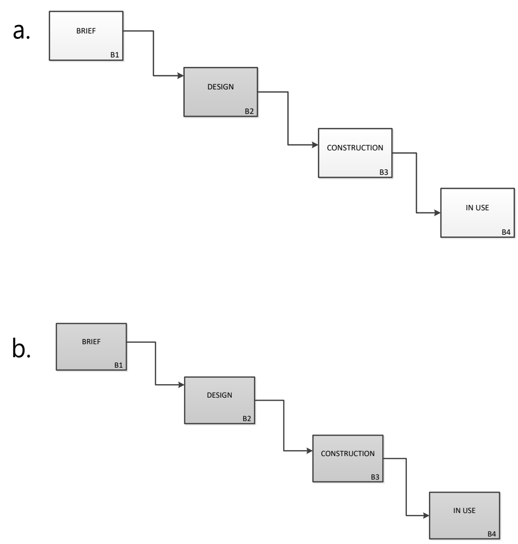


Fig. 7.11 DESIGN stage (a) and links to other stages (b)

can achieve comfort (IN-USE stage). In this way, house design should incorporate the means to achieve, maintain and change comfort.

Another theme that emerged in the discussion was the need for concept drawings as well as for a high level of detail (LOD) and definition. This need was claimed to be due to the fact that the design process occurs within a complex multidisciplinary and organisational territory, with a lack of process integration between BIM and energy-related tools. This fragmentation of information combines with a large number of professionals' involvement.

In this context, it was also noted that:

> *"the difficulty is that some architects work at concept and pass that work to a second architect or to a specialist engineer to get the technical work... The client might just walk away with that and give it to somebody else and turn it into design and build, so that way it is contractual"* [FGP1].

The fact that there is no one single individual responsible within the building process, and so there is no one responsible for overheating, makes it even more evident that the overheating risk has to be viewed in its complete dynamics. Otherwise, we will not be able to avoid it. This point is further elaborated in the discussion, see reflection 7.3.2.

Once all these components are considered, the design stage showed strong links with all the other stages and so could be considered the most crucial stage on the dynamics of overheating (fig. 7.11.b).

7.2.1.3 CONSTRUCTION STAGE

During the exercise it was briefly discussed how overheating could be avoided in the CONSTRUCTION phase (fig. 7.12). The strategies to avoid overheating relate to the development of specific skills and to the fact that "*contractors build according to Building Regulations*" [participant FGP7]. This last statement may be read as having two implications.

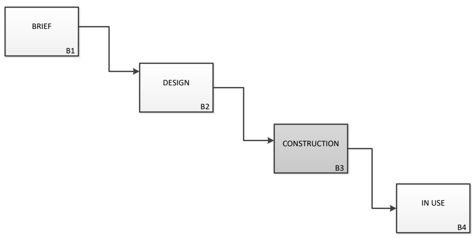


Fig. 7.12 CONSTRUCTION stage

First, the statement indicates that designers' thermal strategies may be overlooked or omitted, especially during a build process in which designers' involvement is completed when they hand over the 'product' design to construction companies. In such a case, a house archetype may be implemented without taking into consideration the actual orientation of the building and so without taking into account the potential solar gains associated with its orientation. This case is widely exemplified in the history of planning in the UK. On this basis, there is no ground to believe that in the future the same issue will not arise again, despite the fact that HIHs design requires a careful consideration of orientation.

Secondly, the statement emphasises the fact that if overheating is to be avoided, it has to be embedded in the Building Regulations as a matter of priority. This is not to claim that it will be sufficient to focus purely on regulations in order to avoid overheating; rather, it is to say that the action of governmental authorities (especially in the form of embedding overheating checks into the Building Regulations) would significantly contribute to avoid the risk of overheating. At the moment of writing there is no compulsory 'overheating' check-list embedded in the Building Regulations.

7.2.1.4 IN-USE STAGE

The IN-USE stage (similar to the DESIGN stage) provided an opportunity for a lengthy discussion with a number of interlinked considerations (fig. 7.13). The discussion undertaken in the DESIGN stage about the need to deliver simpler designs led to a related debate about the manageability of HIHs houses and its effects with regards to the performance of buildings. Part of this debate consisted in elaborating on the thesis that not just occupants but also house managers can play a pivotal role in this respect:

> *"We also, though, should consider the landlord as well…. In another box… it shouldn't be just the tenant; it is the tenant plus the landlord"* [participant FGP5].

Participant FGP5 elaborated on the idea that, within the IN-USE stage, there is a dual responsibility, shared by the house's manager and house's occupants in the overall performance of HIHs. If this dual contribution to house performance is not properly understood, HIHs are at risk of problems that may considerably affect thermal comfort (especially in consideration of the fact that in HIHs comfort is not achieved by turning up/down the heating, like in traditional houses):

> *"if they* (the house managers) *are going to lock everything in a cupboard and the tenants have an issue, they* (the house managers) *have got to react very quickly,*

and they have got to understand the controls to make sure they make the changes they need to" [participant FGP5].

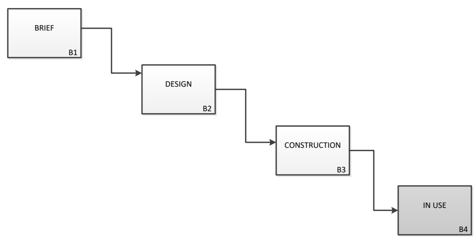
From this, the discussion moved to consider the actual reliance on a house manual. Here, participants seem to have very different views. Some of them supported the idea that HIHs should not rely on a manual to be operated correctly. The manual can, in fact, be lost in the life cycle of a house, especially when tenants or owner change:

"You should be able to come back in 10 years' time, 20 years' time you should still be able to understand what you need to do. So, a manual the first occupier might keep it, might throw it away… So, the design of the house should be as much as possible a successful design irrespectively of what you do to it [participant FGP7].

Another participant instead claimed that, at least in certain kinds of organizations, the manual might be essential:

"I think it is different if you are a social housing provider… I think some really good facility managers groups up in the North East who want to keep those manuals … And they are maintaining the systems, cleaning the filters, and checking the MVHR system on a regular basis… It will be difficult to cope with the situation when the situation changes over time" [participant FGP1].

a.



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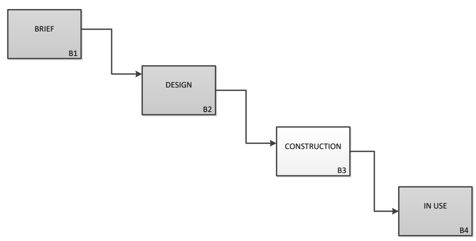


Fig. 7.13 IN-USE stage (a) and links to other stages (b)

Lastly, another participant observed that shared facilities may cause issues as far as maintenance goes:

"In my experience the biggest issue is a shared facility. So, if I have multiple occupancy blocks with one MVHR system, and it's got a mix of rent/owned … or you have terraces with shared occupancies and one heating system, one thermal boiler store for the whole street…who maintains the system?" [participant FGP1].

Overall, the IN-USE stage of the discussion emphasised the need to consider HIHs management even at the DESIGN stage and at the BRIEF stage. For instance, if the BRIEF requirement is the Code for Sustainable Homes level 4 with no renewables (as it was the case with house UK52), a building will end up displaying outstandingly high levels of energy reduction requirements. In turn, at least in certain types of development, the same requirement may lead to the provision of shared technical facilities, which is associated with the risks explained in the previous paragraph. For this reason, the IN-USE stage should be considered as being highly dependent on the other two stages, as shown in fig. 7.13.b.

7.2.2 SUITABILITY OF IDEFØ MAPPING

The usability of IDEFØ as an appropriate, or useful, method to map overheating, received mixed feedback from the participants in the focus group.

During the discussion, the perception of IDEFØ improved from scepticism to [cautious] acceptance. For the discussion begun with the expression of some reservations about the explanatory potential of an IDEFØ map of overheating. Some participants claimed, for instance, that the framework achieved by means of IDEFØ was too complicated if one is only engaged in one stage of the build process. Similarly, in the course of the discussion it was acknowledged that the use of IDEFØ requires familiarity with its language:

> *"it is effectively a list of all the things you need to think about in different stages… but that relies on the person using it* (IDEFØ) *to actually understanding it"* [participant FGP7].

These reservations eased out during the discussion. In fact, by the end of the debate, a more positive view of the potential of IDEFØ had gained some momentum, as participants gradually realised that IDEFØ mapping allows for the possibility of breaking down a complicated issue into more elemental and simpler units.

The table below is indicative of the dynamics just described.

Table 7.2 - Polarity on the views of IDEFØ map during the focus group

-	*"So, I was thinking that we can use less tools or method focus on smaller aspects, maybe it is easier to break it down"* [FGP4]
+	*"Having had the time to break down the map, it is a good way of helping you to understand a complex problem, making sure you got everything covered"* [FGP5]
+	*"Because you are not restricted to looking at design in isolation or construction in isolation or whatever…you get the links in all the different stages…You could see where one thing influences another"* [FGP7]

7.2.2.1 IDEFØ MAP POSSIBLE USES

The positive assessment of IDEFØ further evolved into an almost enthusiastic acceptance, as participants realised the manifold possibilities inherent in the use of IDEFØ. Among those different possibilities envisioned by the participants was the use of the IDEFØ map of overheating as an aid to designers. In this context, it was noticed that IDEFØ can be used as:

- A **methodology for overheating avoidance**, based not only on its potential to establish interconnections between different issues but also on its focus on check-listing specific stages of the whole process. In this context, for instance, actions to be taken at the IN-USE stage to avoid overheating can be listed and, at the same time, linked to the DESIGN stage. In this way, designers may be able to make a list of the adaptive capabilities that occupants need to act on.
- An **analysis tool** for post-occupancy evaluation, which enables one to add information as knowledge from real-life HIHs is acquired and required actions are individuated. In this case, the purpose of IDEFØ will be twofold, as IDEFØ will be instrumental to both analysis and knowledge dissemination.
- A device that can be turned into a **project plan,** especially in projects where multiple stakeholders are involved and are able to work on a single stage, with a complete-process view (cf. "*In a complicated project, with multiple stakeholders coming in it and then that makes sense to show where you fit in the overall jigsaw….. The sequence I think is important for all of us, the checks and feedback loops… It is a systematic approach*" [participant FGP1].
- As a **design tool** providing an understanding of things that need to be considered. As it was noted, *"you could almost form like chambers, where you got to consider the orientation and you look and say, 'ok in this particular instance this building orientation is not a problem because is north facing or whatever, but it acts as a prompt to consider those things'"* [participant FGP7].

Here, it is important to consider the opinion of a participant, who claimed that the IDEFØ map of overheating highlights the importance of POE: *"It is clear how the IN-USE links back to the design and to the brief (*stages*)… So, showing how conducting POE can benefit the earlier stages of future design, so it has a sort of interlinking I think is another useful feature to it"* [participant FGP7]. Therefore, IDEFØ has been acknowledged by the participants in the focus group to be, at the very least, a good enabler of POE findings' communication and discussion.

7.2.3 SUMMARY OF FOCUS GROUP

The issues identified during the focus group are summarised below. From the discussion on overheating avoidance (section 7.2.1) it was determined that:

- The BRIEF stage needs to be informed by an understanding of the impact on comfort that HIHs design has. In this context, the implications of HIHs design of for the use and management of HIHs should also be accounted for.
- The DESIGN stage should inform the BRIEF stage, insofar as the implications of HIHs design are concerned. The suitability of the BRIEF stage also needs to be tested in light of those implications. In addition, design considerations are to be supported by adequate tools to assess their designs or to triangulate different tools. This is required in consideration of the fact that available tools may overlook overheating risks[79]. Finally, it emerged that HIHs are to be understood as a means to achieve comfort, and for this reason they should be effective in their provision of comfort and their maintenance.
- The last point deeply links the DESIGN and the IN-USE stages, because comfort in HIHs is achieved (purely) by the design (not by energy). Therefore, HIHs design should support comfort (in both winter and summer). In other words, if HIHs are understood as a *means for comfort*, then HIHs design, as a practice, may shifts its focus away from the traditional one - the traditional focus being the provision of comfort via energy use and the new focus being the provision of low-carbon comfort via low-carbon design.

The debate about the suitability of the IDEFØ map (section 7.2.2) revealed that IDEFØ provides a discussion-enabling tool. In this particular case, the discussion made possible by the IDEFØ map led to the conclusion that a simplification of the IDEFØ map could be turned into a **design tool for overheating avoidance** in the context of an integrated view of the building process.

In this spirit, the responses given by participants were recorded and subsequently translated into an IDEFØ map during the focus group. But this process proved not to be a straightforward exercise. In fact, the number of the issues involved in relation to the language of IDEFØ itself, for instance, supported the claim that the direction of arrow could vary according to the stage the arrow is linked to. In this respect, the INPUT arrow

[79] The limitations of measuring overheating have been shown in Chapter 5 and discussed further in Chapter 8.

in a stage may well correspond to the OUTPUT arrow from the previous stage. Similarly, discrepancies were noted among the the arrows acting as a MECHANISM (and, hence, supporting a stage's function) and the arrows acting as a CONTROL (and, hence, governing the same stage's function), like the use of SAP or other prescriptive procedures as target designs. Nonetheless, during the mapping exercise it was noted that many issues raised in relation to the DESIGN stage had implications for the other stages of HIHs (see Appendix G for an overview of this map).

7.2.3.1 IDEFØ MAP OF OVERHEATING AVOIDANCE

This research process undertaken in this study has led to the creation of an overheating avoidance map. The creation of this map is an attempt to responding to the second research question underlying this thesis, namely, the question: *How can the process of designing HIHs be improved to reduce the risks of overheating?*

The main issues discussed and presented in the previous sections have been summarized in such a map, which shows the themes that were agreed to be suitable strategies for avoiding overheating. This map cannot be considered complete as it is based on the discussions on one focus group and it is based on a limited amount of case study HIHs. Nonetheless, it can provide the basis of a methodology that aims to avoid overheating, by so constituting the basis of an 'overheating aiding tool', as it were.

The proposed map is based on two drawings (figures 7.14 and 7.15). The first drawing (fig. 7.14) shows a parent box with the task to perform — in this case, 'overheating avoidance'. The second and nested level (child) shows all the stages with some of the issues discussed during the plenary discussion of the focus group. Here, it is evident that the BRIEF stage appears in need of considerable feedback from the new built and design to understand the everyday and long-term implications of their requirements. The CONSTRUCTION stage could have some form of overheating measures embedded within the building regulations. In the IN-USE stage, the needs of the other stages to support this activity box become clear; at the same time, this stage impacts on the inputs of the previous stages by so creating new knowledge.

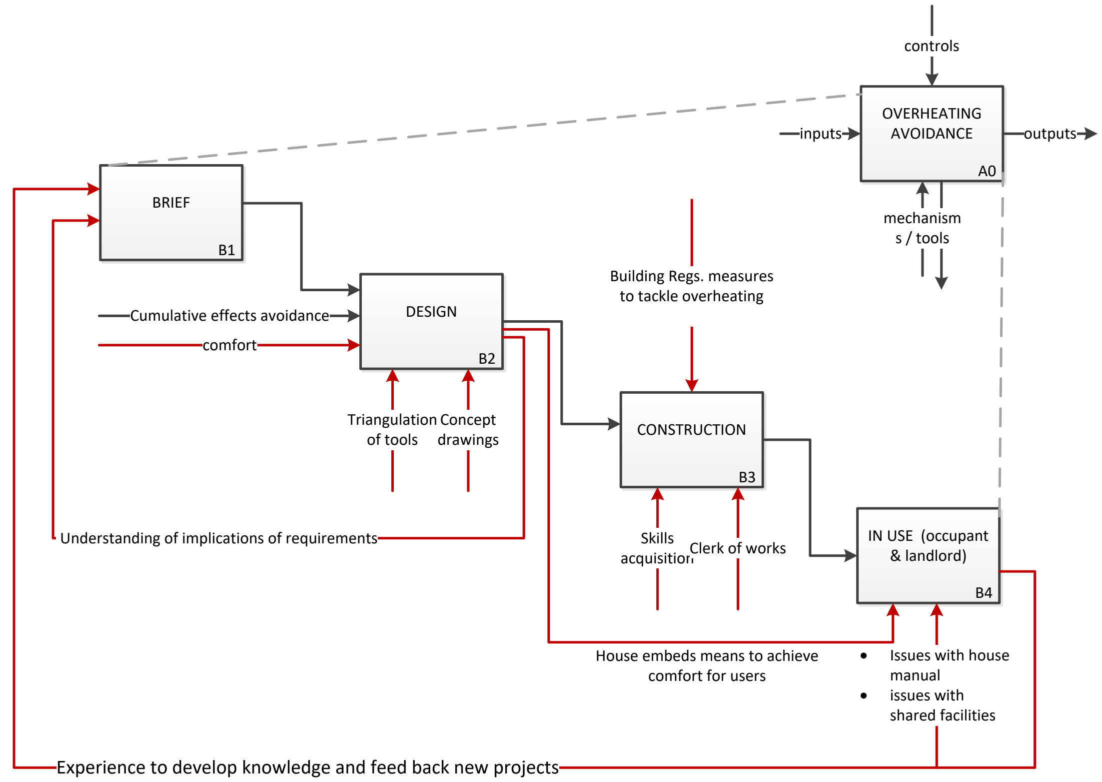


Fig. 7.14 Overheating avoidance map, based on a simplified version of the map drawn during the focus group, levels 1 (A0, parent) and 2 (B1, B2, B3, B4 child)

The second drawing, shown in fig. 7.15, further details the DESIGN stage in order to focus on the issues pertaining to it. Here, the physical factors (such as the avoidance of the cumulative effects of solar gain, inadequate ventilation, and internal gains) are indicated in black (as opposed to being indicated in red, which refers to data derived from the literature review).

As an *input* to the DESIGN stage the issue of comfort has been added. This means that in designing HIHs an understanding of comfort (how to achieve it and maintain it by the occupants) is essential. This understanding on comfort is to be supported by the knowledge gained from the POEs of similar HIHs. This requirement is based on the acknowledgement of the limitation of performance predictions when compared to real-life situations. Moreover, the design should be based on 'informed' brief requirements. This means that an interactive consultation between the early stages of design and brief requirements should be engaged to avoid unsustainable goals.

As *output* from the DESIGN stage, the most relevant concepts relate to the delivery of HIHs that are uncomplicated to operate and that serve as means of comfort. The latter implies that HIHs designs are to be equipped with adaptive opportunities for occupants when controlling their comfort.

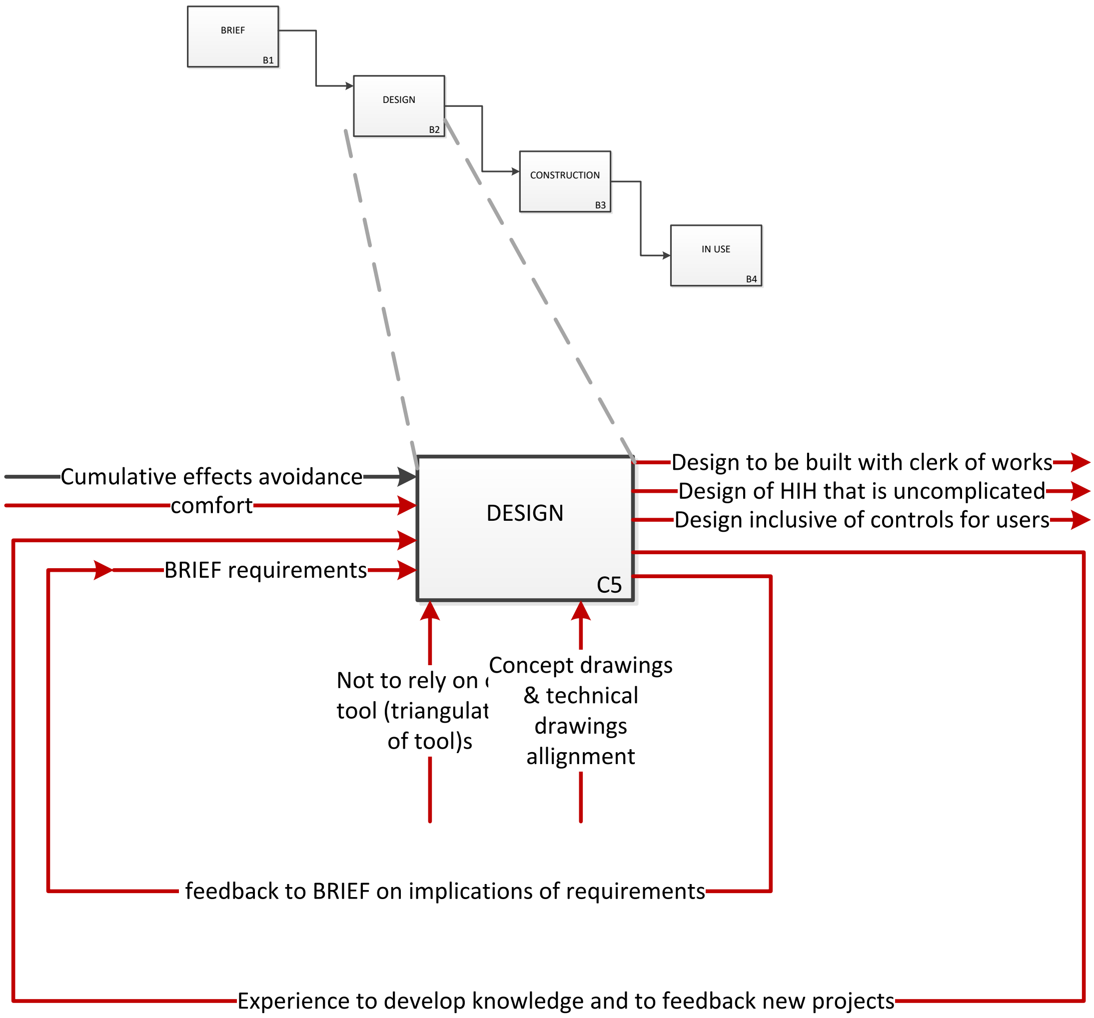


Fig. 7.15 Overheating avoidance map, based on a simplified version of the map drawn during the focus group, level 2 (B2 parent) and level 3 (C5 child)

7.3 DISCUSSION

The feedback on overheating avoidance within the building process and the opinions regarding the usability of IDEFØ to map overheating avoidance expressed by the audience were instrumental to make a number of reflections. The main ones are reported below.

7.3.1 ON THE NOVELTY OF THE IDEFØ LANGUAGE

At first, the complexity of arrows and boxes seemed to overwhelm the audience, especially because of the abstract structure of IDEFØ. Once the familiarity with the semantics of IDEFØ grew, the map developed easily from the suggestions made by the participants during the focus group. As a result, participants came to realise that IDEFØ is only superficially complex and abstract. However, in light of the initial perplexity felt by the participants, it may be advisable to think of ways by which to simplify the IDEFØ map before applying it to the mapping of overheating.

In fact, during the session breaking down the audience's suggestions for overheating avoidance into the proposed framework (IDEFØ map) occasionally proved to be a tall order, especially because participants did not have a clear view of whether a suggestion should be considered an *input*, a *control*, or a *mechanism*. An example of this difficulty is provided by the need for the user controlling their environment to achieve comfort. Comfort-control was attributed as a *mechanism* in the IN-USE stage by one participant. By contrast, another participant referred it to the DESIGN stage. The ability for occupants to control their environments is indeed best regarded as an *input*, if considered in the DESIGN stage, and as a *tool, or mechanism*, when focusing on the IN-USE. The fact that the ability for occupants to control their environments belongs to both stages requires that each arrow in one stage has a corresponding arrow in the other stage(s). Additionally, those arrows have different directions; this also means that the map can become extremely dense.

As a consequence of this feedback, a simplification of the IDEFØ was performed and presented in section 7.2.3.1: the IDEFØ map of overheating avoidance.

The multiple potential positions of the arrow (and consequent meaning) is one of the strengths of IDEFØ; but, as the focus group demonstrated, this can also be a weakness of

IDEFØ since it can be misread by the audience in consideration of the fact that *"it takes a lot of time to understand the arrows' meanings and break them down"* (participant FGP7).

On the other hand, IDEFØ has been proven to effectively contextualise a process, its needs and its implications. In this context, IDEFØ can effectively be considered to focus on the DESIGN stage of HIHs and instigate interconnected thinking.

7.3.2 ON THE FRAGMENTED DESIGN PROCESS

The view, expressed by one participant, that IDEFØ "*is a good way of making you think about it*" (participant FGP5) emphasises the fact that the map presented helps one to think in an interconnected way. This view contributed to reinforce the idea that a 'ticking-boxes' approach to design should be replaced by a more organic way of designing, in which consideration is given to what comes before, or after, a given stage. In other words, while performing a task, a designer should always be aware of the implications of any action along the whole process of building, and s/he should consider the influence of his/her decision making. This could be an advantageous progress when innovation brings new complexities that are to be handled by designers.

7.3.3 ON LOW-CARBON DESIGN

It is clear that the risk of overheating is initiated in the BRIEF stage, where higher targets of carbon reduction can drive into a relatively new and underexplored design practice based on building performance prediction. This is not to say that HIHs should not be built in order to prevent overheating from occurring, though. Instead, this kind of consideration stimulates the adoption of a **different approach to designing HIHs.**

To consolidate this point, one should consider that a non-HIH (or traditional house) achieves its comfort via energy use; by contrast, HIHs delegate this task to proper design, construction and use of the building. Hence, the comprehension of the links between design and other stages is of paramount importance.

This reflection justifies the conclusion that every actor involved in the building process of HIHs should be aware of the implications on thermal environments that the construction of HIHs generates — this is especially the case when one compares HIHs to traditional houses (non-HIH).

To elaborate on this last point and link it to the bigger picture aimed at reducing carbon emissions from buildings, one can conclude that HIHs, under certain circumstances, may be at risk of an increasing (and unintended) demand for cooling.

The need for cooling in this context would correspond to a change (or switch) in energy demand that originated in pursuing energy demand reduction. Hence, there is a need of reducing energy demand. And this requires a new practice of design in which the role of comfort is understood in its complexity, rather than being reduced to a matter of fabric efficiency only. This way, it should be possible to achieve a reduction in energy demand (and not a merely switch in energy demand from heating to cooling).

7.3.4 USE OF THE 'OVERHEATING AVOIDANCE MAP' TO AID BUILDING DESIGN

As this chapter has demonstrated, the use of IDEFØ method has proven to be a straightforward framework for POE findings, as well as a useful graphical tool to communicate lessons learned from POE. It would also be crucial that knowledge gained from POE were shaped by an integrated approach (such as process mapping) since this could help avoid a *siloed* attitude to knowledge development. Hence, there seems to be scope for developing research into a systems thinking approach to aid and channel POE findings.

The lessons learned from POE -urgently needed from innovative designs- can then inform designers. For instance, the overheating map avoidance can have a role in supporting designers. This can be achieved by breaking down every four stages and relate them to the RIBA Plan of Work. The RIBA Plan of Work can be then integrated with an 'Overheating Overlay'; in a way similar to the 'Green Overlay' [Gething, 2011]. While the Green Overlay integrates each RIBA Work Stage with a 'Sustainability Checkpoint', the overheating avoidance map instead can inform the RIBA Work Stage with an "Overheating Checkpoint". However, the target of this aiding map may only be architects.

To extend the umbrella of users of the 'Overheating avoidance map' produced with IDEFØ method, one may consider embedding such map in the building information modelling (BIM) environment. This can be achieved by integrating the IDEFØ Overheating avoidance map with IDEF5. IDEF5 (Integrated Definition for Ontology Description Capture Method) is software engineering method, designed - among other things- to aid researchers in the application of knowledge representation methods to problems in engineering and manufacturing [Benjamin *et al.*, 1994]. In the context of BIM, the IDEFØ map can be translated into a structured ontology (IDEF5) to become a development for Dynamo environment (visual programming for parametric programs such as Revit) and can be used by any building modeller (engineer or architect). In addition, such ontology can be updated as knowledge (in this case of the production of overheating) develops.

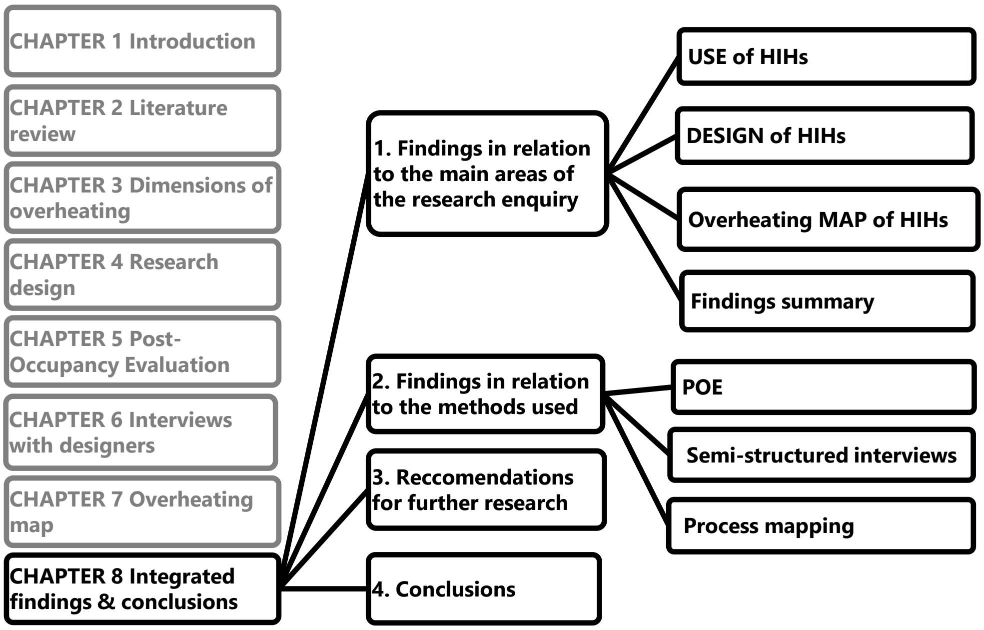
7.4 CHAPTER SUMMARY

The methodology used in this chapter to graphically represent both the data gathered and their functional relationship was instrumental to arrive at a triangulation of the findings of the two previous chapters.

A proper methodology (IDEFØ) and framework (the build process) were chosen, and their benefits of the resulting maps were discussed. The resulting 'overheating maps' of houses UK51 and UK52 were then validated by means of a focus group. The results of this chapter also provide the basis of a possible future development of an 'overheating avoidance aiding tool'.

In conclusion, the findings introduced in this chapter provide an indication that the complexity of overheating production in HIHs can be successfully described only when the *system* where overheating occurs is described. In addition, findings from the discussed maps led to highlighting the limits and benefits of process mapping a complex issue like overheating in HIHs, where knowledge is not yet consolidated and so it should (and can) be 'mapped' to inform future design.

CHAPTER 8: INTEGRATED FINDINGS AND CONCLUSIONS



Synopsis

The intention of this chapter is to convey the findings from the main areas of research (as built on data of a diverse nature) in order to respond to the main research questions underpinning the project. Doing so is essential to closing the loop between the research framework that has guided this research project and the findings of the research itself.

As such, this chapter presents the integrated findings from this research project. It links the main cumulative factors established to lead to overheating (namely, solar gains, inadequate ventilation and internal gains) to the fundamental questions and different components and of the research. Accordingly, the strategies will be discussed to provide an initial contribution to low-carbon housing advancement in knowledge.

8.1 FINDINGS IN RELATION TO THE MAIN AREAS OF THE RESEARCH ENQUIRY

The chief goal of this research work consists of informing the design process through which new HIHs are conceived, so providing aid to architects and designers in their low-carbon designs. This result has been pursued by addressing two specific research questions:

I. *Do HIHs provide an uncomfortable indoor environment for their occupants?*
II. *If so, how can the process of designing HIHs be improved to reduce the risks of overheating?*

To respond to these questions, three main areas of research have been pursued:

i. The **in-use** aspects of the overheating enquiry, which was concerned with the real-world data. This part was essentially devoted to finding evidence of overheating in HIHs by means of objective and subjective measurements collected from the houses that served as case studies in order to determine the likelihood, and the sources, of overheating.

ii. The **design** aspects of the overheating enquiry. This area takes into account all the design considerations as well as issues related to predicting the thermal performance of HIHs. As part of this research, the designers of the case study houses were interviewed in order to gain information about their knowledge, assumptions relating to performance, tools and techniques used, and assumptions regarding user behaviour.

iii. The contextual aspect, or **process,** in which HIHs are conceived, built and used. This part linked the thermal performance of HIHs to the design thinking and processes behind those houses. It was also intended to identify any risk that could lead to overheating during the design stage and in determining how the design process could be improved in order to avoid overheating. This objective was pursued by linking the real-world data and the interviews to designers in one process map. As a result, the functional relationships in the different stages of the building process and their influence on the risk of overheating were graphically represented.

Figure 8.1 illustrates this configuration of the research enquiry and fig. 8.2 shows data from the real-world and data acquired from the interviews to designers have been used to address the main research questions relating to the problem of overheating when designing HIHs. Figure 8.1 also indicates a general strategy that could be applied to any research problem relating to innovation in sustainable design.

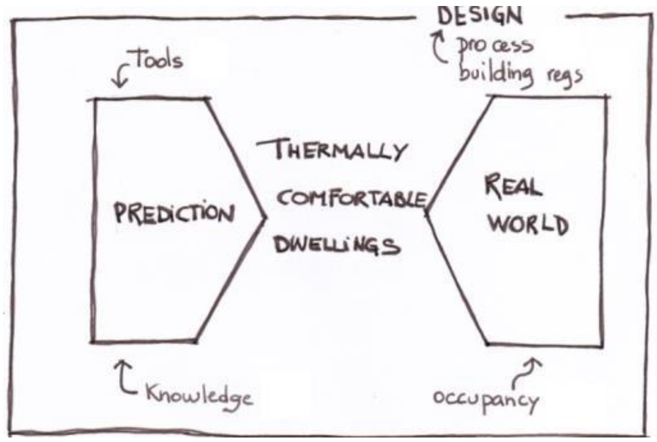


Fig. 8.1 Overview of proposed research methodology for the main areas of enquiry (repeated from Chapter 4)

8.1.1 THE *IN-USE* ASPECT OF HIGHLY INSULATED HOUSES

The aim of this part of the enquiry consisted of examining the thermal performance of HIHs and the role of the occupants in terms of their house's performance. This aim was achieved by means of continuous environmental monitoring of the four case study houses and the longitudinal questionnaires completed by their occupants (in other words, via post-occupancy evaluation). These real-world data have been analysed and presented in Chapter 5.

The post-occupancy evaluation - spread across 11 months - consisted of both objective and subjective measurements. Objective measurements were used to assess the summer performance, with a special attention given to heat wave vulnerability, of the case studies. This analysis was integrated with an overview of the year's performance and related to some of the points raised by the occupants during the surveys. In addition, an overheating assessment was performed, which took into account the limitations inherent to the recourse to monitored data in such types of analyses. The objective measurements were integrated with subjective measurements, which consisted of two different questionnaires, submitted to the occupants of the case study houses. One of these questionnaires (Q1) was designed to collect information about the occupants' attitudes, behaviour, and controls; the other (Q2) was designed to determine the occupants' subjective thermal preferences.

This – extensive- part of the enquiry revealed that the question "Is there evidence of overheating?" did not receive a straightforward answer: while evidence of uncomfortably warm temperatures was found, overheating is underestimated by some assessment methods. In addition, in some instances, occupants tend to understate overheating because they are overall very satisfied with such homes.

However, with due regards for the limitations of these assessments, it can be argued that finding such evidence is less relevant than actually demonstrating that there is a latent risk. In this context, the findings did illustrate a number of vulnerabilities, in both design and occupancy, of three out of four of the case study houses. In other words, the HIHs surveyed showed a significant risk of overheating. This finding has important implications for both the design and use of such houses. This is not to say that the design of HIHs should be abandoned; rather, it means that low-carbon housing design is in urgent need of a better understanding of the risk of overheating.

8.1.1.1 VENTILATION

Inadequate ventilation was found to be **one of the most significant factors** in the production of overheating. Houses where natural ventilation was applied consistently saw reduced internal temperatures in two out of the four case study houses (incidentally, such houses had no thermal mass exposed).

Occupants seemed to need to 'fine tune' their indoor environments. The fact that most occupants kept their windows partially open throughout the whole year remains an issue worthy of further investigation because this choice could be due to hedonic reasons (not only the fact that temperatures were uncomfortably warm). However, despite the fact that ventilation was showed to be an essential component of adaptive behaviour, it may be not always accessible for a number of ordinary and quite justifiable reasons (security concerns, noise, etc.).

MVHR proved to be a complex factor, as its interaction with layout design was shown to potentially have a dramatic impact on comfort. In fact, it was found that even though in one of the case studies a room was provided with an air supply valve for fresh air (tested and found to be working properly), it suffered from lack of air flow because the nearest outlet was located in the lower floor bathroom.

8.1.1.2 SOLAR CONTROL

Even though ventilation was key to providing comfort during summer, in one case it proved to be insufficient. In this case (bedroom in the loft), a combination of house layout and the solar gains through the Velux windows made this room uninhabitable at times. Where provided, solar control alone was also found to be insufficient to maintain comfortable temperatures in some rooms in one of the case study houses (UK55). This risk becomes a problem when there is no other room in which occupants can find shelter.

8.1.1.3 CROSS-SECTIONAL FINDINGS

The evidence from the post-occupancy evaluation (as presented in Chapter 5) showed some issues with the cumulative factors leading to overheating (namely, external gains, internal gains and inadequate ventilation). These cumulative factors have been linked to the design factors proposed in Chapter 6 (see fig. 8.2). Here, it can be appreciated that the effects of the combined factors leading to overheating (as found in case study houses UK52 and UK55) result in a combination leading to overheating. This combination can be referred to as the ***site-orientation-ventilation-occupancy*** combination (as shown in fig 8.2).

For instance, in the development where case studies UK54 and UK55 are located (Yorkshire), the same typology has been placed throughout the entire site (as is traditional with UK planning). The site layout was designed with a number of planning considerations (such access, SUDS, closeness to district heating, etc.). However, it failed to incorporate specific orientation-related changes in order to adjust solar gain. While it is known that the site layout contributes in different ways to the thermal performance of each unit (i.e., according to orientation), it seems that designers underestimate the effects of excessive solar gains when rotating the house units.

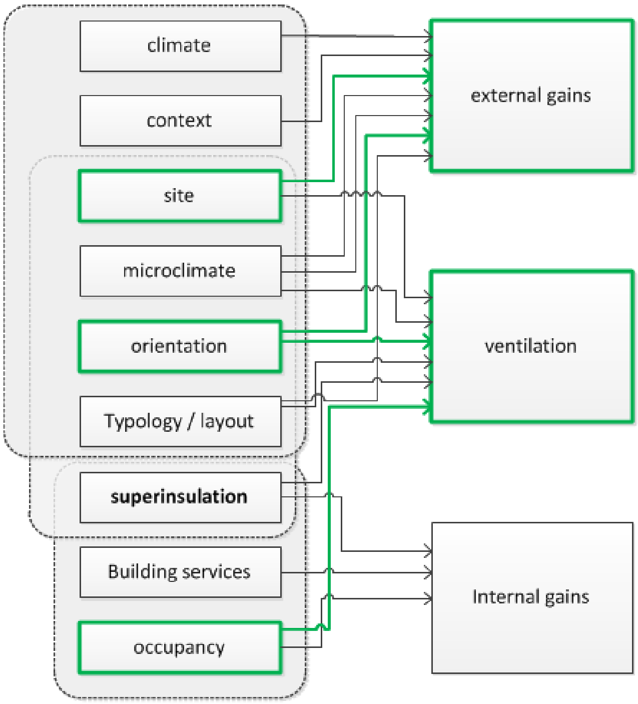


Fig. 8.2 Interlink between factors leading to overheating as found in case studies UK52 and UK55

In fact**,** in house UK55 excessive solar gains in the sunspace facing east led to extremely high recorded temperatures that reached 42°C on occasions. In this case, the lack of synergy between site layout and typology resulted in the inability to mitigate solar gains. This fact should be regarded as a missed opportunity which increased the risk of overheating. In this case the risk of overheating was thus due to the exclusive reliance on the ***occupant-ventilation*** to lower temperatures (which, incidentally, was found not to occur in house UK55).

The case study UK52, which is located in Sandiacre, does not have solar control because the designers considered that cross-ventilation was sufficient to purge high temperatures. In fact, the occupant did not perform night ventilation due to security issues. The reliance on *occupant-ventilation* to lower temperatures was then shown to be a misconception in ventilation design that could result in it being impossible to remove heat from within the house.

8.1.2 THE *DESIGN* ASPECTS OF HIGHLY INSULATED HOUSES

The aim of this part of the enquiry was to examine the design process that leads to an HIH. To achieve this aim, it was necessary to evaluate the architects' and designers' current knowledge on how to deliver their low-carbon designs whilst simultaneously designing for thermal comfort. Interviews held with architects and designers were analysed in Chapter 6.

In order to investigate the impact that the designs of the selected case studies had on their thermal performance, interviews with the designers of the case study HIHs were conducted. Their analysis, which was carried out in Chapter 6, was guided by a supporting framework presented in the same chapter before the analysis. Within that framework, open coding and axial coding was undertaken. These led to the conclusion that a number of themes could be related to the problem of overheating.

This part of the enquiry showed that designers find themselves on a learning curve, constantly meeting new requirements in terms of energy efficiency, since HIHs design carries the risk of producing overheating. While this process is part of the history of design (and design will eventually be fine-tuned through direct experience), it should be noted that current HIHs may put the health of occupants at risk. This factor highlights the need for extraordinary measures and immediate forms of control.

Content analysis revealed that this was most of the interviewees' first experience of Passivhaus-like design, despite the fact that they had many years of experience in the building sector. As a consequence, they had a number of misconceptions as far as the specific design of HIHs is concerned. These misconceptions were exemplified by the tendency to overlook the combined effects that could lead to overheating. This observation led to conclude that, currently, overheating in HIHs is the result of a transitional design that is asked to respond to the fast-growing need to deliver energy efficient houses.

The research into the novelty of HIHs design brought two additional main findings. First, it was found that comfort is, for the most part, only considered by designers in terms of winter comfort. Secondly, it was found that, when different consultants and providers bring their expertise, there is no one individual who is ultimately responsible for looking at the performance of the 'kit' (house). Also, some designers confessed that the standard *design and built* procurement process, in which construction companies were claimed to have the final decisions on, for instance, the provision of external shading is a factor that reduces their capacity to minimise the risk of overheating.

8.1.2.1 VENTILATION

Ventilation was found to be more intricate than other aspects and to be underestimated in some of the case studies. Ventilation serves to supply and remove air (by natural and/or mechanical means). It "*normally comprises a combination of purpose-provided ventilation and infiltration*" [HM Government, 2013a].

However, the *means* and the *purpose* of ventilation are often somehow confused. This confusion may be attributed to the fact that in the UK the approach to HIHs is entirely different to the approach to traditional houses. In HIHs, the *means* of ventilation can consist of both windows and MVHR, whereas the *purpose* of ventilation can be either the removal of stale air (air hygiene or control of thermal comfort). By contrast, in traditional UK houses, where the levels of air infiltration were ten time higher (fig. 8.3) [Johnston *et al.*, 2004], *purpose* and *means* were fused within the 'traditional' requirement of removal of stale air. This situation is perhaps triggered by the fact that the historically high levels of infiltration and the UK's mild climate require little or no consideration for the need to quickly dissipate high temperatures. Also, the low or zero levels of insulation have historically made British traditional houses quite cool.

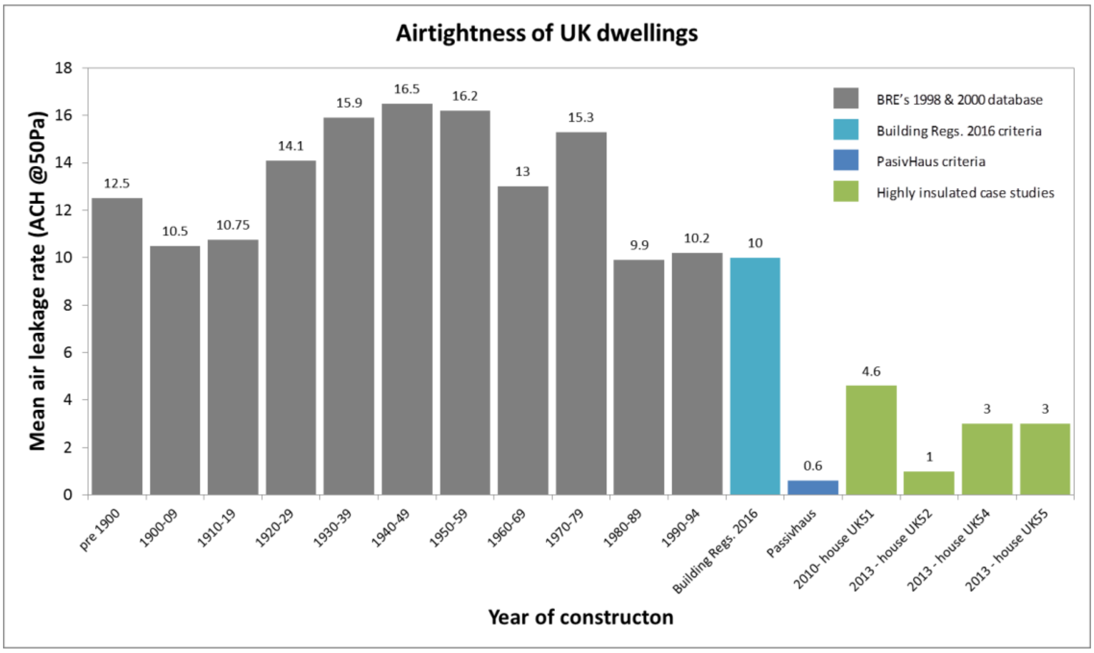
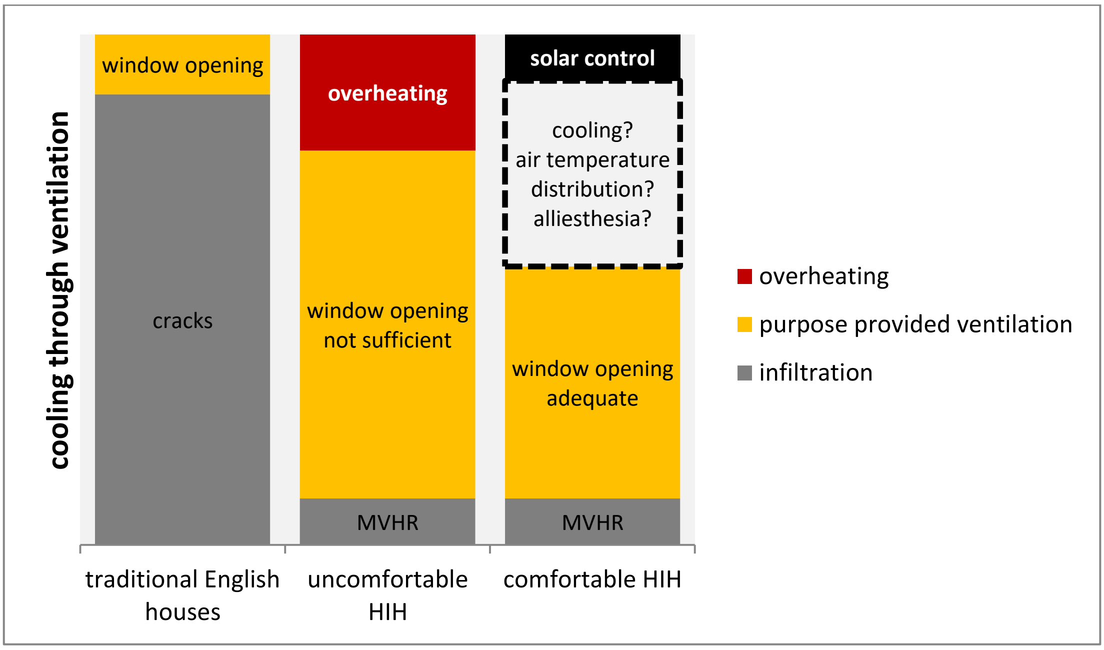


Figure 8.3 Relationship between dwellings age and air leakage [Johnston *et al.*, 2004 after Stephen 2000; HM Government, 2013b; Toledo, Cropper and Wright, 2016], repeated from Chapter 3.

It is likely that due to this traditional approach to ventilation, some designers - as well as other stakeholders – wrongly think that MVHR can cope with both the need for fresh air and comfort. While this may be true in terms of winter comfort, findings from the POE revealed that it is not the case when a (new) need for purging excessively warm temperatures arises. In other words, when there is a (new) need to cool rooms and/or to ventilate them to provide comfort. This need requires further investigation in order to understand whether it relates to (a) the necessity of cooling (excessively warm temperatures), or (b) the need to tackle warm air distribution and stratification, or (c) an individual search for pleasure (known as thermal alliesthesia) (fig. 8.4).



`Fig. 8.4 Conceptualisation of strategies needed in residential to avoid overheating

Another hypothesis as to why high levels of airtightness in the UK may have an uneasy relationship with the search for comfort may be that, while in the UK the traditional figure for airtightness is 10 ACH ($m^3/(h.m^2)$ at 50 Pascals), in Germany, where the Passivhaus standard was invented, the same figure is 0.6 (see table 8.1). This stark difference means that in Germany both designers and occupants are aware of the need to operate the windows to a greater extent than in the UK, where in certain traditional houses some windows could not even be reached to be opened.

Table 8.1 - Air permeability standards in different countries, as proposed by NHBC [NHBC Foundation, 2009]

	Maximum air permeability ($m^3/h.m^2$) at 50 Pa
Approved Document L1A of the Building Regulations (England and Wales),[4] Technical booklet F1 (Northern Ireland)[5] and Building (Scotland) Regulations 2004 technical handbook section 6: Energy[6] – poorest acceptable standard	10
Energy Saving Trust (naturally ventilated)	5
Energy Saving Trust (mechanically ventilated)	3
The Netherlands	6
Germany (air changes per hour at 50 Pa)	1.8–3.8 (n_{50} h^{-1})
PassivHaus	<1
Super E (Canada) (air changes per hour at 50 Pa)	1.5 (n_{50} h^{-1})

In the case studies (see Chapter 5), cross-ventilation was found to be important in order to achieve comfort. Currently, the Building Regulations Part F only encourages cross-ventilation. However, in consideration of the different environment provided by HIHs, and due to the higher risk of overheating in the absence of the possibility of cross-ventilation, the requirement for cross-ventilation should arguably be incorporated into the Building Regulations.

Finally, some issues pertaining to ventilation, MVHR and airtightness revealed a number of misconceptions such as the risk of poor air quality and the lack of durability of the airtightness barrier over time. In relation to MVHR installation, a best practice location of the units seems not, as yet, to have matured; some designers favoured installing the units in the loft in order to tackle air stratification whilst others preferred the ground floor in order to facilitate maintenance with no interference to the occupants' routines. In relation to airtightness, questions arose among designers regarding the suitability and necessity of Passivhaus airtightness levels[80].

8.1.2.2 SOLAR CONTROL

The study showed that the negative effects of increased temperatures from solar gains are largely underestimated and the level of knowledge in this regard on the part of different designers was not uniform. Solar gains were either explicitly claimed to be "*not an issue in the UK*" or regarded as a positive contribution to the thermal balance in passive design (at least in winter).

[80] The Building Regulations require a max. of 10 ACH ($m^3/(h.m^2)$ at 50 Pascals), and 5 ACH ($m^3/(h.m^2)$ at 50 Pascals) is considered good practice a 5. The houses in York are 3 ACH ($m^3/(h.m^2)$ at 50 Pascals), and the U51 and UK52 below 1 ACH ($m^3/(h.m^2)$ at 50 Pascals.

Particularly, designers who used PHPP as a calculation tool were aware of the excessive heat gains caused by uncontrolled solar gains. Even so, the case study houses where PHPP was used as a tool (namely, houses UK51 and UK52) did not incorporate any form of solar control. In such cases, designers 'trusted the tool' when cross-ventilation was apparently found to be sufficient to avoid overheating. It has also to be noted that designers using PHPP were aware of the excessive heat gains caused by uncontrolled solar gain.

While the tool used for the overheating check, such as PHPP, may be insufficient to predict overheating (TM59 assessment) to require calibration for the UK context (see Chapter 6), the role that PHPP has on educating designers is undeniable, especially in developing a sensibility towards both the positive and negative impacts of solar gains in HIHs. This component proved to be an advancement in the knowledge associated with passive design. However, regulation (and SAP assessment in particular) does not obligate designers to provide measures of solar control.

Solar control was found to be delegated by most designers to internal curtains or to cross-ventilation. On the current consideration that external shading is sufficient to reduce the risk of overheating, some designers concluded that external shading is too expensive and need not be implemented (at most it should be considered an add-on to the project). This way the relative costs were postponed to future refurbishments[81]. This attitude is rather risky, though, since it does not seem to give any serious consideration to the phenomenon of climate change.

Some designers have already incorporated a number of cost-effective design strategies (such as layout control or extended balconies and eaves) to avoid excess heat gains from the sun. Their efficiency proved reliant on the coordination of appropriate ventilation strategies (see Chapter 5, case study UK55 and previous section).

[81] Although anecdotal, evidence from a Passivhaus development in Frankfurt (Germany) with no external solar control (for the same budget reason) was claimed to not show any problems with overheating by its occupant. After this claim, the researcher contacted the architects to gain some further insight (perhaps another form of cooling provided?) but it was not possible as the architects were not available for interview.

8.1.3 OVERHEATING MAP OF HIHS

The aim of this part of the enquiry was to triangulate data from the case study houses and from the interviews with the designers of these houses with a view to mapping the overheating risk within the entire build process. Chapter 7 presented the modelled process of the case study houses and also presented a validation of the overheating map.

In order to represent both the physical and the non-physical aspects that govern the nature of overheating in HIHs, a transdisciplinary approach was adopted to map the occurrence of overheating. The integration of this data relied on a process mapping methodology referred to as IDEFØ. This methodology was chosen because of its simple graphics, precision, relatable vocabulary (input, control, mechanisms and output[82]), and its capacity to incorporate parent-child diagrams (nested stages within a process) in a similar manner to BIM.[83]

The elaborated maps of overheating risk were subsequently presented to an expert audience by means of a focus group involving experts in sustainable building in order to validate its usability. In the focus group, participants were asked to use a blank map of overheating and then comment in an open plenary session. The findings of this workshop, which were presented in detail in Chapter 7, are summarised below.

The integration of the data concerned with overheating into an IDEFØ map proved to be successful and so could potentially constitute a **design tool for overheating avoidance** that is useful to all stakeholders in the build process. Nonetheless, the exercise also showed that it may be advisable to think of ways in which to simplify the IDEFØ map in order to make its findings more user-friendly and so more accessible to possible users.

From the feedback on overheating avoidance received from the selected audience, it also became clear that design is a crucial stage in the production of overheating.

Moreover, the focus group made it clear that planning and design are in need of the **feedback from recently built projects (POE).** For instance, user adaptive behaviour showed that occupants tend to over-ventilate their houses. While the reasons for this

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[82] Similarly, CIBSE uses a similar vocabulary to illustrate the integrated design [CIBSE, 2015].

[83] BIM is the process through which the data for planning, design, construction, operation and maintenance can be integrated through a unified model using graphic and non-graphic machine-readable attributes for each facility/building component, new or old, which contains all appropriate information created or gathered throughout the building life cycle.

behaviour were not established with any real certainty, its impact on waste energy is likely to be noticeable.

The discussion within the focus group also indicated that designers should investigate the impact of their designs in more depth and from it draw lessons about what works and deserves resources and what may underperform (or run the risk of underperforming). The example of the bungalow (house UK52), where designers relied on night ventilation to avoid overheating, showed that night ventilation is not necessarily practiced (in this case because of the occupants' security concerns). Cases such as this one indicate to designers that while PHPP may have not shown overheating at the *design* stage, it may lead to overhearing at the *in-use* stage.

The ***design*** output was found to be crucial as it **influences comfort**. The study showed that the output should be an HIH that has the sufficient adaptive capacities for the occupants to control their comfort at low energy costs. In other words, the output of the *design* stage (and *construction* stage) should be the means by which to achieve comfort in the *in-use* stage. Accordingly, the design output (HIH) should incorporate all the required means to support both winter and summer comfort in a way that occupants (and housing managers) would find it manageable. This means that design needs to allow for as many means for (low-carbon) summer comfort as possible.

The study also showed that ***design*** **has the potential to provide feedback the *brief* stage,** by so redefining the requirements in the light of the outcomes of the design stage. This circle in which the initial requirements are reconsidered could potentially change the strategy to achieve given targets, such as the Code for Sustainable Homes Level 4. In this context, one may consider, for instance, the case of houses UK52 (Passivhaus uncertified in Sandiacre) and UK55 (in York). House UK55 had a halved dwelling emission's rate compared to the uncertified Passivhaus (UK52), mainly due to the contribution of the fuel factor (biomass) from the district heating to UK55's dwelling emission rate.

This highlights the possibility of gaining carbon savings from other strategies of low-carbon design that may be considered during the *brief* stage when summer comfort may be at risk. Reflecting back in terms of costs, maintenance, and benefits to the brief stage will allow one to opt to reconsider the implications of the chosen strategies.

Another significant finding of this research was that the *design* stage is in need of an appropriate methodology to avoid overheating. Those who took part in the focus group agreed that assessments should be triangulated with different tools. This hypothesis is supported by the findings in Chapter 5 and Chapter 6, where overheating assessments were found to underestimate the risk of overheating. To support this activity, best practice (or worst practice avoidance) should be engaged. To do so, learning from recently built HIHs is crucial.

Lastly, the map was found to be useful to think in an **interconnected way**, namely in accordance to strategies enabling designers to be aware of the implications of any action throughout the entire building process, and so of the influence of their decision-making. For instance, the *brief* stage can be used to revise aspirations once the risks during the *in-use* phase are understood. The IDEFØ map should be considered a tentative means to contribute to such an integrated design framework.

In sum, this part of the study engaged with the question *"How can the process of designing HIHs be improved to reduce the risks of overheating?*" and reached the following three fundamental conclusions:

- The design stage (and construction stage, if of the design and built procurement type) is to provide houses that incorporate diverse adaptive capacities for occupants to achieve comfort. Likewise, ventilation should not be relied on as the only strategy for heat rejection (*OUTPUT* in IDEFØ language)

- The design stage should not rely purely on compliance tools (like SAP) to evaluate the risks of overheating. In addition, in consideration of the fact that no single tool can be uncritically engaged with, designers should make use of the lessons learnt in recently built HIHs in the UK (*MECHANISM* in IDEFØ language)

- Lastly, design as a practice should revise and fine-tune its ambition and the strategies it implements to achieve low-carbon houses. This requires designers to reflect and (re)discuss with those responsible for the planning stage and the brief (commissioning) stage in order to gain optimal solutions for the context. Here, 'context' indicates not only the location where a building stands (e.g., UK climate) but also the knowledge and best practice available in a particular historic moment. In this way, design could balance the benefits and risks inherent to low-carbon design when being informed by the POE.

8.1.4 FINDINGS SUMMARY

In the context of an overall project aimed at decarbonising the built environment, HIHs are necessary. This research, which has specifically considered the risk of overheating in HIHs, was intended to contribute to the broad understanding of this innovative design (HIHs).

The results presented in the previous chapters indicate that there is considerable scope for improvement in the design of HIHs as implemented in the UK. In what follows, based on the discussion carried out in the rest of this work, the main findings of the research are summarised and some recommendations for future research concerning HIHs are given.

FINDING 1: SEASONAL PERFORMANCE OF HIHS

The (almost) one year of environmental monitoring of internal temperatures showed that the season giving the greatest variability of internal temperatures is summer. Also, it was found that spring and autumn differ significantly insofar as the recorded peak indoors temperatures are concerned. Based on the case studies, it can be concluded that there are different risks and advantages associated with any given season.

FINDING 2: MEAN TEMPERATURES

Both the summer analysis and overheating analysis showed that *mean* indoor temperatures can mean (almost) anything, as they can be linked to very different environmental conditions. For instance, the mean indoor temperature of 24°C proved to be associated with the occurrence of overheating in one house, whilst it could not be associated with overheating in another case study. More specifically, the mean indoor temperature of 24°C was:

- linked to overheating (TM59) in the context of the south-facing lightweight room of house UK52 (Passivhaus bungalow);
- not linked to overheating (TM59) in the context of the east-facing bedroom1 and living room of house UK51 (refurbished terrace).

One of the differences between the two cases was the temperature range (larger in house UK52, smaller in house UK51). It is important to note that temperature interpretability cannot be considered in the context multi-storey apartments.

When it comes to modelling the design of HIHs for overheating avoidance, it is likely that reference to average temperature alone could be misleading in terms of assessing the level of comfort experienced by occupants, especially when predicting performance via building simulation.

FINDING 3: ASSESSMENTS OF OVERHEATING

There are limitations to an overheating analysis based exclusively on the data monitored in summer. The analysis carried out in the case studies showed disparate results between the various forms of assessment (CIBSE 2006, TM52 and TM59), but also certain similarities at least between some of them (CIBSE 2006 and TM59).

The consideration of the actual occupancy of the case study houses revealed that vulnerability among occupants changed throughout the survey period, particularly with regards to their vulnerability to heat stress. This finding suggested that the concept of '*temporarily vulnerable occupants*' should be included in the overheating assessments, especially in consideration of the fact that HIHs tend to be warmer environments than traditional buildings.

The research finally indicated that with the right considerations at hand (judgement of vulnerability, risk factors, etc.) TM59 is a step forward in the assessment of overheating. Future research should then assess the real-world performance of houses against the criteria set in TM59 which, however, as a tool remains directly applicable to building simulation only.

FINDING 4: OCCUPANTS' PERCEPTION OF OVERHEATING

When it comes to assessing the perception of overheating, it was found that occupants tend to underrate overheating. From the seasonal questionnaires, it emerged that the occupants who did not report overheating at the beginning of the summer changed their opinion of comfort and their attitude towards window opening by its end.

Such a forgiving factor could be explained by the fact that, in the case studies presented, occupants relocated from one room to another when one room was affected by overheating. Such relocation within different rooms is an adaptive behaviour that requires a variability of microclimates within one house. It has then been categorised as an adaptive opportunity.

In addition, the seasonal questionnaires showed that when occupants were asked about 'rooms difficult to keep comfortably cool' (even if not necessarily affected by overheating), answers had a direct correspondence with the loggers' temperatures. However, some responses changed throughout the monitoring period, which means that the judgements of the environmental conditions rendered by occupants have a 'short memory' and necessitates longitudinal research.

FINDING 5: NATURAL VENTILATION

Reliance on natural ventilation during summer was found to reduce overheating and to mitigate excessive temperatures. This is no surprise, since the recorded outdoor temperatures were lower than the temperatures recorded inside the case study HIHs, except during three days of heat wave.

Another salient finding was that some occupants also leave the windows in trickle during winter time. This may provide an initial indication that window opening is used not only to prevent the occurrence of overheating but also to achieve air movement (and can so be linked to the phenomenon of thermal alliesthesia).

FINDING 6: MECHANICAL VENTILATION (MVHR)

It was found that exclusive reliance on MVHR during summer produced overheating, whereas the one case study with no MVHR, and so relying on natural ventilation strategies (combined with thermal mass in house UK54) performed at its best (including during the heat wave).

The above is not yet sufficient to conclude that MVHR is the main contributory factor to overheating, but is at least an indication that the background ventilation provided by the MVHR is not effective in purging high temperatures, and further that some occupants and designers were not aware of this.

FINDING 7: HEAT WAVE VULNERABILITY

Findings from the vulnerability analysis carried out during the heat wave showed that in some cases HIHs may vulnerable to high temperatures during such periods. During the heat wave that occurred during the period of monitoring, some rooms became uninhabitable and in fact actively collected unneeded heat which was then distributed around the rest of these houses. The reasons for it are attributable to both HIHs design and house management.

This was not the case for the naturally ventilated, heavy weighted, north-south oriented houses where the main bedroom temperatures were below the peak day external temperature and where recorded temperatures never exceeded 26°C during the heat wave. Also here, the reasons for it are attributable to both HIHs design and house management.

The analysis also showed a persistence of high indoor temperatures after the peak day (i.e., four days) in some houses. Such persistence encourages one to hypothesise a further degree of risk of overheating in HIHs, despite the fact that it was not established if the reason for this increased risk was the super-insulated building fabric, the inadequate ventilation, or the solar gains control. This specific point requires further investigation, possibly with other methods of data collection such as building simulation applied to combined variations in HIHs design (MVHR, orientation, etc.).

FINDING 8: HIDDEN SOURCES OF HEAT GAINS

The present research also found some instances of design that should be regarded as being at risk of becoming sources of unwanted gains. This was the case with the sunspace built in one of the case studies. That **sunspace** was found to be **used improperly**, and so to collect heat at times of the year when heat was not needed. This situation could be avoided if there were some form of engagement between design intentions and occupancy. This was not the case for this case study, though.

In another case study, the **loft conversion** presented a problem in terms of air flow (even though in the presence of a balance system of air in/out). In such cases, house layout and temperature stratification may be deemed to contribute to the excessively high internal temperatures (this fact could hardly be foreseen by a designer, hence the importance of real-world research).

Lastly, the research indicated that transitory spaces (such as halls or corridors containing **building services**) release heat to the entire house, and that this phenomenon may escape a standard overheating assessment. It is hence suggested to consider the location of building services outside the thermal envelop the case of HIHs.

FINDING 9: THERMAL COMFORT STUDY

The thermal comfort survey was not conclusive due to the limited data; however, significant discoveries were made. On this basis, the existence of a number of extra risk factors in HIHs can be concluded.

The thermal comfort survey suggested that there is a shorter window for thermal sensation in HIHs. On the one hand, this could be considered a positive outcome of their low-carbon design; on the other, however, the low values of CLO and correlation with outdoor temperatures indicate that occupants may already been adapting in the attempt to cope with warm temperatures. This combination has two risky consequences: (a) window reliance for comfort may trivialise efforts to reduce carbon emissions; and, more importantly, (b) in case of inadequate natural ventilation (building typology, heat wave, UHI, noisy area, etc.), occupants could be deprived of this form of adaptation.

FINDING 10: IMPORTANCE OF ADAPTIVE OPPORTUNITIES

From the overheating assessments analysis, it emerged that assessments may not be reflecting all the risks accompanying HIHs design. The overall reliance on window opening was not found to be sufficient to guarantee a reduced risk of overheating. This finding reinforces the idea that designers should not settle for designs with just one means of adaptation, as this adaption might become temporarily unavailable.

In HIHs where design is the provider of comfort (as opposed to traditional houses, which use energy to achieve comfort), it appears appropriate to conclude that adaptive behaviour is key to occupancy. However, it is crucial that occupants are offered more options for adaptation. Such opportunities should be given at the design stage and there should be several and of different types (according to the contextual design possibilities).

FINDING 11: DESIGNERS' KNOWLEDGE

In general terms, the fact that the case studies represented most interviewees' first **experience** with HIHs can be claimed to have significantly impacted on their capacity to acknowledge the risk of overheating. As a result, they had the tendency to overlook not only the combined effects that could lead to overheating but the also the potential risk of increased energy consumption, and even any threat to health. The lack of knowledge was reflected in the following areas:

1. **External heat gains unawareness**

The research found that most designers consider external gains to be a positive contribution to heat in the context of passive design. While this feature is not wrong in itself, in some case studies these led designers to underestimate the effects of excessive solar gains in HIHs (and by so, retrofit of traditional houses to a highly-insulated fabric should be regarded as a potential risk). Moreover, the effects of excessive solar gains were understated in the retrofitted terrace house. This may be because designers do not associate existing traditional Victorian stock with the risk of solar gain.

The research also showed that there is a reluctance to allocate project funds to control solar gain, even with the awareness that the climate is in the process of changing. Because of this, some consultants considered the possibility of incorporating solar control in new HIHs designs. However, this intention may encounter resistance in the 'traditionally looking' design of houses.

2. Ventilation unawareness

With regards to inadequate ventilation, the interviews showed the existence of lacunae in the knowledge of (1) MVHR as a technology, (2) the concept of airtightness, and (3) the need for window opening in HIHs by their occupants.

Some designers were found to have the tendency to underestimate the need for window opening by occupants, who by contrast relied on constant window opening to regulate their indoor environment while MVHR operation was maintained. This could be a problem both in terms of energy consumption and in terms of the actual provision of adequate means of natural ventilation (natural ventilation that in Chapter 5 was found to be essential in these houses).

In addition, the lacunae in embedded knowledge of airtightness are due not only to the novelty of the concept of airtightness but also due to the different metrics and diverse paradigms of means of ventilation. The gaps in embedded knowledge of HIHs design (in terms of ventilation and MVHR, airtightness) impact on the already existent factors contributing to overheating (tools unreliability, lack of guidance, etc.).

FINDING 12: IMPORTANCE OF PROCESS MAPPING COMPLEX REALITIES

Process mapping - as a methodology to analyse and communicate findings- with IDEFØ proved to be effective in contextualising a process, its needs and its implications. In this context, IDEFØ can effectively focus on the DESIGN stage of HIHs and instigate interconnected thinking at the same time; by relying on IDEFØ, a designer is in the position of always being aware of the implications of any action during the entire building process and so of the influence of their decision making.

Processing the fragmented findings and arranging them into an overheating IDEFØ map shaped by a suitable framework proved to be a task that was both challenging and useful. The focus group conducted after the mapping had taken place confirmed the complexity of mapping as well as its usability.

For instance, thermal comfort has been found to be important at every stage of the build process; it needs to be considered from the design stage by considering how such comfort will be maintained or achieved during the in-use stage. During the research project, it also became clear that it is of paramount importance that such designs should be uncomplicated in operation and that it serves as a means of comfort by being equipped with adaptive opportunities for occupants when controlling their comfort levels.

8.2 FINDINGS IN RELATION TO THE METHODS USED

The present research focussed on the *integrated* aspects that led to overheating in the context of HIHs in UK. As such, it adopted a **descriptive and explanatory** multi-case study approach. Both the objective and subjective knowledge gained through this research were framed through the two main research questions underpinning this study. Accordingly - and in line with the principles of pragmatism - diverse approaches were integrated into the construction of a set of knowledge that disengages with concepts of *truth* and *reality* (this idea was elaborated in Chapter 4 section 4.2).

Table 8.2 - Study typology (repeated from Chapter 4)

(Pragmatic) critical realism	A dialogue of divergent mental models to expand, deepen and reflect on the nature of overheating in HIHs
Mixed methods	Integration of data of different sources type: POE, interviews, process mapping, focus group
Multiple case study	In-depth study of four HIHs in England (descriptive and explanatory multiple case studies)
Longitudinal study	Data collected over a period of 11 months, to cover four seasons.

This research used of different methods of data collection, such as (originally explored) building simulation, environmental monitoring, subjective monitoring, interviews, and focus groups.

The novelty of the topic under consideration was argued to require reliance on different methods of analysis (overheating assessments, explorative statistical plots, hour-to-hour temperatures change inspections, thermal comfort analysis). Making use of this variety of methods proved to be time consuming. Particularly, the post-occupancy evaluation in Chapter 5 was found to be very eclectic in nature (see actual data collected in fig. 8.5). At the same time, it enabled the researcher to depict different areas of concern in a holistic manner and to understand how diverse factors interact in what is considered to be 'innovative design'. As a result, post-occupancy evaluation reveals the existence of a whole virgin *territory* for exploration: the practices of ventilation in HIHs.

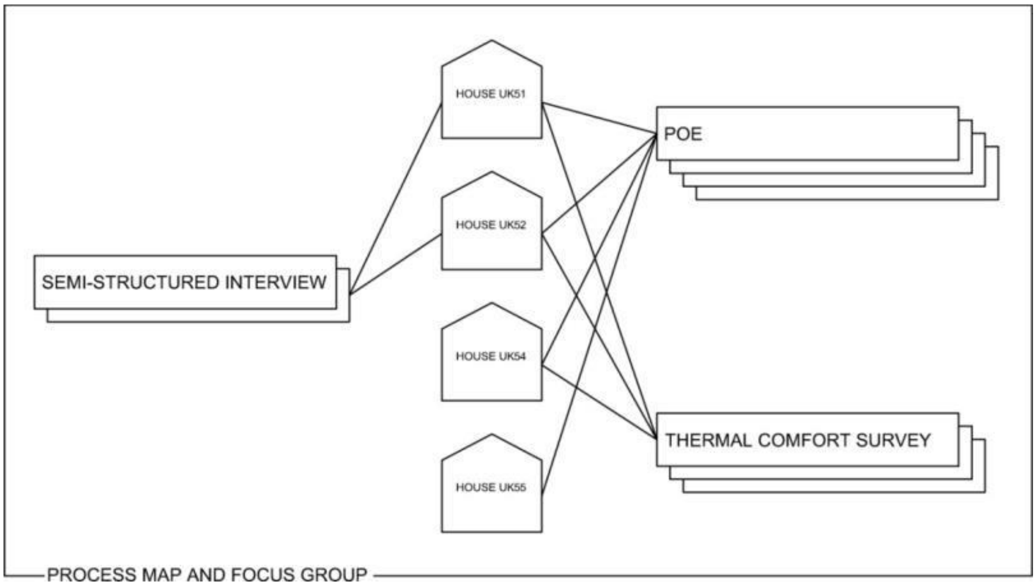

Fig. 8.5 Actual data collected. This caption evidences the difficulty, when doing real-world research, of maintaining the original research plan, at least for what the number of cases.

All in all, the methodology used in this research allows one to map specific areas of concern, the mechanisms of overheating in HIHs, and how these could inform the design process of HIHs. Such knowledge can inform both the build process and design as practice. The latter was defined in Chapter 3 as *the act that (intentionally or unintentionally) initiates change in man-made things to deliver the optimum solution to the sum of the true needs of a particular set of circumstances*. Here, *optimum solution* is that of an energy efficient house; true *needs* are the requirements to achieve thermal comfort and IAQ; and the *set of circumstances* is the context (a given historical time, the design process in the UK).

8.2.1 POE

The post-occupancy evaluation (POE) made it possible to allow for the sensorial contribution from the occupants. The occupants' feedback was facilitated by means of periodic surveys, which walked them through the whole evaluative process and contributed to identifying areas of concern, especially in relation to high temperatures. The use of periodic surveys and the addition of open questions embedded in the questionnaires also functioned to assist occupants to identify first-hand the difficulties that they were experiencing and yet were not able to explicitly acknowledge.

In addition, the POEs allowed for the interaction between occupants and researcher. Such interaction is likely to have affected the understanding occupants developed in relation to their HIHs, and therefore possibly their actions and responses (action research).

The POEs revealed a number of risks and vulnerabilities in both design and occupancy which would have been difficult to identify through other methodologies such as building simulation. However, it should also acknowledge that the findings of POEs are not conclusive and some aspects need be further explored, also by means of building simulation, in order to secure their statistical validity.

POE was instrumental to arriving at numerous of findings (listed in section 8.1), which also corroborate the conclusion that the importance of longitudinal real-world studies to HIHs cannot be overstated.

8.2.2 SEMI-STRUCTURED INTERVIEWS

The methodology of semi-structured interviews was found to be most appropriate, especially in consideration of the fact that while open coding fragmented the discourse into key words, axial coding made a unified interpretation possible, at least in some cases. Since the researcher remained in direct contact with the occupants of the case study houses throughout the research, it was possible to 'make sense' of their answers, and facilitate this way a reliable interpretation by the researcher.

The face-to-face interviews resulted in in-depth conversations with architects and designers about both specific aspects of the cases study and generic aspects of the low-carbon-driven design. Designers proved to be willing to talk about the substantial dimensions of their projects and were open to acknowledging the weaknesses of their project as well as to talk about things they would change.

8.2.3 PROCESS MAPPING

The map of overheating presented by the researcher was found to be useful in many respects by the audience: (1) as an analysis tool; (2) as a project plan; and as (3) a design tool. Most importantly, it stimulated an interconnected thinking approach. The outcomes of the focus group proved to be insightful (and spread across all stages on the build process), especially in relation to strategies for the avoidance of overheating.

The methodology has its own limits, though, the most obvious of which is that it requires familiarity with the IDEFØ language—a familiarity that not every specialist may be presumed to have.

This methodology also showed the importance of a shared construction of meaning when it comes to tackling the problem of overheating in HIHs. In fact, the first maps (overheating maps of houses UK51 and UK52) drawn by the researcher, provided only the first step towards the simplified map that was produced as a consequence of the collective effort within the focus group (overheating avoidance map). The latter map was presented at the end of the Chapter 7 and can be regarded as having great potential to become an overheating tool.

8.3 RECOMMENDATIONS FOR FUTURE RESEARCH

HIHs design is a low-carbon design strategy in which fabric efficiency is instrumental to achieving the objective of carbon reduction by means of reducing the energy demand to absolute minimal quantities. The appropriate understanding of comfort provision and the means by which to achieve comfort should inform the design of HIHs, since they have the potential to optimise the performance of the building fabric and so give the opportunity to achieve low-carbon comfort in UK houses.

8.3.1 POE AND SYSTEMS THINKING (REAL-WORLD RESEARCH)

With POE, the integration of different techniques of data collection enabled the determination of aspects that could have remained hidden if only one method had been used. In Chapter 5, POE was shown to play a central role in the evaluation and knowledge development of HIHs. In particular, the findings revealed traits of occupants' behaviour that would have been otherwise difficult to predict. Accordingly, it is recommended that future research should specifically focus on new residential units with a view to gaining more real-life lessons of innovation in building design. The outcomes of the real-world research can then feed into the technological aspects of the HIHs as well as their social (user) components.

It would also be crucial that knowledge gained from POE were shaped by an integrated approach (such as process mapping) since this could help avoid a siloed attitude to knowledge development. Hence, there seems to be scope for developing research into a systems thinking approach to aid and channel POE findings.

8.3.2 MVHR (EXPERIMENTS INFORMED BY REAL-WORLD RESEARCH)

The research found that there are a number of challenges concerning MVHR systems at both the *design* and the *in-use* stages, which can be informed by further research.

In Chapter 6, it was noted that there were different rationales behind MVHR unit location depending on the issue under consideration. The opinion as to the optimal position (within a house) for these units differs depending on the objective the MVHR is taken to serve. For instance, if the MVHR location is meant to facilitate maintenance, its optimal position might be in a cupboard (on the ground floor); if the MVHR location is intended to achieve warm air removal efficiency, it is best located in the top floor; finally, if the MVHR location is instrumental to securing the efficiency of the duct system, it should be positioned close to a wall. There is thus scope for future research to inform the UK best practice design of HIHs' MVHR systems.

Such experiments may include scenarios informed misconceptions and misuse of MVHR, as reported in Chapter 5. Examples of misuse included (a) the technical staff forgetting to turn the system on after maintenance, (b) the occupants failing to understand the instructions as to how operate features provided by the system, and (c) the occupants delegating cooling to the MVHR system during the heat wave.

8.3.3 HIHS DESIGN OPTIMISATION (REAL WORLD RESEARCH)

Low-carbon design (specifically the design of HIHs) needs to be fine-tuned not only to avoid heat stress to occupants but also to incorporate a number of thermal adaptation opportunities.

For instance, the findings of this research indicated that in the case study HIHs, window opening was frequently used as a means of cooling. At the same time, the research did not conclusively establish when window opening served the purpose of cooling and when it served the purpose of improving the thermal experience of occupants (alliesthesia). This aspect thus necessitates further research, arguably based on field studies aimed at investigating both *patterns* of window opening and *reasons* for window opening. Such research has the potential to enable one to understand not only how the occupants' thermal experience can be improved but also how unnecessary energy losses can be avoided (for instance, energy losses associated with the fact that the MVHR was constantly turned on while windows were open).

8.3.4 ARCHITECTURAL LANGUAGE DEVELOPING

In terms of solar control, it was found that some designers underestimate the effects of the absence of a device for solar control (see Chapter 6 Section 6.4.1). This finding suggests that further research should be undertaken to explore strategies for incorporating solar control during the very early stages of concept design by maximising the use of the building fabric. From this future research, a new architectural language could be developed in order to exploit fabric performance not only in relation to the thermal dimension of buildings but also in relation to their spatial/volumetric dimension (i.e., eaves extensions maximised from the thick fabric). The wide availability of powerful building simulation software may well aid this investigation.

8.3.5 MULTIDISCIPLINARY-LED DESIGN TEAMS

As noted in the context of the analysis of the interviews with designers, with the increasing demand for of carbon reduction and the associated implementation of low-carbon design at its first trials there is the risk that the multi-team processes involved in design will not implement a creative problem-solving approach to design. In particular, the interviews with designers (see Chapter 6) showed a tendency to discharge responsibilities from one team to another. This shift of responsibilities has a negative impact on the whole process of problem solving—a process that is, or at least ought to be, the very basis of *design*. Further qualitative studies of the modern design process in the construction industry may then be appropriate for this purpose.

8.3.6 DESIGN TOOLS

As demand for the design of HIHs increases, predictions of thermal performance are essential. However, in Chapter 5 (from the overheating assessment and internal temperature plots) and in Chapter 6 (from the interviews with designers) it emerged that the available tools may well underestimate overheating. There is hence scope for further research aimed at evaluating the appropriateness of the different tools available for prediction (from PHPP steady-state and dynamic building simulation) and their most effective use during different design stages (from concept design to detailing).

In this context, it should be recognised that Passivhaus (and with it, PHPP) will most likely to remain popular in the UK due to its user friendliness and spread among designers. However, this research provided an initial indication that PHPP (a tool calibrated with data from German buildings) may underestimate overheating in the context of British houses (see Chapter 5, summer analysis). Research directed at calibrating PHPP to the UK context is thus recommended. Such research can be expected to require longitudinal field studies in the UK and advanced building simulation.

8.3.7 ASSESSMENT PROTOCOLS

As the demand for low-carbon design increases, the innovative designs of HIHs are being built. However, this research provided an initial indication that occupants of HIHs may be vulnerable to high indoor temperatures as a result of the number of concurring factors. Concern increases when urbanisation and climate change are considered. Furthermore, this research suggested that the recognition of some categories of occupants as being temporarily vulnerable should be incorporated in the appropriate design standards (see Chapter 5, overheating assessment).

At the same time, future research may be directed towards the development of an overheating assessment based on field studies in the UK. The goal of reducing the risk of overheating may be served by the practice of undertaking overheating assessments at the early stages of the design. Nevertheless, it should be emphasised that thermal comfort is not just a matter of temperature (this point was made in particular in Chapter 5 as a result of both the overheating assessment and the thermal comfort study). Therefore, a specific type of diagnosis for overheating may incorporate the principles of adaptive capabilities offered by the indoor environment to avoid overheating, no matter whether overheating is (a) of a temporary nature (vulnerable occupants, heat wave, misuse) and easily tackled, or (b) of a chronic nature (houses or rooms where action might be required to correct the unintended consequence of innovative design).

8.4 CONCLUSIONS

Based on the findings of this research and having English houses as case studies, one can conclude that, under certain circumstances, HIHs are at risk of overheating and an increased (and unintended) demand for cooling, which if unaddressed, may lead to heat stress. The need of cooling in this context would correspond to a change (or switch) in energy demand that originates in the pursuit of reduced energy demand; hence the need to reduce energy demand for comfort in both winter and summer. This need calls for a new practice of design in which the role of comfort (and how it is achieved by occupants) can be understood in its complexity, rather than being reduced to a matter of winter comfort only. This way, it should be possible to achieve a reduction in energy demand (and not a merely a switch in energy demand from heating to cooling).

This research was (also) started because the researcher had a conflicted personal stance between carbon reductions and health risks, as presented in the UK. The conflicted perspective towards the suitability of HIHs that contributed to initiating this research project has by now resulted in the recognition that low-carbon houses, and with it, the move towards designing HIHs, ought not to be called into question. And this work has attempted to illustrate, there are design-related areas that are in urgent need of knowledge development and issues that need be handled as immediate *risks* while knowledge is developed and, later, tacitly embedded.

While this knowledge develops, the complexity of the design of HIHs in the UK remains high and thus vulnerable to discomfort in certain contexts. Therefore, knowledge acquisition (via POE) and systems thinking beyond disciplinary boundaries are needed as a matter of urgency. This work has been an attempt to indicate the direction of such a multidisciplinary approach, as it has put different disciplines in communication with a view to enhancing the knowledge underlying the design of HIHs.

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APPENDIXES

APPENDIX A – LIST OF PUBLICATIONS

Földváry, V., Cheung, T., Zhang, H., de Dear, R., Parkinson, T., Arens, E., Chun, C., Schiavon, S., Luo, M., Brager, G., Li, P., Kaam, S., Adebamowo, M. A., Andamon, M. M., Babich, F., Bouden, C., Bukovianska, H., Candido, C., Cao, B., Carlucci, S., Cheong, D. K. W., Choi, J.-H., Cook, M., Cropper, P., Deuble, M., Heidari, S., Indraganti, M., Jin, Q., Kim, H., Kim, J., Konis, K., Singh, M. K., Kwok, A., Lamberts, R., Loveday, D., Langevin, J., Manu, S., Moosmann, C., Nicol, F., Ooka, R., Oseland, N. A., Pagliano, L., Petráš, D., Rawal, R., Romero, R., Rijal, H. B., Sekhar, C., Schweiker, M., Tartarini, F., Tanabe, S., Tham, K. W., Teli, D., Toftum, J., Toledo, L., Tsuzuki, K., Vecchi, R. De, Wagner, A., Wang, Z., Wallbaum, H., Webb, L., Yang, L., Zhu, Y., Zhai, Y., Zhang, Y. and Zhou, X. (2018) 'Development of the ASHRAE Global Thermal Comfort Database II', *Building and Environment*, 142, pp. 502–512. doi: https://doi.org/10.1016/j.buildenv.2018.06.022.

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APPENDIX B – PARTICIPANT INFORMATION AND CONSENT FORM

PARTICIPANT INFORMATION SHEET (p. 1 of 2)

Dear Sir/Madam,

We would like to ask you to participate in the data collection for a study on thermal comfort in energy efficient homes, conducted by the Institute of Energy and Sustainable Development (De Montfort University). This is a University Research project, it is not a commercial or a governmental project. The results will be published in academic journals and conference proceedings and their purpose is solely relating at contributing to the knowledge of energy efficient dwellings.

Participation in this study is entirely voluntary. It will involve a survey to you home where (a) some environmental parameters values (such as temperature, air movement, etc.) will be recorded and (b) a questionnaire will be completed. In total the visit should last approximately 30-45 minutes in length to take place by arrangement. We will initially contact you by email or telephone.

What is the study about

Today's concern about fossil fuels combustions has led to government strategies aimed at reducing greenhouse gases emissions. In an attempt to reduce energy consumption and associated carbon emissions from the buildings sector, substantial changes in the domestic sector have recently been made resulting in homes with significantly improved standards of thermal insulation and much higher levels of airtightness.

The primary purpose of all domestic buildings is to provide their occupants with a stable indoor environment, to protect them from wind and rain and from extremes of heat and cold. It is important therefore to ensure that houses designed to comply with improved standards of energy efficiency are comfortable and providing appropriate levels of indoor air quality.

In order to achieve this, we would like to evaluate the performance of new energy efficient homes and, this way, gaining an understanding whether new energy efficient homes are providing the improved indoor environmental conditions as designed.

We hope better to understand the following issues:

- How comfortable is the home where you live;
- The level of user-interaction with the house (such as opening the windows, operating the heating systems, etc.;
- The thermal performance of the house (temperatures, levels of humidity, air movement, etc.) recorded through sensors.

What happens if you want to change your mind?

If you agree that you wish to join the study you are still able change your mind and withdraw at any time. We will completely respect your decision. If you notify us of your withdrawal, all identifiable data will be destroyed. Once data has been anonymised it will be impossible to identify the origin and cannot be destroyed.

PARTICIPANT INFORMATION SHEET (p.2 of 2)

Are there any risks?

There are absolutely no risks to you or your family in completing the questionnaire. There is also no risk or harm in recording the measurements required for this study (i.e. air temperature, levels of humidity, of air movement, etc.).

Your rights

Joining the study does not mean you have to give up any legal rights.

What happens to the data?

The information you provide is confidential, except that with your permission anonymised quotes may be used. If you request confidentiality, beyond anonymised quotes, information you provide will be treated only as a source of background information, alongside literature-based research and surveys in other homes. Your name or any other personal identifying information will not appear in any publications resulting from this study.

The study findings will be published in international conferences and journals, and only the research team will have access to the interview data itself.

If you have any questions regarding this study or would like additional information please ask the researcher before, during, or after the interview.

What happen next?

In the case you were willing to volunteer for this research project, I would be most grateful to be contacted (see details below) to arrange a meeting at you property at your most convenient time.

Many thanks in advance,
Linda Toledo

Contact details of researcher:
Mrs Linda Toledo (MA, Dip. Arch)
Institute of Energy and Sustainable Development - De Montfort University
Queens Building -The Gateway
Leicester - LE1 9BH
Tel: 0116 250 6145
Email: linda.toledo@email.dmu.ac.uk

PARTICIPANT CONSENT FORM (p.1 of 1)

Participant to put a tick or cross in the relevant boxes.

1. I _____________________________ [participant's name] I have read or been informed about the purpose of the study and understand this. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason and by contacting a member of the De Montfort University research team.

3. I understand that while the material generated by my involvement in this research project will be anonymous and confidential it may be used for a variety of research purposes during and after the lifespan of the project (e.g. reports, publications, presentations) by the research teams at De Montfort University.

4. I agree to take part in the above study

Signature of the participant _________________________ Date: _________________

Name of person taking consent______________________ Date: _________________

Signature of person taking consent ___________________ Date: _________________

** When completed, 1 copy for participant & 1 copy for researcher*

Contact details of researcher:
Mrs Linda Toledo (MA, Dip. Arch)
Institute of Energy and Sustainable Development - De Montfort University
Queens Building -The Gateway - Leicester - LE1 9BH
Tel: 0116 250 6145
Email: linda.toledo@email.dmu.ac.uk

APPENDIX C – QUESTIONNAIRES Q1A Q1B Q2

QUESTIONNAIRE Q1A – FIRST TIME

Q1a	To be performed only at the first visit to homes. To be compiled by the researcher This questionnaire is aimed at collecting the background information about the house: • info of the dwellings and its tenancy (such as tenure, occupancy); • some elements that will inform the physical survey (such as information regarding the microclimate, physical dimensions, etc.

1. Information of house

1. **Day & time of survey ___________________________**

2. **Site context**

urban	suburban	rural

3. **Microclimate (TAKE A COUPLE OF PHOTOS, front and rear)**

Majority of paved surface	Majority or greenery	Paved surface and greenery equal
Exposed to wind	Sheltered to wind	
Water features	trees	

4. **Shading: presence of trees or other obstructing solar radiation to any glazed area** (yes/no)

Deciduous trees (summer shading)	living room	dining room	hall	kitchen	Main bedroom	2^{nd} bedroom	Other room	Bathroom
Evergreen trees or other (all year shading)	living room	dining room	hall	kitchen	Main bedroom	2^{nd} bedroom	Other room	Bathroom

5. **Layout description of house (orientation, front room/back room, possibility of cross ventilation, ceiling highs, windows types) – TAKE A COUPLE OF PHOTOS**

6. **Materials description of house (lightweight, heavyweight, ceilings expose, carpets, etc.)) – TAKE A COUPLE OF PHOTOS**

7. **Description of windows (floors to ceiling?, operable? presence of trickle vents, blinds? curtains? etc.) – TAKE A COUPLE OF PHOTOS, SKETCH THE OPENING OF WINDOWS**

8. **Heating system description (type of heating/radiators and controls, location of thermostat) – TAKE A COUPLE OF PHOTOS**

9. **Mechanical ventilation system description (type of ventilation –e.g. MVHR or fans, location of inlets/outlets) – TAKE A COUPLE OF PHOTOS**

2. Background household

10. **Name and Surname** ____

11. **Address including postcode** ______________________________________

12. **Home telephone** ____

13. **When is the most convenient time to contact you** ___________________________

14. **What is the preferred method to inform you prior to visiting?**

text	Phone call	email	Other

15. **Which of the following best describes the home occupier?**

Owned	Shared ownership	Rented	Other

16. **Type of house and number of bedrooms**

detached	Semi-detached	terrace	bungalow	flat	other

17. **When did you move into this house?** ___________________________

18. **Spaces in your house**

	downstairs	**upstairs**	**front**	**rear**
Living room				
Dining room				
kitchen				
hall				
Main bedroom				
2nd bedroom				
3rd bedroom				
Bathroom 1				
Bathroom 2				
conservatory				
Winter garden				
other				

19. Have you ever lived in a country with a hotter climate? If yes, please provide details.

Comments	

20. Details about you and your family

	Name	**Initials**	**Gender**	**DOB**	**Mobile number**
Adult 1					
Adult 2					
Adult 3					
Adult 4					
Child 1					
Child 2					
Child 3					
Child 4					
Child 5					

21. ….(continue) Details about you and your family

			Device they would use for the thermal comfort survey			
	Initials	**Email address**	**tablet**	**mobile**	**Computer**	**Wouldn't do the survey**
Adult 1						
Adult 2						
Adult 3						
Adult 4						
Child 1						
Child 2						
Child 3						
Child 4						
Child 5						

22. What periods of the day is your houseoccupied

During weekdays	morning		afternoon			evening			night	else
Living areas	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Bedrooms	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
At weekends										
Living areas	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Bedrooms	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	

23. Please specify the months when you have the *heating* turned ON (mark all that apply)

Jan	Feb	Mar	Apr	May	June	July	Ago	Sept	Oct	Nov	Dec

24. During the heating season, what is the actual temperature setting in your heating thermostat at?
_______ ˚C

25. Please specify the months of the year when temperatures inside your house get *uncomfortably warm*(mark all that apply)

Jan	Feb	Mar	Apr	May	June	July	Ago	Sept	Oct	Nov	Dec

26. Please specify the months of the year when you need to cool your (mark all that apply)

Jan	Feb	Mar	Apr	May	June	July	Ago	Sept	Oct	Nov	Dec

3. Overall opinions about the house

As a recently built house, and all things considered, generally speaking….

27. What do you like best/find most useful about this house?

28. What do you dislike/have most trouble with this house?

29. What would you change about this house?

30. Any comments about comfort (in terms of temperature) in your house?

31. Is there any specific place in this house where the thermal environment feels different compared with all the other rooms of this house?

4. Health

Since you started living in this house …

32. Do you ever experience any of the following: (Please mark all that apply)

Cold feet	Sleep deprivation
Irritated nose	Swelling of legs
Irritated eyes	Air stuffiness
allergies	Persistent cough

Comments:

Photo or sketch of affected areas & Comments from tenant

33. Have you noticed any of the following in each of the rooms listed at any time in the past months? (Please mark all that apply)

	Light brown stains	Dark spots/mould	Mould around edges of windows/doors	Mould on furniture, carpets or clothes	None of these problems in this room
Living room					
Dining room					
Hall					
Kitchen					
Bathroom					
Main bedroom					
2nd bedroom					
Other room					

5. Overall opinion about comfort

34. Do you find it difficult to keep *comfortably cool* any of the following rooms? (Specify which time of the year)

Living room	Spring	Summer	autumn	winter	no difficulty
Dining room	spring	summer	autumn	winter	
Hall	spring	summer	autumn	winter	
Kitchen	spring	summer	autumn	winter	
Bathroom	spring	summer	autumn	winter	
Main bedroom	spring	summer	autumn	winter	
2^{nd} bedroom	spring	summer	autumn	winter	
Other room	spring	summer	autumn	winter	

Comments:

35. Can you provide any comments about comfort in regards to:

temperature	
natural ventilation (windows)	
mechanical ventilation	
solar radiation	

QUESTIONNAIRE Q1B – SEASONAL

Q1b	To be performed every season (4 times in total, for each house). To be compiled by the researcher it is aimed at collecting information for specific times of the year (spring, summer, autumn, winter) and relating to: • what occupants think of their thermal environment, • how occupants adapt/interact with their thermal environment (CLO, controls, technology,...)

1. Conditions before, during and after the interview

1. **Day & time of survey ___________________________**

2. **External conditions at interview start**

Air Temperature	Operative temperature	Relative Humidity	Air velocity outside	Solar radiance	CO^2 levels
˚C	˚C	%	m/s	kW/m^2	ppm

3. **Internal conditions at interview start**

Air Temperature	Operative temperature	Relative Humidity	Air velocity inside	Solar radiance	CO^2 levels
˚C	˚C	%	m/s	kW/m^2	ppm

4. **Which room is used for the interview?** (circle one)

Living	dining	kitchen	bedroom 1	bedroom 2	other room	hall

5. **Setting of interview room *radiator* / *ventilator* / *air conditioning* / thermostat and other HVAC at start of interview (PHOTOS)**

6. **Is the window open at start of interview? _______________________(complete with PHOTO)____**

7. **Are there any other windows open at start of interview? ____________________**

8. **Are the *blinds* / *curtains* / *venetians* close at start of interview? ____________________**

9. **Layout description: interviewer sketch the plan of the room where interview is taking place**

(please show: main dimensions / North deviation / location of window)

INSTRUCTIONS ON HOW TO SKETCH THE ROOM ARE PROVIDED IN THE FOLLOWING PAGE

2. Comfort during *hot weather*

Some questions specific to when the *weather is hot*:

10. During hot weather, how often do you open the windows in order to cool your house?

Living room	Day & night	night	daily	weekly	rarely	never
Dining room	Day & night	night	daily	weekly	rarely	never
Hall	Day & night	night	daily	weekly	rarely	never
Kitchen	Day & night	night	daily	weekly	rarely	never
Bathroom	Day & night	night	daily	weekly	rarely	never
Main bedroom	Day & night	night	daily	weekly	rarely	never
2nd bedroom	Day & night	night	daily	weekly	rarely	never
other	Day & night	night	daily	weekly	rarely	never

11. During hot weather, how often do you use fans?

Living room	Day & night	night	daily	weekly	rarely	never
Dining room	Day & night	night	daily	weekly	rarely	never
Hall	Day & night	night	daily	weekly	rarely	never
Kitchen	Day & night	night	daily	weekly	rarely	never
Bathroom	Day & night	night	daily	weekly	rarely	never
Main bedroom	Day & night	night	daily	weekly	rarely	never
2nd bedroom	Day & night	night	daily	weekly	rarely	never
Other	Day & night	night	daily	weekly	rarely	never

12. During hot weather, how often do you use portable air conditioning units?

Living room	Day & night	night	daily	weekly	rarely	never
Dining room	Day & night	night	daily	weekly	rarely	never
Hall	Day & night	night	daily	weekly	rarely	never
Kitchen	Day & night	night	daily	weekly	rarely	never
Bathroom	Day & night	night	daily	weekly	rarely	never
Main bedroom	Day & night	night	daily	weekly	rarely	never
2nd bedroom	Day & night	night	daily	weekly	rarely	never
other	Day & night	night	daily	weekly	rarely	never

Comments to questions 11-13

3. **Comfort during *this time of the year***

Now, some questions specific to this time of year:

13. During this time of the year, do you find it difficult to <u>*keep comfortably cool*</u> any of the following rooms?(please specify time slot)

During weekdays	morning		afternoon			evening			night	none
Living room	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Dining room	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Hall	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Kitchen	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Bathroom	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Main bedrooms	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
2nd bedroom	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Other	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	

At weekends	morning		afternoon			evening			night	none
Living room	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Dining room	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Hall	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Kitchen	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Bathroom	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Main bedrooms	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
2nd bedroom	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	
Other	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-8	

14. During this time of the year, are there any particular room or rooms where the air is particularly: (mark as appropriate)

	Dry	Humid	Stale (no longer fresh air)	Smelly	Draughty (currents of cool air)
Living room					
Dining room					
Hall					
Kitchen					
Bathroom					
Main bedroom					
2nd bedroom					
Other					

15. During this time of the year, how often in an average week do you *open the windows*? (mark as appropriate)

	Never	Once	2-3 times	4-5 times	6 times or more	Not applicable
Living room						
Dining room						
Hall						
Kitchen						
Bathroom						
Main bedroom						
2nd bedroom						
Other						

16. During this time of the year, how often in an average week do you *cool the rooms* to comfortable temperatures? (mark as appropriate)

	Never	Once	2-3 times	4-5 times	6 times or more	Not applicable
Living room						
Dining room						
Hall						
Kitchen						
Bathroom						
Main bedroom						
2nd bedroom						
Other						

Comments to questions 15-17

4. Controls (interaction user-house)

17. How much control do you feel you have over the temperature in this house? Please circle one number that reflects your opinion.

	No control					full control	
Living room temperature:	1	2	3	4	5	6	7
Dining room temperature:	1	2	3	4	5	6	7
Hall temperature:	1	2	3	4	5	6	7
Kitchen temperature:	1	2	3	4	5	6	7
Bathroom temperature:	1	2	3	4	5	6	7
Main bedroom temperature:	1	2	3	4	5	6	7
2nd bedroom temperature:	1	2	3	4	5	6	7
Other temperature:	1	2	3	4	5	6	7

Comments:

18. How much control do you feel you have over the ventilation in this house? Please circle one number that reflects your opinion (including both *natural* ventilation –e.g. by opening the windows- and *mechanical* ventilation e.g. by boosting fans)

	No control					full control	
Living room ventilation:	1	2	3	4	5	6	7
Dining room ventilation:	1	2	3	4	5	6	7
Hall ventilation:	1	2	3	4	5	6	7
Kitchen ventilation:	1	2	3	4	5	6	7
Bathroom ventilation:	1	2	3	4	5	6	7
Main bedroom ventilation:	1	2	3	4	5	6	7
2nd bedroom ventilation:	1	2	3	4	5	6	7
Other ventilation:	1	2	3	4	5	6	7

Comments:

19. How do you feel about the usability of the following systems?(if applicable) Please circle one number that reflects your opinion

	difficult to use					easy to use	
Heating system	1	2	3	4	5	6	7
Windows	1	2	3	4	5	6	7
mechanical ventilation system	1	2	3	4	5	6	7
Shading devices:	1	2	3	4	5	6	7

Comments

5. Behaviour (interaction user-adaptive behaviour)

20. Is the *cooker extractor* turned ON when cooking?

never	sometimes	at all times

21. Is the bathroom fan turned ON when showering?

never	sometimes	at all times

22. During this time of the year, if you feel cold in your house, what do you do? (please rank as appropriate: first=1, second=2, etc. and leave blank those features that are not applicable)

Raise the temperature of the heating thermostat	
Manipulate the radiator valve	
Use supplementary heater	
Wear an extra layer of clothing, such as a jumper	
Leave house	
Other (Please specify)	

23. During this time of the year, if you feel too warm in your house, what is the first thing you do? (please rank as appropriate: first=1, second=2, etc. and leave blank those features that are not applicable)

Lower the temperature of the heating thermostat	
Turn off the central heating	
Boost the mechanical ventilation	
By-pass the mechanical ventilation	
Remove a layer of clothing, such as a jumper	
Open the windows	
Close the windows	
Use an electric fan	
Use air conditioning	
Leave house	
Other (Please specify)	

QUESTIONNAIRE Q2 – THERMAL COMFORT SURVEY

Home Thermal Comfort and Air Motion Survey

Welcome

General guidance notes:

1. Thank you for agreeing to take part in the
   Building and Occupant Indoor Thermal Comfort Study.

2. We would greatly appreciate it, if you could complete the survey when you receive the email request, however, If this is not a convenient time please do feel free to defer completion to a more suitable time for you.

3. Please **do not complete** this survey today if you are **not feeling very well**. Please complete it when you are better.
   We hope you get better soon.

4. Each time you complete the survey, please
   complete **indoors** in your **own home.**

5. If you have a covering such as a **blanket** or **sheet** over you, or are eating or drinking, then please do not complete the survey now, and do it at a later time or date.

6. Please ensure that you read the questions carefully and respond with
   your **first immediate thoughts** on your sensations..

7. All data will be kept anonymously.

We greatly appreciate your time and effort in completing the survey and assisting us with our research.

First a few questions so we can identify you.

1 Have you got any covering over you such as a blanket or sheet or are you eating or having a drink?

○ Yes ○ No

1.a Please do not complete this survey now. Please complete this survey at another time, when you do not have a blanket on you, or are not having a drink.

Thank y

DATE & TIME when completing this survey ______________________________

2 Please tell us your house number.

3 Please tell us your house code we have given you for this project. For exampe UK22 *
Required

4 Are you under 18?

○ Yes ○ No

4.a How old are you?

4.b 18 and over, please select your age group.

Now for some questions about what you are wearing.

5 Please can you tell us your gender and what you are wearing?

- Male
- Female

5.a Please would you tell us what you are wearing on your upper body **NOW**.

Please select at least 1 answer(s).

- Shirt Heavy weight (long sleeved)
- Shirt Heavy weight (short sleeved)
- Shirt Light weight (long sleeved)
- Shirt Light weight (short sleeved)
- Sweatshirt or Jumper
- T-Shirt
- Vest
- Pyjama Top
- Nothing
- Other (items not listed or multiples of items listed)

5.a.i If you selected Other, please specify:

5.b Please will you tell us what you are wearing on your lower body **NOW**.

Please select at least 1 answer(s).

- Trousers (Heavy Weight)
- Trousers (Light Weight)
- Shorts
- Boxer shorts
- Pyjama bottoms
- Lungi (Loose)
- Lungi (Tied)
- Other (items not listed or multiples of items listed)

5.b.i If you selected Other, please specify:

5.c Please will you tell us what you are wearing on your feet **NOW**.

Please select at least 1 answer(s).

- ☐ Socks Long
- ☐ Socks Ankle
- ☐ Shoes (thick soled)
- ☐ Shoes (thin soled)
- ☐ Slippers
- ☐ Flipflops
- ☐ Nothing (bare feet)
- ☐ Other (items not listed or multiples of items listed)

5.c.i If you selected Other, please specify:

5.d Are you wearing a dress?

- ○ Yes
- ○ No

5.d.i Please tell us what type of dress you are wearing

Please select at least 1 answer(s).

- ☐ Long sleeved dress (Heavy weight)
- ☐ Long sleeved dress (Light weight)
- ☐ Short sleeved dress (Heavy weight)
- ☐ Short Sleeved dress (Light weight)
- ☐ Thin strap or strapless dress (Light weight)
- ☐ Other type of dress not listed.

5.d.i.a If you selected Other, please specify:

5.e Are you wearing a Sari or Punjabi Suit?

- ○ Yes
- ○ No

5.e.i Please tell us what type and style of Sari or Punjabi Suit you are wearing

- ○ Sari Pleated covering both arms
- ○ Sari Pleated covering one arm
- ○ Silk sari pallu unpleated covering both arms
- ○ Silk sari pallu unpleated covering one arm
- ○ Sari pallu pleated covering one arm and back
- ○ Sari pallu unpleated covering one arm

- Sari pallu pleated, both arms uncovered
- Silk sari pallu pleated, both arms uncovered
- Punjabi Suit (please describe style in Other option)
- Other (Style Sari or Punjabi Suit)

5.e.i.a If you selected Other, please specify:

5.f Please would you tell us what you are wearing on your upper body **NOW.**

Please select at least 1 answer(s).

- No other item
- Undergarment top (eg Vest)
- Tube top with or without straps
- T-Shirt (Long Sleeved)
- T-Shirt (Short Sleeved)
- Blouse
- Sweatshirt or Jumper
- Cardigan
- Shawl
- Other (items not listed or multiples of items listed)

5.f.i If you selected Other, please specify:

5.g Please will you tell us what you are wearing on your lower body and legs **NOW.**

Please select at least 1 answer(s).

- Trousers/Jeans (Heavy weight)
- Trousers (Light weight)
- Fleece jogging/sweatpants
- Shorts
- Skirt (Heavy weight)
- Skirt (Light weight)
- Leggings (Full length)
- Leggings (Shorter)
- Tights Woollen
- Tights Nylon
- Bare legs
- Other (items not listed or multiples of items listed)

5.g.i If you selected Other, please specify:

5.h Please will you tell us what you are wearing on your feet **NOW.**

Please select at least 1 answer(s).

- Socks Long
- Socks Ankle
- Knee high socks Nylon
- Tights Nylon
- Tights woollen
- Shoes (thick soled)
- Shoes (thin soled)
- Slippers
- Flipflops
- Nothing (bare feet)
- Other (items not listed or multiples of items listed)

5.h.i If you selected Other, please specify:

6 Have you added or removed any items of clothing in the last 15 minutes?

- Yes
- No

6.a If yes please can you tell us what items of clothing you have added.

More info

6.b If yes please can you tell us what items of clothing you have removed.

More info

Now for some questions about what you have been doing.

7 Please can you tell us the **main** activity you were doing in the previous 15 minutes

7.a If you selected Other, please specify:

7.b Please select any other activities you were doing during the last 15 minutes.

Please select at least 1 answer(s).

- No other activity
- Reclining
- Seated, quiet (e.g. watching TV, using tablet, reading)
- Seated working (e.g. computer, paperwork.)
- Seated eating a meal
- Seated having a drink
- Standing, relaxed
- Walking around the house
- Walking up and downstairs
- Light housework: cooking, washing up; ironing, making beds
- Heavy housework: washing floor, washing windows, hoovering(check on Ashrae)
- Gardening: digging, raking, weeding, mowing lawn with power mower
- Outside relaxed seating/standing
- Outside physical activity (e.g. walking, running, cycling)
- Travelling in a car or on bus
- Other

7.b.i If you selected Other, please specify:

8 Please tell us where you are now?

8.a If you selected Other, please specify:

8.b How long have you been here?

- Less than 5 mins
- 5 to 40 mins
- More than 40 mins

8.b.i Please tell us where you were immediately prior to your current location:

8.b.i.a If you selected Other, please specify:

8.b.ii How long were you there?

- Less that 5 mins
- 5 to 40 mins
- More than 40 mins

9 Please tell us how you are seated/stood now whilst you are filling out the survey.

9.a If you selected Other, please specify:

The following questions are all about your thermal comfort Right Now.

When completing the following questions please give your first immediate thoughts on what you feel NOW, and do not think about it too much.

Thank you.

10 Please indicate how YOU feel **NOW** in relation to your thermal comfort. Please select any point across the scale.

	Please select any point across the .																
	Cold	......	.....	Cool	....	...	Slightly Cool	..	.	Neutral	,	,,	Slightly Warm	,,,	,,,,	Warm	,,
Overall	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
Head	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
Shoulders	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
Trunk	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
Arms	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
Hands	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
Above Knee	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
Below Knee	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	
Feet	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	

11 Right now, how acceptable do you find the following in the room you are in.

	Please select any point across the scale * Required						
	Very acceptable	++	+	*	-	--	No at all acceptable
The thermal environment	○	○	○	○	○	○	○
The air movement	○	○	○	○	○	○	○

12 Would you prefer to be

○ Warmer ○ No Change ○ Cooler

13 Would you prefer

○ More air movement ○ No change ○ Less air movement

Now we are going to ask a few questions about different elements of your thermal comfort

14 Please tell us about any air movement you are feeling on your body.

More info

	On which sides of your body do you feel air movement now?					Do you find this air movement *Optional*		
	None	Left	Right	Front	Back	Pleasant (e.g. Breeze)	Neither Pleasant or Unpleasant	Unpleasant (e.g. Draught)
Head	☐	☐	☐	☐	☐	○	○	○
Neck	☐	☐	☐	☐	☐	○	○	○
Shoulders	☐	☐	☐	☐	☐	○	○	○
Trunk	☐	☐	☐	☐	☐	○	○	○
Arms	☐	☐	☐	☐	☐	○	○	○
Hands	☐	☐	☐	☐	☐	○	○	○
Above Knee	☐	☐	☐	☐	☐	○	○	○
Below Knee	☐	☐	☐	☐	☐	○	○	○
Ankles	☐	☐	☐	☐	☐	○	○	○
Feet	☐	☐	☐	☐	☐	○	○	○

15 With regards to your thermal comfort please indicate how you feel now:

- ○ Not Uncomfortable
- ○ Slightly Uncomfortable
- ○ Uncomfortable
- ○ Very Uncomfortable

16 With regards to dryness please indicate how you feel now:

- ○ Not Dry
- ○ Slightly Dry
- ○ Dry
- ○ Very Dry

17 With regards to how sticky you feel please indicate how you feel now:

- ○ Not Sticky
- ○ Slightly Sticky
- ○ Sticky
- ○ Very Sticky

Now we would like to know about how you are keeping cool in your room and the layout of the room you are in now.

18 Please tell us which of the following devices you have in the room you are in now, whether they are in use, and the setting they are on.

	Please state if you have this in your room * *Required*		Please indicate for each device whether it is in use and its setting.				If you have a fan that oscillates please tick if it is oscillating now. *Optional*
	Yes	No	Closed or not in use	Slightly open or low speed	Partially open or medium speed	Fully open or high speed	Oscillating
Windows that can be opened or closed	○	○	○	○	○	○	○
Roof Vents	○	○	○	○	○	○	○
Doors opening to outside	○	○	○	○	○	○	○
Hand held fan	○	○	○	○	○	○	○
Desk top fan	○	○	○	○	○	○	○
Pedestal fan	○	○	○	○	○	○	○
Tower fan	○	○	○	○	○	○	○
Ceiling fan	○	○	○	○	○	○	○
Air multiplier fan	○	○	○	○	○	○	○
Air cooler	○	○	○	○	○	○	○
Air conditioner	○	○	○	○	○	○	○

Diagrammatic Floor Plan - Bird's Eye View

A1	A2	B1	B2
A3	A4	B3	B4
C1	C2	D1	D2
C3	C4	D3	D4

19 It is helpful for us to know whereabouts you are in relation to other things in the room you are in. Please complete the following questions by refering to the diagrammatic floorplan above to help us understand the layout of your room. Thank you.

More info

	Please refer to diagrammatic plan to indicate the position of things in the room.																	For **windo** or **doors** please stat they are **Open Closed**	
	N/A	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4	Open	Clos
Where are you positioned?																			
Which part of the room are you facing towards?																			
Where is a door ?																			
Where is a another door?																			
Where is a window?																			
Where is another window?																			
Where is a roof vent?																			
Where is another roof vent?																			

Where is a free standing fan?																			
Where is a ceiling fan?																			
Where is a built in fan/air conditioner?																			

19.a If there are any other items, devices etc about the room that you haven't been able to tell us about in the above list, we would appreciate it if you can tell us what it is and its location in the box below. For windows and doors please say which ones are open. Thank you

19.b Please tell us on which sides of your body the sun is shining now.

	No Sun	Left	Right	Front	Back
Head					
Shoulders					
Trunk					
Arms					
Hands					
Above Knee					
Below Knee					
Feet					

Thank you once again for helping us in our research and completing our weekly survey

If you are going away next week and would prefer us not to send you the survey, then please contact Lynda on

l.h.webb@lboro.ac.uk

01509 228745

and also inform us when you would like to start receiving the survey again.

Thank you

Key for selection options

4.a - How old are you?
- 7 years old
- 8 years old
- 9 years old
- 10 years old
- 11 years old
- 12 years old
- 13 years old
- 14 years old
- 15 years old
- 16 years old
- 17 years old

4.b - 18 and over, please select your age group.
- 18-24 years
- 25-34 years
- 35-44 years
- 45-54 years
- 55-64 years
- 65-75 years

7 - Please can you tell us the main activity you were doing in the previous 15 minutes
- Reclining
- Seated, quiet (e.g. watching TV, using tablet, reading)
- Seated working (e.g. computer, paperwork.)
- Standing, relaxed
- Walking around the house
- Walking up and downstairs
- Light housework: cooking, washing up; ironing, making beds
- Heavy housework: washing floor, washing windows, hoovering(check on Ashrae)
- Indoor physical activity (e.g. running, cycling on turbo's etc)
- Gardening: digging, raking, weeding, mowing lawn with power mower
- Outside relaxed seating/standing
- Outside physical activity (e.g. walking, running, cycling)
- Travelling
- Other

8 - Please tell us where you are now?

Front Room
Back Room
Kitchen
Conservatory
Study (Downstairs)
1st Largest bedroom
2nd Largest bedroom
3rd Largest bedroom
4th Largest bedroom
5th Largest bedroom
Other

9 - Please tell us how you are seated/stood now whilst you are filling out the survey.

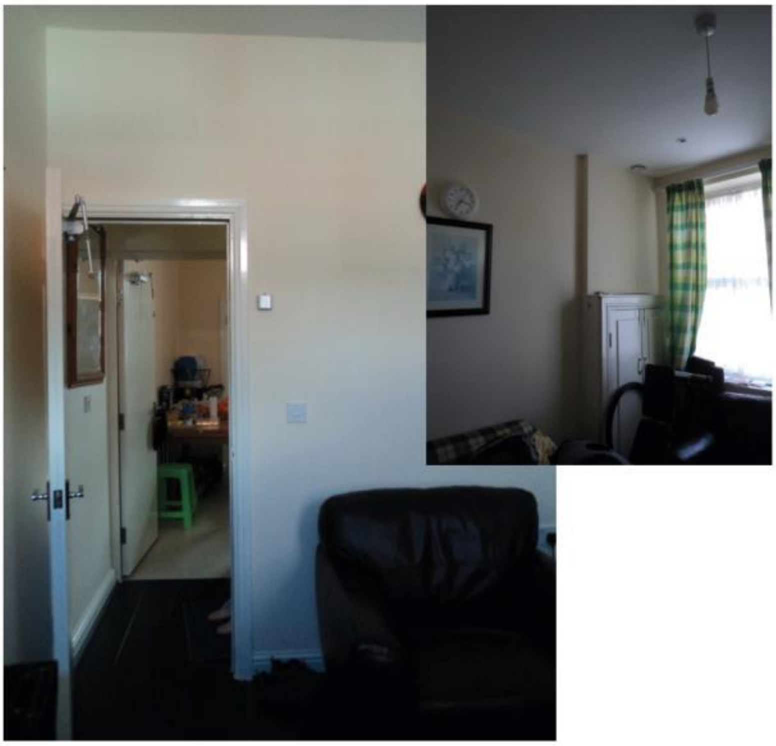
Seated on a soft seat
Seated on a hard seat
Seated on the floor
Seated in an armchair or on a settee
Lounging on a bed or soft settee.
Standing up
Other

APPENDIX D – HOUSES DETAILS

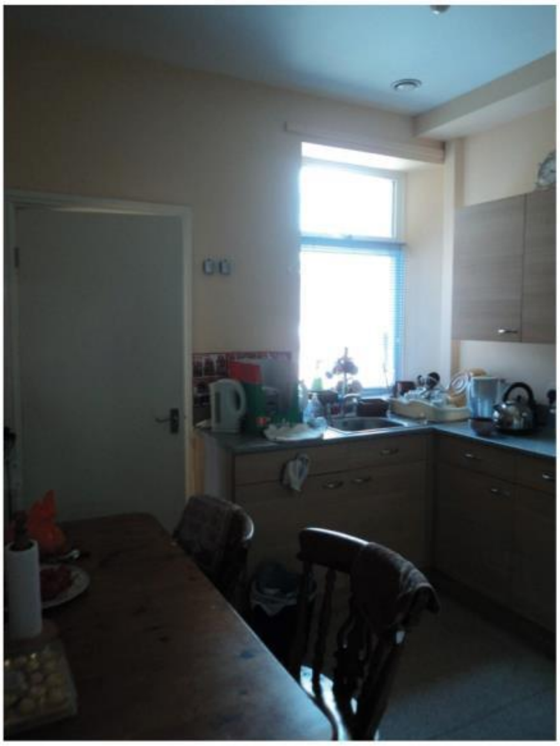
UK 51 / street view

UK 51 / back view

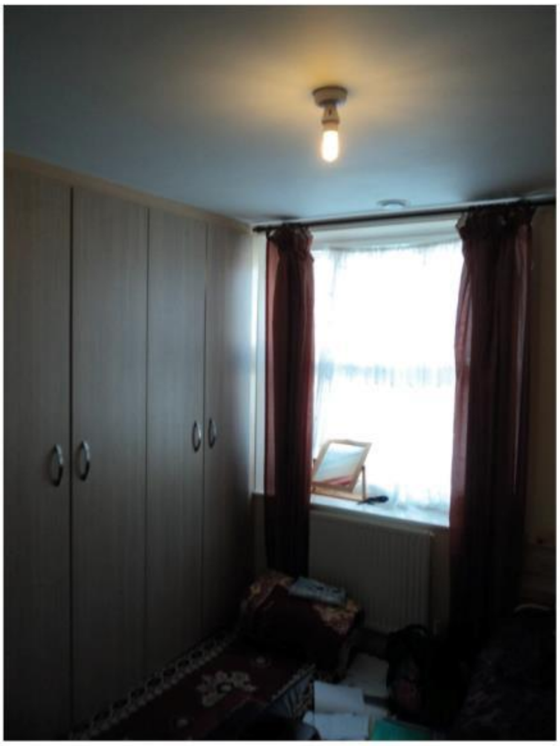
UK 51 /
GF front room
(living room)



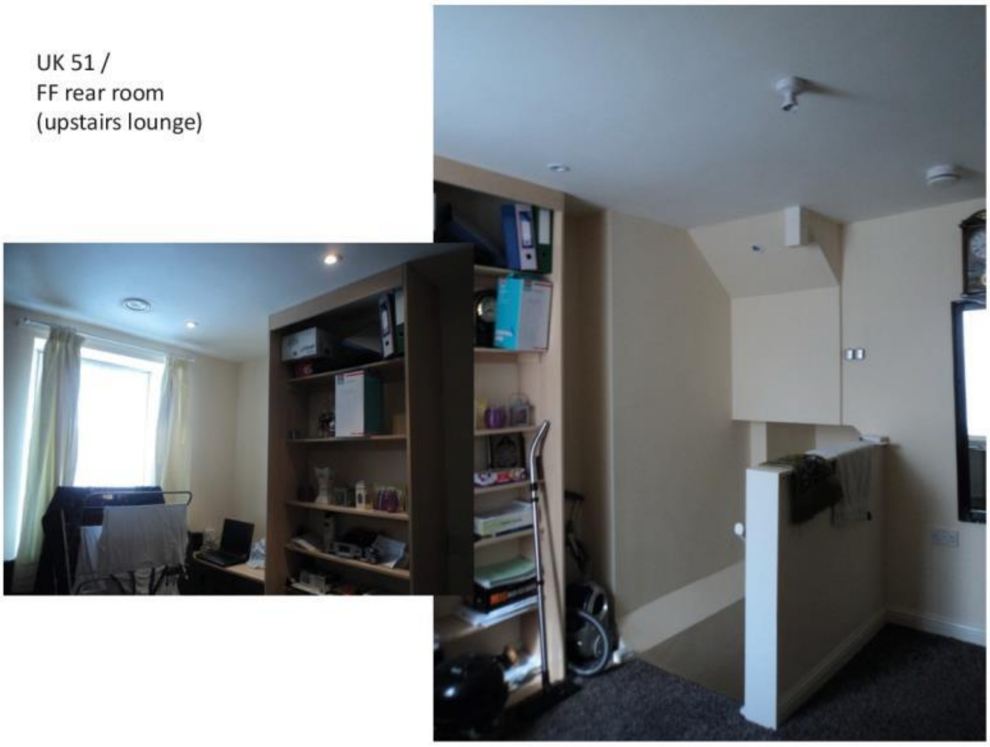
UK 51 /
GF rear room
(dining-kitchen)



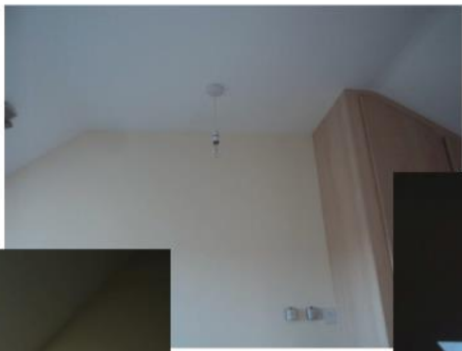
UK 51 /
FF front room
(bedroom 1)

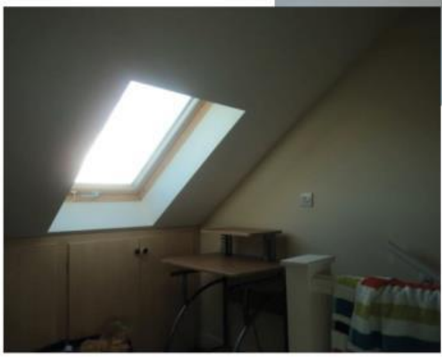


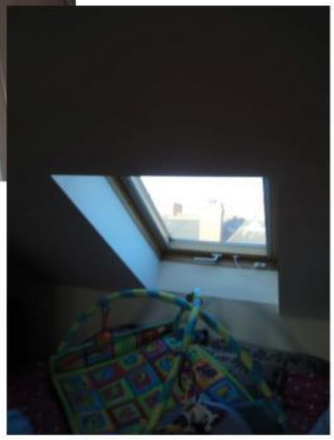
UK 51 /
FF rear room
(upstairs lounge)



UK 51 /
SF bedroom 2







UK 51 / list of loggers

HOUSE CODE	location HOBO			labels	2nd HOBO Serial Number	CHANGE DUE BY	location	HOBO blinking (yes/no)	Light covered (yes/no)	Height (Head, Chest, mm)	Heat & Sun source re location	Picture taken
uk51emh	E	external	rear	temp ext	1272 666	19/09/2015	side passage	y		above head	n	y
UK51EMH	L0-F	level 0	front	temp down-front room	1272 651	19/09/2015	living room, above EMH loggers	y		head	n	y
UK51EMH	L0-R	level 0	rear	temp down-rear room	1272 638	19/09/2015	kitchen/dining, above EMH loggers	y		head	n	y
UK51EMH	L1-F	level 1	front	temp up-front room	1272 659	19/09/2015	main bed, hanging on frame picture	y		head	n	y
UK51EMH	L1-R	level 1	rear		1272 620	19/09/2015	lounge upstairs	y		above head	n	y
UK51EMH	L2-tr	level 2	throughout	temp up-rear room	1272 643	16/09/2015	roof bed, hanging above MVHR door	y	y	head	n	y
UK51EMH	L2-tr	level 2	throughout	(temp/RH/dew/CO2)			roof bed, hanging above MVHR door	y	y	head	n	y

UK 51 / location loggers

external

Living room

Dining- kitchen

Upstairs lounge

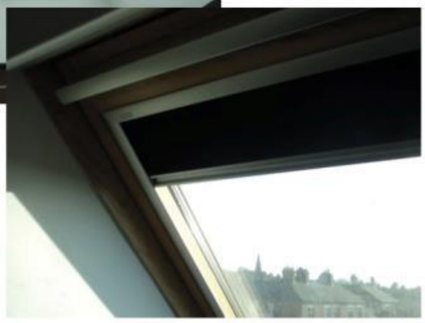
Bedroom 1

Bedroom 2

UK 51 / Indoor climate controls / upstairs bathroom /
water tank for DHW (collected from solar panels)
boiler (check)
window always open

UK 51 / Indoor climate controls / bedroom 2/
MVHR
cross ventilation
velux blinds





UK 51 / Indoor climate controls




UK 51 / cooling devices

House : UK51EMH Researcher: Linda Toledo Date: 22 June 2015

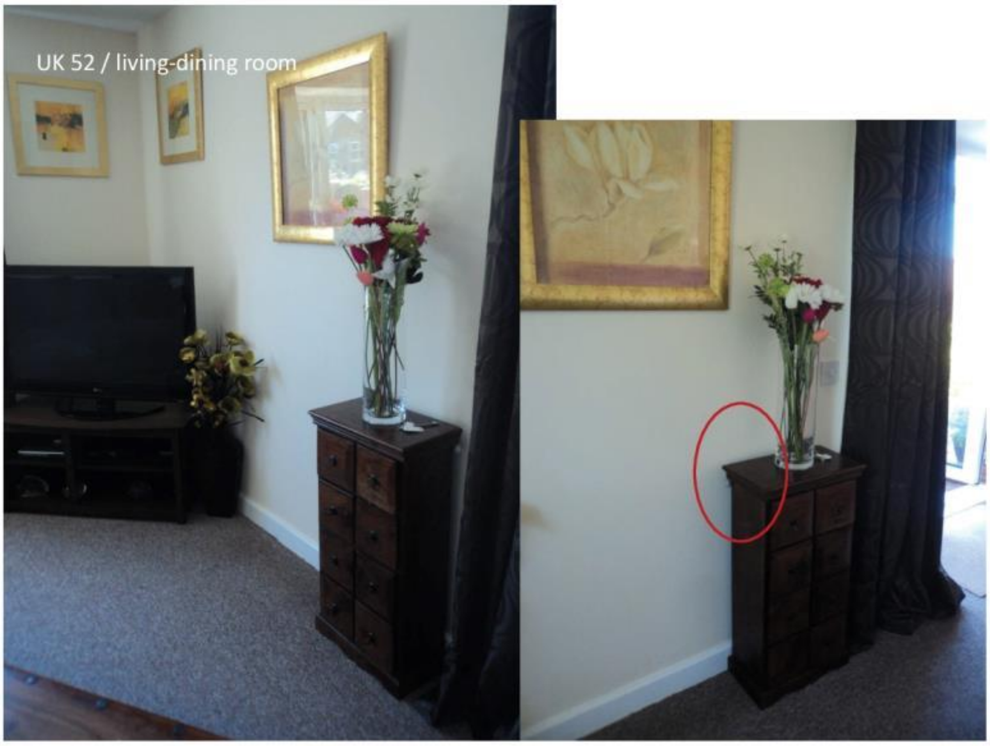
ID	Description	Room / rooms Usually Used in	Device picture taken	Label picture taken	Variable Speed? No. of Settings	Oscillating? No. of settings	Brand	Model	Notes
1									
2									
4									
5									
6									
7									

no cooling devices

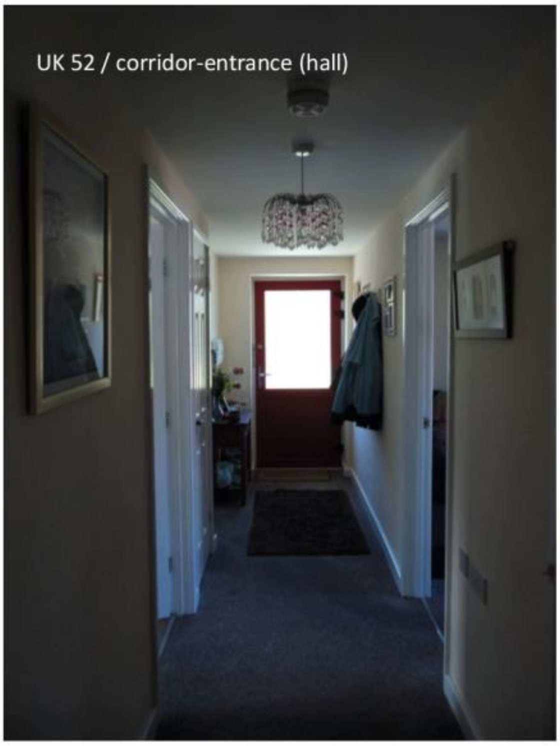
strategies for cooling are:

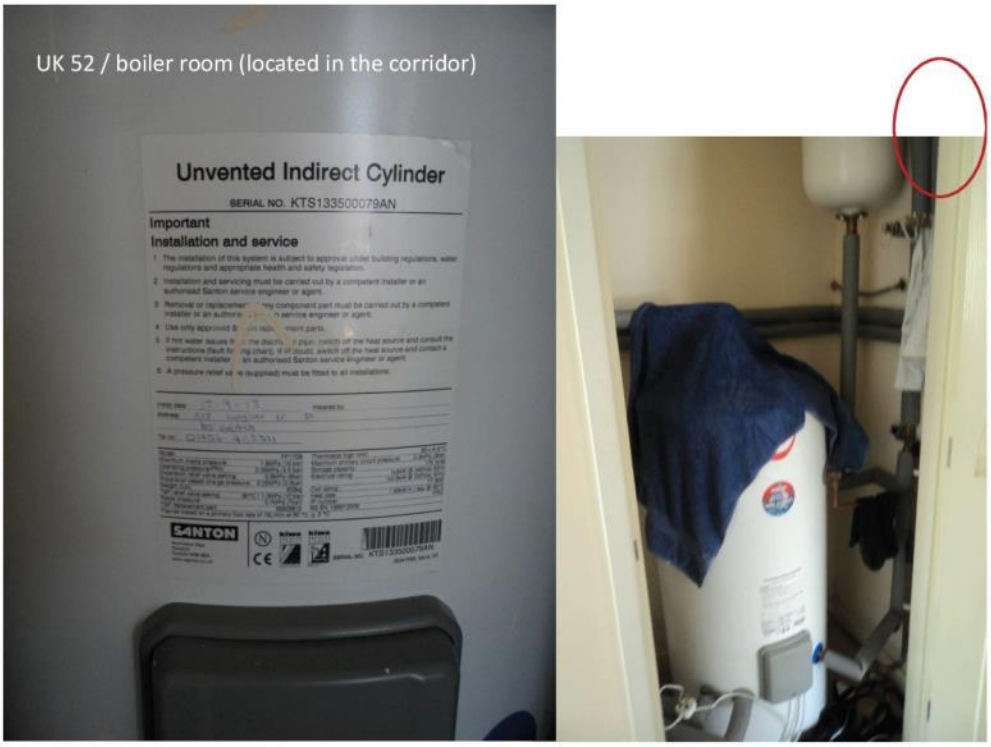
1 windows opening
2 cross ventilation where possible
3 night cooling
4 solar control
5 MVHR boosting

UK 52 / street view




UK 52 / kitchen


UK 52 / corridor-entrance (hall)



UK 52 / boiler room (located in the corridor)

UK 52 / main bedroom / ground floor / south facing

UK 52 / second bedroom / ground floor / south facing

UK 52 / list of loggers

HOUSE CODE	type of measurement	location	Height (Head, Chest, ...)	serial 1st HOBO	log interval (minutes)	start log	set up at home	comment	battery level	log duration (days)	CHANGE DUE BY	HOBO blinking (yes/no)	Light covered (yes/no)	Heat & Sun sources in location	Picture taken	2nd HOBO Serial Number	set up at home	comment	Battery level	CHANGE DUE BY
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]		[illegible]					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]		[illegible]					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]		[illegible]					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]		[illegible]					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]		[illegible]					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]		[illegible]					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]		[illegible]		[illegible]					

UK 52 / Indoor climate controls

UK 52 / HVAC systems (located in a technical room accessed from the rear garden)

UK 52 / cooling devices

House : UK52EMH Researcher: Linda Toledo Date: 22 June 2015

ID	Description	Room / rooms Usually Used in	Device picture taken	Label picture taken	Variable Speed? No. of Settings	Oscillating? No. of settings	Brand	Model	Notes
1									
2									
4									
5									
6									
7									

no cooling devices

strategies for cooling are:

1 windows opening

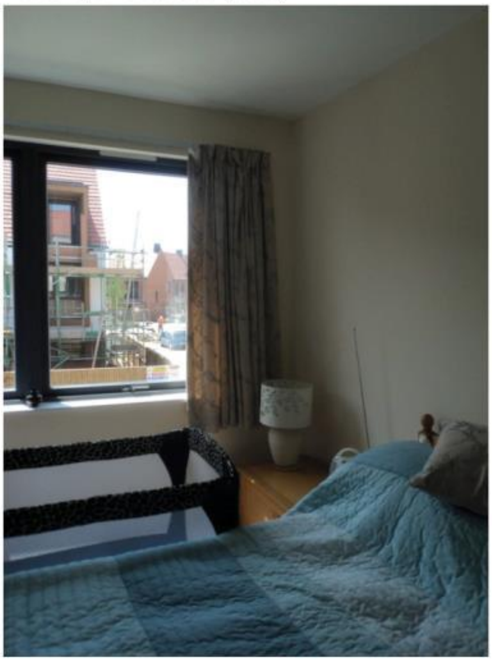
2 cross ventilation where possible

UK 54 / street view

UK 54 / GF throughout dining kitchen

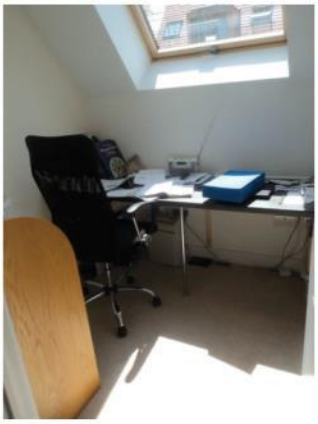
UK 54 / FF throughout living room

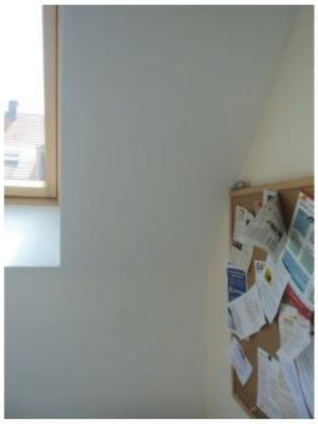
UK 54 / FF bedroom (front)



UK 54 / FF bedroom (rear)

UK 54 / FF office





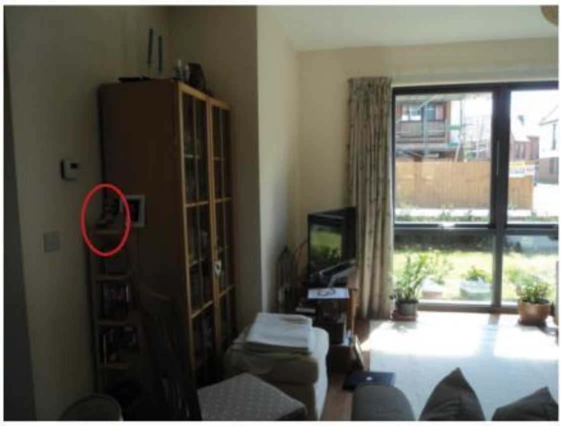
UK 54 / SF bedroom (balcony)

UK 54 / list of loggers

HOUSE CODE	location HOBO			serial 1st HOBO	log interval (minutes)	start log	set up at home	battery level	log duration (days)	CHANGE DUE BY	location	HOBO blinking (yes/no)	Light covered (yes/no)	Height (Head, Chest, mm)	Heat & Sun source re location	Picture taken
UK54/RHT	L1-R	level 1	rear	1109210	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	main bedroom (back north)	y	Y	chest?		Y
UK54/RHT	L0-F	level 0	front	1166156	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	winter garden downstairs	y		waist		Y
UK54/RHT	L0-F	level 0	front	1272626	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	hall/entrance	y		head		Y
UK54/RHT	L0-tr	level 0	throughout	1272631	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	dining room (close to the winter garden)	y		head		Y
UK54/RHT	E	level 0	rear	1272629	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	at low level on a North wall in a narrow passage way	y				Y
UK54/RHT	L1-tr	level 1	throughout	1272635	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	living room (close to the winter garden)	y		head		Y
UK54/RHT	L2-tr	level 2	throughout	1272630	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	bed north	y				Y
UK54/RHT	L1-F	level 1	front	1272637	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	office	y		head		Y
UK54/RHT	L2-tr	level 2	throughout	1272657	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	bed south balconi	y				Y
UK54/RHT	L1-tr	level 2	throughout	1272628	10	12/06/2015 12:00	20/06/2015 12.00	100%	100	19/09/2015	winter garden upstairs	y				Y

UK 54 / location loggers

GF exterior



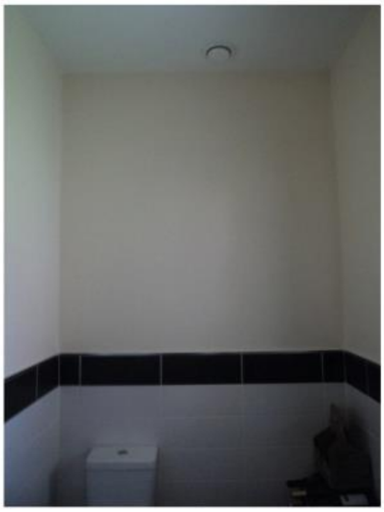
GF living room

UK 54 / location loggers

SF bedroom

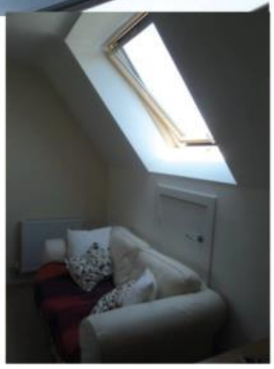
FF office

UK 54 / Indoor climate controls / active devices /
mechanical ventilation (1 fan for whole house)
boiler



UK 54 / Indoor climate controls / passive devices /
purge ventilation
cross ventilation
velux blinds

window practically always open (when weather allows for it) and the MV is switched off



UK 54 / cooling devices

House : UK54JRHT Researcher: Unda Toledo Date: 12 June 2015

ID	Description	Room / rooms Usually Used in	Device picture taken	Label picture taken	Variable Speed? No. of Settings	Oscillating? No. of settings	Brand	Model	Notes
1									
2									
4									
5									
6									
7									

no cooling devices

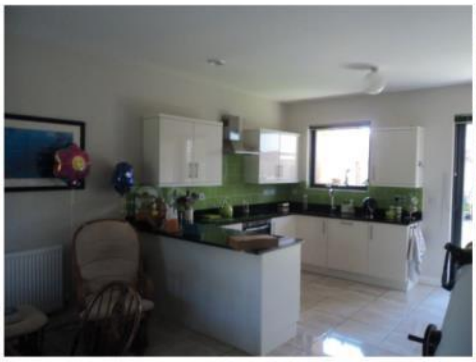
strategies for cooling are:

1 windows opening
2 cross ventilation where possible
3 night cooling
4 MV boosting


UK 55 / street view


UK 55 / back view

UK 55 / GF throughout dining kitchen

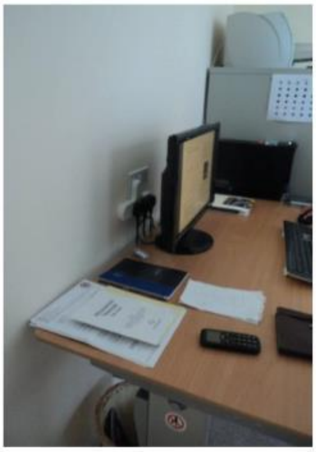
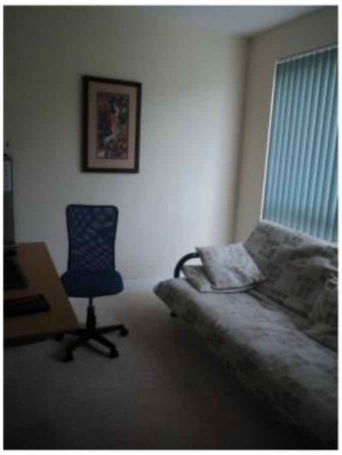
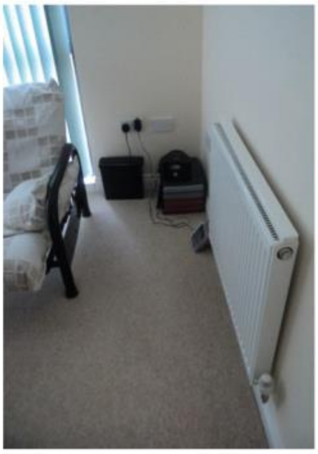




UK 55 / FF throughout living room




UK 55 / wintergarden

UK 55 / FF office



UK 55 / FF bedroom 1

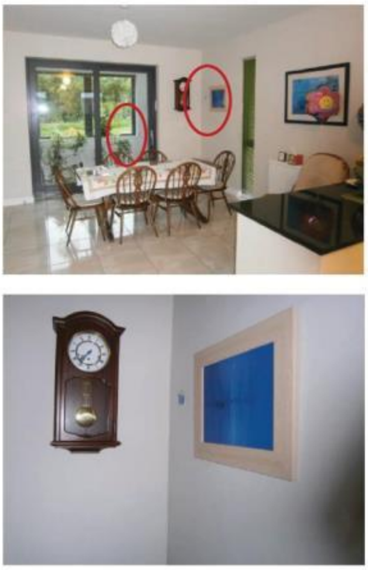
UK 55 / SF bedroom 3 (balcony)

UK 55 / SF bedroom 4

UK 55 / list of loggers

HOUSE CODE	location HOBO			serial 1st HOBO	log interval (minutes)	start log	set up at home	battery level	log duration (days)	CHANGE DUE BY	location	HOBO blinking (yes/no)	Light covered (yes/no)	Height (Head, Chest, mm)	Heat & Sun source re location	Picture taken
UK55/RHT	L1-R	level 1	rear	1109210	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	main bedroom (back north)	y	Y	chest?		Y
UK55/RHT	L0-F	level 0	front	1166156	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	winter garden downstairs	y		waist		Y
UK55/RHT	L0-F	level 0	front	1272626	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	hall/entrance	y		head		Y
UK55/RHT	L0-tr	level 0	throughout	1272631	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	dining room (close to the winter garden)	y		head		Y
UK55/RHT	E	level 0	rear	1272629	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	at low level on a North wall in a narrow passage way	y				Y
UK55/RHT	L1-tr	level 1	throughout	1272635	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	living room (close to the winter garden)	y		head		Y
UK55/RHT	L2-tr	level 2	throughout	1272630	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	bed north	y				Y
UK55/RHT	L1-F	level 1	front	1272637	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	office	y		head		Y
UK55/RHT	L2-tr	level 2	throughout	1272657	10	12/06/2015 12:00	12/06/2015 19.00	100%	100	19/09/2015	bed south balconi	y				Y
UK55/RHT	L1-tr	level 2	throughout	1272628	10	12/06/2015 12:00	20/06/2015 12.00	100%	100	19/09/2015	winter garden upwstairs	y				Y

UK 55 / location loggers



GF dining- kitchen & winter garden

FF living room & winter garden

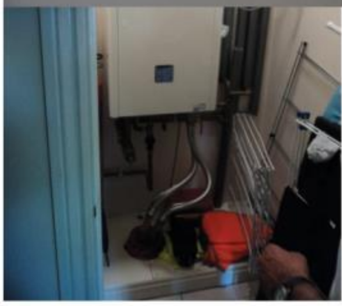
UK 55 / location loggers

FF bedroom 1

GF hall

FF office

UK 55 / Indoor climate controls / upstairs bathroom /
boiler for DHW and space heating
MVHR



UK 55 / Indoor climate controls / bedroom 2/
MVHR
cross ventilation
velux blinds

UK 55 / cooling devices

House : UK55JRHT **Researcher:** Linda Toledo Date: 12 June 2015

ID	Description	Room / rooms Usually Used in	Device picture taken	Label picture taken	Variable Speed? No. of Settings	Oscillating? No. of settings	Brand	Model	Notes
1									
2									
4									
5									
6									
7									

no cooling devices

strategies for cooling are:

1 closing windows
2 MVHR boosting

APPENDIX E – INTERVIEW WITH DESIGNERS

LOOKING AT THE DESIGN PROCESS OF A 'THERMALLY EFFICIENT' HOME

1.	Explain the aims and objectives of the interview: what this interview is about and how it will be conducted (to engage his/her answers to the subject).	**1 min**
2.	Consent form signature	**1 min**
3.	Begin interview (see questions above) and make sure bulleted points are covered in their responses	**28 min**

Question 1: Can you please tell me a bit about your background as a designer?

- For how long designing energy efficient homes? Their role ?
- Worked in what countries? (this affects the thermal design considerations)

Question 2: Why highly efficiently homes?

- Where you designing into a (energy efficiency) standard?
- What tools were used?

Question 3: Can you take me through the design process? How do you started the design of an energy efficient house?

location

- Where taken considerations regarding the **climate**?
- Where taken considerations regarding the **site/microclimate**?

Design choices

- Where taken considerations regarding the **orientation/layout/typology**?
- Where taken considerations regarding the building **materials**: heavyweight/ lightweight/ thermal mass?
- Where taken considerations regarding the building **services**: heating, ventilation, MVHR? (where they are *located* and *volumetric implications*)
- Where taken considerations regarding the **occupant** behaviour?

Comfort (any caution/precaution /care)

- Strategies to control (if any) the **external heat gains** (from sun, location, UHI, hot spells)
- Strategies to control (if any) **internal heat gains** (from lighting, behaviour, technical rooms, building services?)
- Strategies to control (if any) for natural and mechanical **ventilation**? Ceiling highs?
- Any considerations on **winter** comfort - on **summer** comfort

Question 4:

Do you know how your houses are performing? – If not, why not?

- Any **characteristic** found to be contributing or risky to thermal discomfort
- Any **lessons learnt** for next project? Gained **feedback?**

Question 5:

Do you have a complete *decision control* over the construction phase, in a way that the decisions that have been taken at the design stage implemented during the construction phase?

<u>Question 6</u>: Do you generally produced any document (handed to the client/developer) that would explain the occupant how to interact with the house? Building **book** or house **manual**
<u>Question 7</u>: In your experience, do you try to avoid overheating, if so how?
<u>Question 8</u>: In your experience in general, has the role of architect's changes in consideration of the requirement of more energy efficient homes?
<u>Question 9</u>: In light of all the things we have spoken**, what do you think is the most important factor(s) in the design of a thermally efficient home?** Can you **rank** them?
<u>Question 10</u>: Do you have any questions?

4. Thank you	
5. Ask if they could be contacted again	

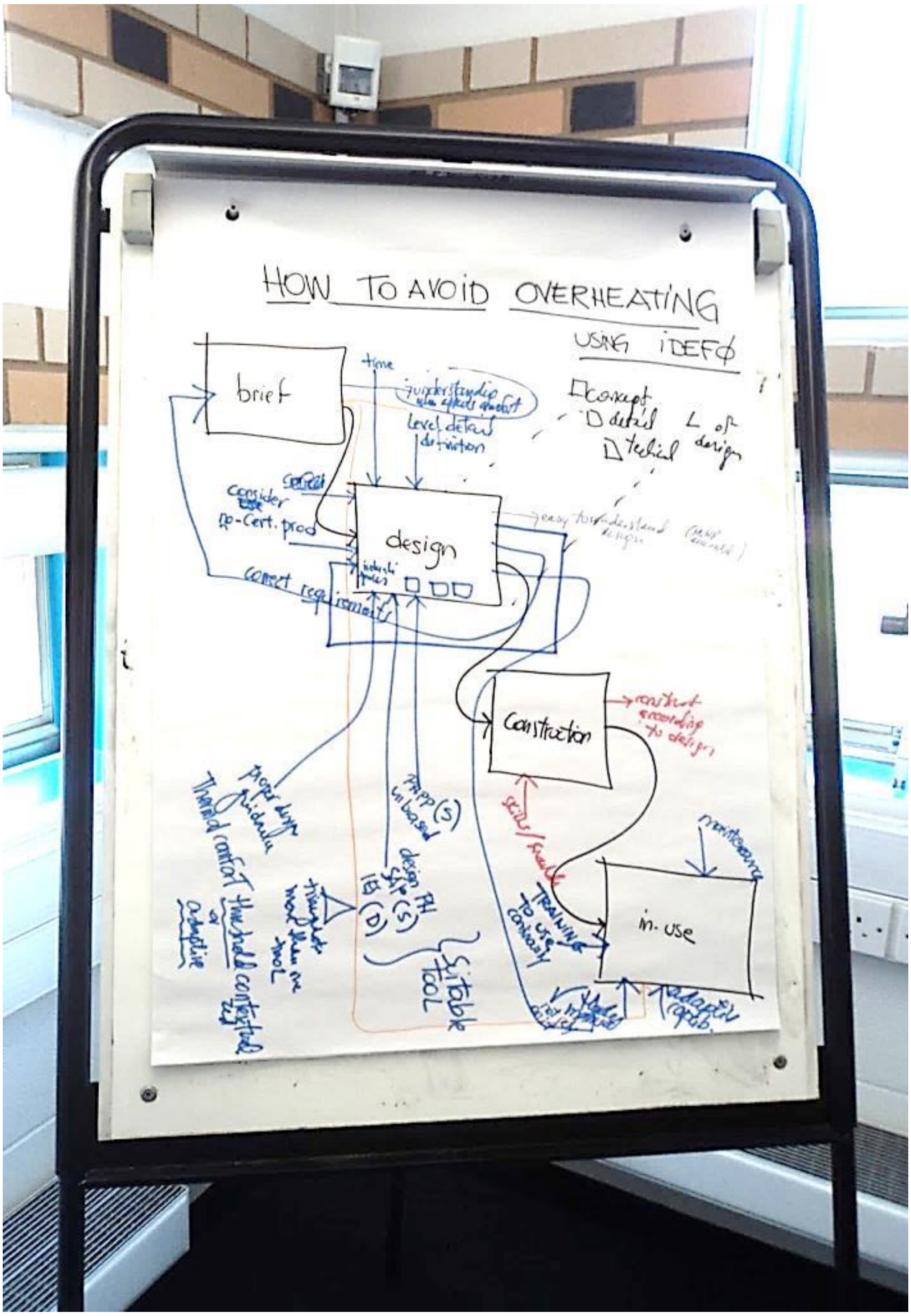
APPENDIX F - OPEN CODING (NODES)

Name	Sources	References
knowledge_overheating awareness	5	35
process_Passivhaus	5	31
factor_solar gains	5	30
process_design	4	25
factor_MVHR	5	23
process_standards required	4	23
factor_airtightness	4	21
factor_ventilation	5	20
knowledge_experienced designer	5	18
factor_materials	5	16
process_tools	3	16
process_conflicts	4	15
process_construction management	4	13
process_after	4	12
process_multidisciplinarity	3	12
process_experimentation	3	11
factor_end user	5	10
factor_site	2	10
process_confusion	3	10
process_funding	4	10
process_intent-trigger	4	10
process_language	3	10
process_procurement	3	10
process_role	5	10
factor_climate change	4	8
factor_IAQ	3	8
factor_typologyLayout	3	8
process_deadline	3	8
process_control	3	7

critique to constructor	3	6
else_land consumption	2	6
factor_urban considerations	3	6
factor_windows	3	6
factor_climate	1	5
factor_orientation	2	5
process_constrains	2	5
critique to government	2	4
critique to Passivhaus	1	4
critique to tools	1	4
factor_other HVACs	3	4
knowledge_learning on the go	1	4
process_responsibility	2	4
critique to client	1	3
else_for PHPP	1	3
factor_stack	2	3
critique to funding process	1	2
else_MM	2	2
factor_internal gains	2	2
process_concept drawings	1	2
process_product	1	2
factor_cooling	1	1
factor_UHI	1	1
knowledge_innovation	1	1

APPENDIX G – OVERHEATING MAP DURING FOCUS GROUP

Overheating avoidance map drawn during the focus group, compiled by the researcher as the plenary discussion unravelled.



APPENDIX H – WORD ANALYSIS WITH NVIVO FROM INTERVIEWS

D1-UK51

D2-UK51

D3-UK52/UK56

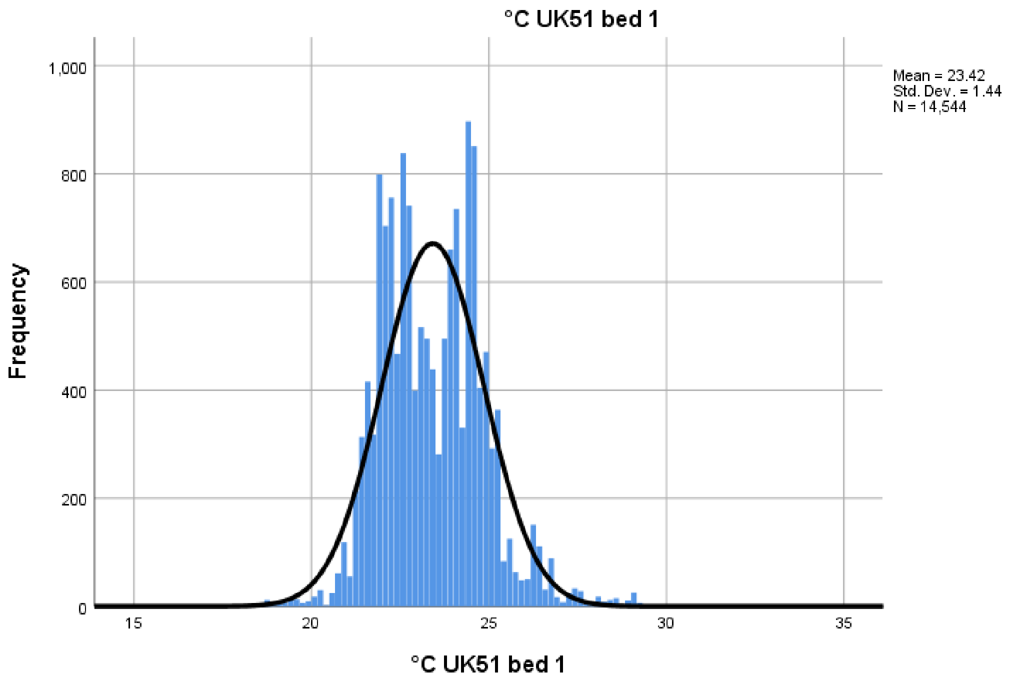
D4-UK52

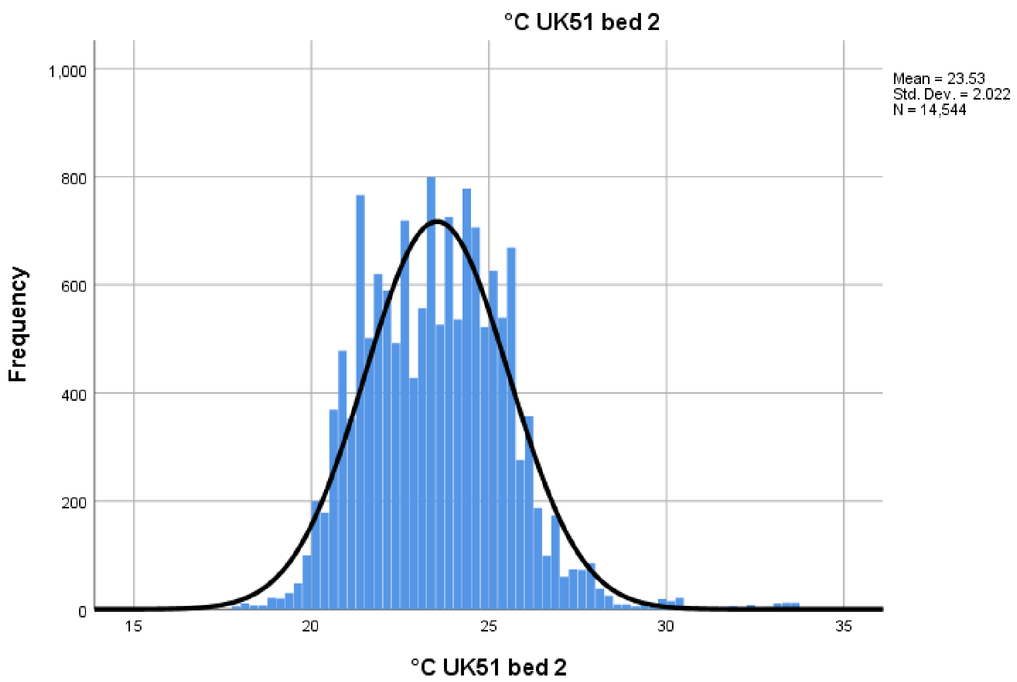
MK-UK56:

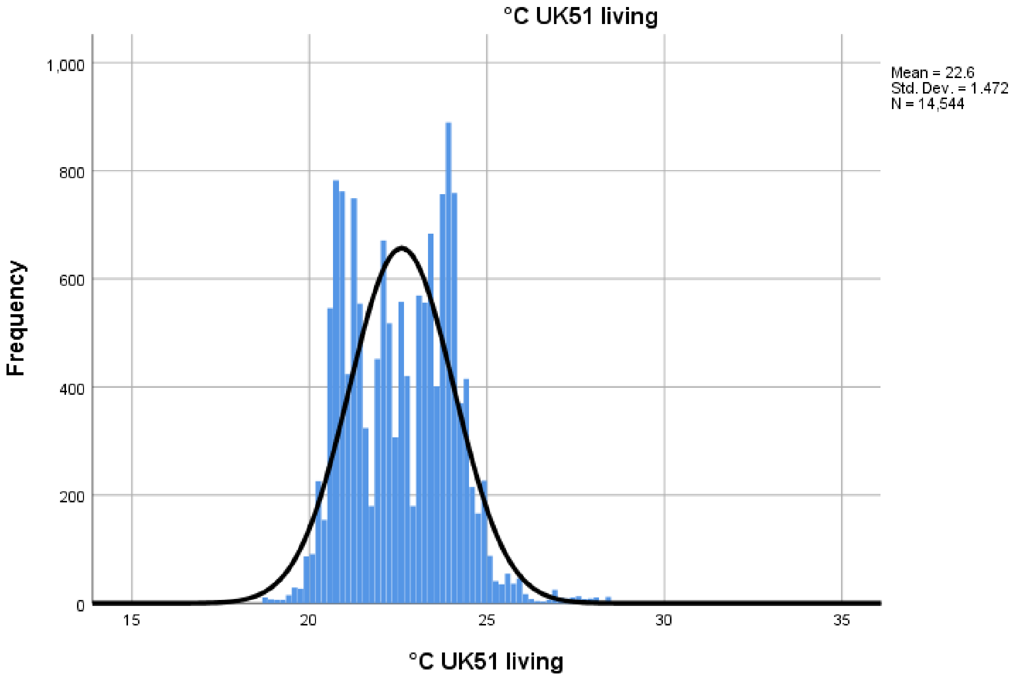

targets
something
therefore
living
problems
deliver
bungalow
control
issue
actually
much
give
right
outside
mvhr
property
ended
construction
project
local
scheme
uk56
trying
open
well
summer
always
haus
little
find
look
need
south
ventilation
passiv
gain
still
house
make
timber
think
going
insulation
done
just
help
inside
consultant
back
cold
heat
first
built
leakage
design
coming
facing
cost
model
homes
achieve
time
know
case
question
obviously
mass
work
units
comfort
establish
enough
solar
site
builder
assessment
windows
came
answer
might
floor
thermal
part
level
ground
years
like
building
develop
talking
manage
difficult
pass
study
thing
also
energy
getting
bedrooms
community
temperatures

APPENDIX I – HISTOGRAMS AND STANDARD DEVIATIONS GRAPHS

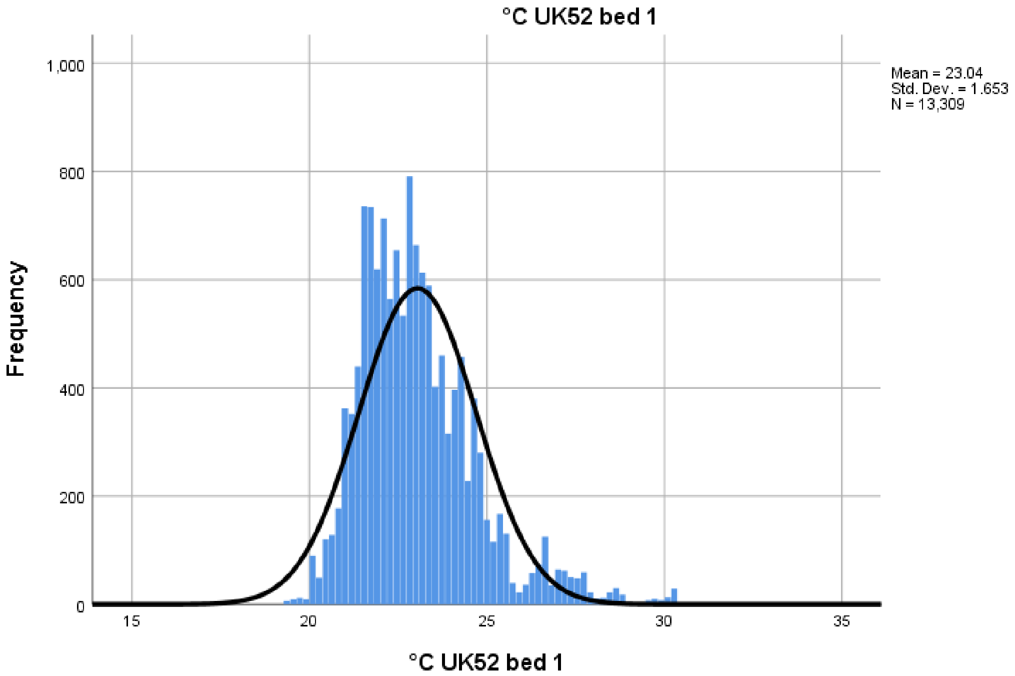
HOUSE UK51

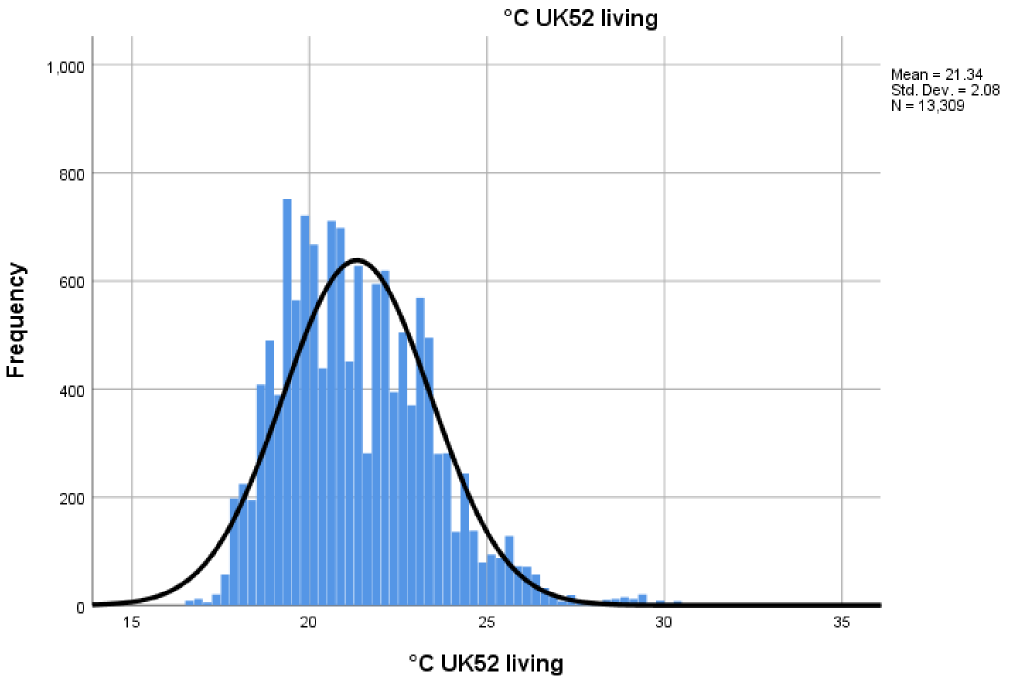




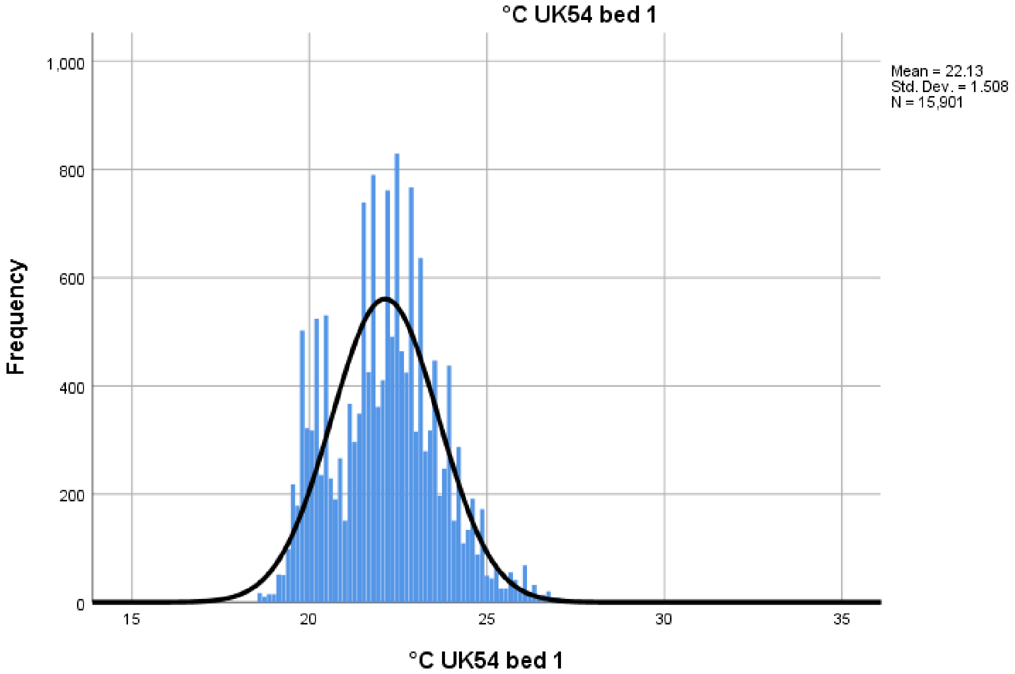

°C UK51 living
Mean = 22.6
Std. Dev. = 1.472
N = 14,544
Frequency
1,000
800
600
400
200
0
15
20
25
30
35
°C UK51 living

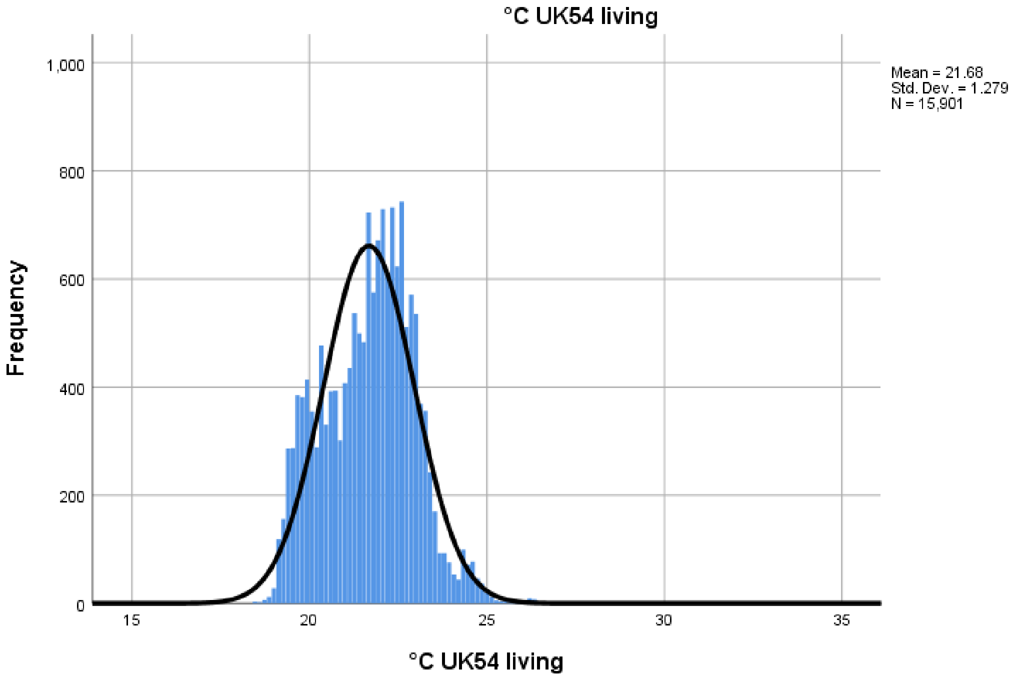
HOUSE UK52


°C UK52 bed 1
Mean = 23.04
Std. Dev. = 1.653
N = 13,309
Frequency
1,000
800
600
400
200
0
15
20
25
30
35
°C UK52 bed 1

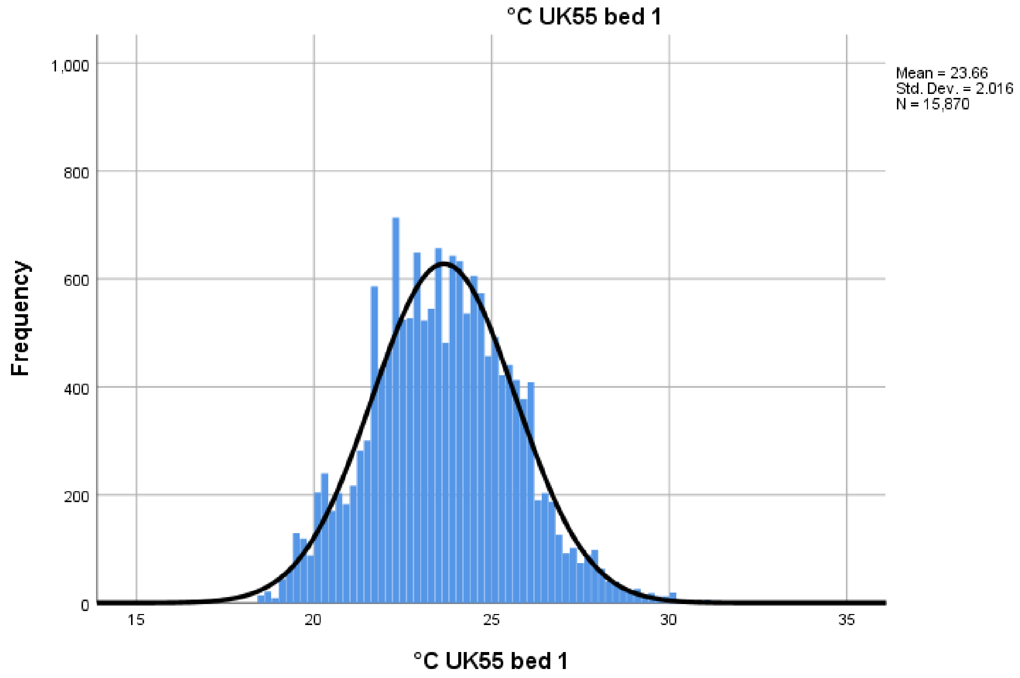

°C UK52 living
Mean = 21.34
Std. Dev. = 2.08
N = 13,309
Frequency
1,000
800
600
400
200
0
15
20
25
30
35
°C UK52 living

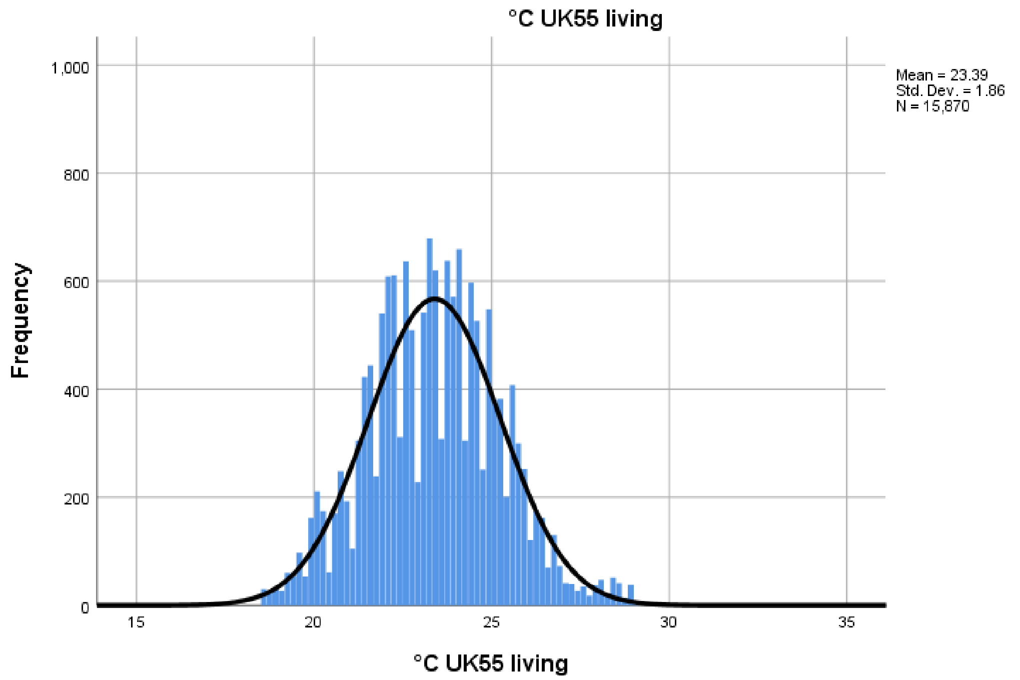
HOUSE UK54


°C UK54 bed 1
Mean = 22.13
Std. Dev. = 1.508
N = 15,901
Frequency
1,000
800
600
400
200
0
15
20
25
30
35
°C UK54 bed 1


°C UK54 living
Mean = 21.68
Std. Dev. = 1.279
N = 15,901
Frequency
1,000
800
600
400
200
0
15
20
25
30
35
°C UK54 living

HOUSE UK55


°C UK55 bed 1
Mean = 23.66
Std. Dev. = 2.016
N = 15,870
Frequency
1,000
800
600
400
200
0
15
20
25
30
35
°C UK55 bed 1


°C UK55 living
Mean = 23.39
Std. Dev. = 1.86
N = 15,870
Frequency
1,000
800
600
400
200
0
15
20
25
30
35
°C UK55 living

APPENDIX J – SUMMER GAINS/HEAT LOSS RATIO CALCULATION (APPENDIX P OF SAP)

Without going into de detail of the points 2 and 3, it seems worth to explore in detail what it is considered in the calculation of the SUMMER GAINS/LOSS RATIO (point 1). The SUMMER GAIN LOSS RATIO it is made up by the following formula:

$$\boldsymbol{SUMMER\ GAIN/LOSS\ RATIO} = \frac{\boldsymbol{G}}{\boldsymbol{H}} = \frac{G_i + G^{\substack{summer \\ solar}}}{H^{(summer) ventilation} + H^{(all\ year) fabric\ heat\ loss}}$$

Where **G SUMMER GAINS** is made by the sum of the internal gains and the solar gains:

$$G_i + G^{(summer)\ solar}$$

The internal gains [$\boldsymbol{G_i}$] in summer are assumed equal as in winter, and gains associated with heating systems are not included. In fact, for the purposes of SAP calculations, gains from MVHR are not added, because their effect is included in the MVHR efficiency: the specific fan power and heat exchange efficiency are multiplied by the appropriate in-use factor for specific fan power and In-use factor for efficiency. These values affect the air change rate and in an adjusted infiltration rate [BRE, 2014]. Even though it is stated that these factors will be updated as research on practical performance of MVHR systems is produced [BRE, 2014]., MVHR systems are an emerging market with products that update at very high speed.

In other words, for the purpose of SAP calculations, MVHR it is not considered as heating system, but the heat recovered is allowed for via an effective air change rate. It is only considered as a fan and the heat recovery is encountered as an adjustment of only the infiltration rate (not even the efficiency of the heating systems) [BRE, 2014]. And no mention of its efficiency is been found on the heating systems section in SAP worksheet.

Therefore the internal gains of the incoming air pre-heated by the heat exchanger (since most of the times there no summer bypass) it is not included.

Table A1: SAP internal gains list, heat gains in watts [BRE, 2014]

Source	(A) Typical gains
Metabolic	$60 \times N$
Lighting	equation (L9) in Appendix L
Appliances	equation (L13) in Appendix L
Cooking	$35 + 7 \times N$
Water heating	$1000 \times (65)_m \div (n_m \times 24)$
Losses	$-40 \times N$
Pumps and fans	Table 5a

The solar gains [$\boldsymbol{G}^{(summer)\ solar}$]is made up by the solar gains separately for each summer month, and separately for each orientation. The formula is made up by the climatic data provided and geometric information of the house.

- Mean global solar irradiance (W/m^2) on a horizontal plane, and solar declination (i.e. in the Midlands, the mean global solar irradiance for July is 194 W/m^2 and the solar declination for July is 21.2°
- Solar radiation on vertical and inclined surfaces, for 8 orientations (and tilt, using the given month's horizontal solar flux in W/m^2, including latitude in degrees and the declination for that given month.

H SUMMER LOSSES are made by the sum of the summer ventilation and the (winter) fabric heat losses.

$$H^{(summer) ventilation} + H^{(all\ year) fabric\ heat\ loss}$$

The procedure for calculating the summer ventilation [$\boldsymbol{H}^{(summer)ventilation}$] accounts for the air change rate (in ach) specified in a table and for different types of dwellings for different window opening position) and provides a figure ach/m3. To this and in case of mechanical ventilation (MV), it is possible to use the specified air change rate and volume of the house (MVHR not treated in this calculation).

Table A2: SAP effective air change rate, in ach [BRE, 2014]

Window opening	Effective air change rate in ach			
	Trickle vents only	Windows slightly open (50 mm)	Windows open half the time	Windows fully open
Single storey dwelling (bungalow, flat) Cross ventilation possible	0.1	0.8	3	6
Single storey dwelling (bungalow, flat) Cross ventilation not possible	0.1	0.5	2	4
Dwelling of two or more storeys windows open upstairs and downstairs Cross ventilation possible	0.2	1	4	8
Dwelling of two or more storeys windows open upstairs and downstairs Cross ventilation not possible	0.1	0.6	2.5	5

Not only no graphics are provided by these values, knowing that depending on the position of the ceiling, the effective air change rate of a windows (for instance tilted) can vary hugely.

The procedure for calculating the fabric heat losses [$\boldsymbol{H}^{(all\ year)fabric\ heat\ loss}$] is made up by the sum of the fabric heat loss (W/K) and the thermal bridges calculation (W/K).

The points above mentioned making one to do some considerations in regards to the risk of overheating as it is calculated in SAP, Appendix P.

APPENDIX K – OVERHEATING RELATED EVENTS ATTENDED

A component of the methodology of this PhD consisted in the attendance of a number of events (seminars/workshops/masterclass) that were held during the PhD timeframe. They provided a glimpse of what was going on the industry, academia and government.

date	event
12-06-2013	UCL Energy Institute Masterclass: BUILDING PERFORMANCE: THE BIGGER PICTURE, Bill Bordass and Adrian Leaman, Usable Buildings Trust
25-06-2013	GHA conference: Climate Change and Overheating: Opportunities and risks for Designers and the supply chain
10-09-2013	Urban Energy Research Group at Heriot Watt University: Low-carbon Futures project follow up
07-10-2013	Loughborough University research seminar: Integrating Indoor Air Quality and Energy Efficiency in Buildings, Bill Bahnfleth
10-06-2014	UCL research seminar: Energy and built form: geometry and history', Prof Philip Steadman
30-07-2014	BRE training: Part L, revision of awareness
07-11-2014	Leicester BSF workshop: Sustainability Lessons Learnt
12-12-2014	GHA Masterclass: Closing the Building Performance Gap
23-06-2015	Workshop: Overheating and Indoor Air Quality in new homes - Peterborough , organised by Homes and Communities Agency (HCA).
20-10-2015	UK Passivhaus Conference 2015, Business Design Centre, 52 Upper St, London N1 0QH
27-11-2015	7CEPH - 7ª Conferencia Española Passivhaus - 26 y 27 de noviembre del 2015 - Barcelona
26-04-2017	UKIEG 2017 Conference: Indoor Environments and Health in Buildings, Glasgow School of Art, Glasgow G3 6RQ

APPENDIX L – GENEROSITY OF PARTICIPANTS

This appendix serves to provide '*evidence*' of the generosity of the participants who patiently received the researched five times in each house. During the research period, their enthusiasm developed at times in jointed meals and later in friendships.