A study of the implications for the health of UK passive houses:

Investigating indoor climate and indoor air quality and understanding occupants' practices

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Submitted for the degree of Doctor of Philosophy

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July 2018

Abstract

Policies related to the reduction of both carbon dioxide emissions and energy consumption within the residential sector have contributed towards a growing number of passive houses and other highly energy-efficient dwellings being built in many countries. Since these dwellings are very well insulated and airtight, concerns have been raised over the quality of the indoor air and, consequently, the possible health effects for their occupants. Additionally, following well established evidence from the residential energy consumption literature, it has been considered vital to explore occupants' practices when trying to understand possible contributions to the quality of the indoor environment in passive houses, and thus any potential effects to the health of occupants. Nevertheless, very little research has explored this issue. This longitudinal, mixed methods, interdisciplinary study has collected and analysed qualitative data (from house occupants' interviews and diary) and quantitative data (from the monitoring of the indoor climate and indoor air quality) over three different seasons (winter, spring and summer) from different rooms in five passive houses and in four conventional (control) houses in the UK. Additionally, data has been compared with reviews of epidemiological, toxicological and other health related published studies to reveal the following: Passive houses can provide either a potentially healthy or unhealthy environment for their occupants, depending on the hazard being analysed. For instance, when analysing indoor temperatures, passive houses were found to be potentially healthy during cold months but potentially unhealthy during the summer. On the other hand, the analysis of relative humidity levels suggest that passive houses are potentially heathy during the summer and potentially unhealthy during the winter. Potential health risks in passive houses were caused by one or a combination of variables, including passive house design and construction and occupants' practices.

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Acknowledgements

I would like to give sincere thanks to all the families who participated in this research project. Without their willingness to talk about their everyday routines, to fill in activity diaries and to let the researcher place the monitoring equipment in their homes, this thesis would not have been possible.

I am also very grateful to the Housing Association, responsible for building and managing the passive house scheme, for allowing me access to the houses and for contributing financially to the research, by providing funds which were used towards buying part of the monitoring equipment.

A special thanks also goes to the other research organisation 'Spire Group', whose real name, unfortunately, I cannot reveal as I have to protect the identity of the research participants. Spire Group helped me greatly by booking the appointments with the households for interviews, installation/removal of monitoring equipment and for the collection of activity diaries. Since this was a longitudinal research project, their commitment to the study through the one year period is highly appreciated.

I also would like to thank the Engineering and Physical Sciences Research Council for providing the studentship which funded this research and to the Tyndall Centre for Climate Change Research which offered me the opportunity to understand and reflect on many themes directly or indirectly related to this research.

Thank you to all academics and colleagues from the University of East Anglia who supported me by offering great ideas for my research and for commenting and discussing some parts of my project. These include Dr Tom Hargreaves, Dr Jane Powell and Jonas Schoenefeld.

Many thanks to my three supervisors Dr Alan Bond, Dr Iain Lake and Eur. Ing. Gregory Luxford for guiding and supporting my research. A special thanks goes to Dr Alan Bond for being so patient and supportive, and for helping me to obtain the necessary funding for the monitoring equipment purchase and conference attendances.

I would like to give sincere thanks to all my close friends and family who have listened patiently to all my PhD struggles, always having something positive and comforting to say. I am very grateful for their kind words of encouragement, which made my PhD journey less overwhelming.

Finally, my most special thanks are reserved to my husband, Mark, and to my beautiful daughter, Sofia. Mark has, kindly and consistently, supported me through all stages of this PhD research. He, more than anyone, has believed in me, even at times when I doubted myself. Although it has been certainly challenging to undertake a PhD whilst being a parent to a very young daughter, Sofia has been my source of inspiration and motivation. Her smile, laughter, talks and songs provided me with

much joy during this process. Also, for me, completing a PhD study also meant that I could show my daughter that woman can indeed pursue their goals and fly very high.

Chapter 1 – Introduction to the thesis

In response to concerns about the impact of climate change, the UK government seeks to reduce the use of fossil fuels in order to meet ambitious greenhouse gas (GHG) reduction targets (UK Government, 2008). Special concern has been demonstrated in relation to the built environment since GHG emissions from heating and powering buildings represented 37% of the total emissions in the UK in 2011 (HM Government, 2011). More specifically, according to more recent figures on GHG emissions, the residential sector contributed around 12% of the UK's GHG emissions in 2014, with carbon dioxide being the most prominent emitted gas (DECC, 2016). Accordingly, carbon reduction policies have been applied to this sector in an effort to reduce this contribution. With the introduction of the Code for Sustainable Homes (CSH)[1] (Zero Carbon Hub, 2013) and the progressive tightening of the Building Regulations 'Part L' (HM Government, 2010b), passive houses[2] and other highly energy-efficient dwellings, built with high levels of thermal insulation and airtightness are on the rise. In recent years, however, debates over airtight buildings and the possible risks associated with poor indoor climate and indoor air quality have started to emerge (Bone et al., 2010; Offermann, 2010).

Although problems related to the indoor air quality in non-industrial buildings are not a new trend (Jones, 1999), with evidence showing associations between inadequate ventilation and highly polluted indoor environments going as far back as pre-historical times (Spengler & Sexton, 1983), it was only since the 1970's that the adverse effects of indoor air pollution have been increasingly investigated (Samet et al., 1987). One possible explanation for this may be that most of the public perceive the risks from poor air quality as being substantially higher outdoors than indoors (LHEA, 1997). However, research shows that people in developed countries spend an average of 87% of their time indoors (Leech et al., 2002; Klepeis et al., 2001), making indoor personal exposure to airborne pollutants very significant (Dales et al., 2008). Furthermore, because concentrations of some air pollutants are much higher indoors than outdoors (Kotzias, 2005), and many of these indoor pollutants are associated with acute and chronic health effects (Mitchell et al., 2007), maintaining good indoor air quality is therefore vital in order to prevent adverse health outcomes (Jones, 1999).

In addition to concerns related to indoor air quality, other studies have also pointed out that the quality of the indoor climate in non-industrial buildings can also influence the health and comfort of

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[1] The Code for Sustainable Homes is an environmental assessment method for rating and certifying the performance of new homes in England. In March 2015 the Code for Sustainable Homes was withdrawn by the Government in England. Some of the standards required by the Code became an optional part of the Building Regulations.

[2] Passive house is the term used in the UK which refers to the German 'Passivhaus' building standard. Further details regarding the passive house is provided in the Literature Review chapter.

building occupants (Mølhave, 1991; Mølhave, 1989; Skov et al., 1990). For instance a review of the literature (Jevons et al., 2016) shows the negative health effects of low indoor temperatures on house occupants, particularly on the elderly. Furthermore, home occupants can potentially be exposed to a large range of chemicals and other pollutants released from building materials, household products and furnishings (Spengler & Adamkiewicz, 2009).

These pollutants usually released in residential environments include three categories: 1. chemical exposure from tobacco smoke, household furnishings, occupants' activities and building materials; 2. biological contaminants exposure such as allergens and dust mites, which can also be the result of poor indoor climate (e.g. high relative humidity levels) and; 3. carcinogens exposure from radon gases and asbestos (Dales et al., 2008).

More recently, great concern has been demonstrated in relation to indoor climate (IC) and indoor air quality (IAQ) of energy-efficient housing, such as passive houses. This is due to the fact that these houses are more airtight than conventional houses and therefore the reduced air infiltration could potentially lead to a poor indoor environment quality since stale indoor air may not be replaced with fresh outdoor air at an adequate flow rate (Davies & Oreszczyn, 2012; Crump et al. 2009). Additionally, because these energy-efficient dwellings are built with more thermal insulation, there is an increased risk of indoor overheating (NHBC, 2012a).

Nevertheless, passive houses and many other highly energy-efficient dwellings incorporate a whole house balanced supply and extract mechanical ventilation with heat recovery (MVHR) system, which aims to provide continuous ventilation. Because energy-efficient houses are generally very airtight, this is seen as the key for achieving good indoor environment quality since continuous ventilation has the potential to dilute harmful pollutants and allergens and to maintain the indoor climate at comfortable levels (Dimitroulopoulou, 2012).

However, research on MVHR has already demonstrated that these systems are failing to perform as initially intended (Balvers et al., 2012). Other studies show that the ability of these systems to provide adequate indoor air quality depends on many factors such as the existence of user friendly controls (Stevenson et al. 2013) maintenance of the system (Lowe & Johnston, 1997), performance (Kurnitski et al. 2007) and operation (Park & Kim, 2012; Balvers et al., 2008; Stevenson & Rijal, 2008). Many of these factors place the MVHR user as a key determinant of the effectiveness of the system, contradicting some assumptions that domestic technologies will produce the expected results if they are installed and functioning well (Shove & Guy, 2000).

Studies suggest that in many cases, the under-performance of MVHR is closely related to how home occupants understand, operate and interact with the system (Kurnitski et al., 2007). Although the design, construction and installation of MVHR are important factors associated with its performance

(Balvers et al., 2012; Lowe & Johnston, 1997), these factors alone do not warrant the provision of acceptable indoor climate and indoor air quality in airtight homes.

As a result, there has been some scepticism on the ability of MVHR systems to achieve the recommended ventilation rates post occupancy, and consequently, concerns about the quality of the indoor environment and the possible impact on the health of house occupants started to emerge (Bone et al., 2010; Dimitroulopoulou, 2012).

Although the indoor environment of passive houses and other highly energy-efficient dwellings have received much attention in recent years, studies investigating these houses have mainly focused on their thermal performance from an energy efficiency perspective (e.g. Feist & Schnieders, 2009; Ridley et al., 2013; Larsen et al., 2012) and on the indoor comfort of occupants (Derbez et al., 2014a; Derbez et al., 2014b; Engelmann et al., 2013; Rohdin et al., 2014; Yao & Yu, 2012), whilst rarely addressing their indoor climate and indoor air quality from a health viewpoint. Since there have been concerns over the quality of the indoor environment in very airtight dwellings, it has been considered vital to investigate the indoor environment in these houses, by redirecting the focus of the study from the energy efficiency and indoor comfort aspects, to the possible health effects on occupants.

Additionally, when investigating the indoor environment of passive houses or other highly energy-efficient dwellings from a health perspective, it was also considered very important to understand the role of occupants' everyday practices in contributing to the quality of their indoor environment. The importance of occupants' everyday practices was highlighted by the literature on 'practices and behaviours and domestic energy consumption'(Hargreaves et al., 2013; Firth et al., 2008; Owens & Driffill, 2008). Research exploring occupants' practices and the possible effects on energy consumption show that there is a significant gap between the predicted and the actual energy performance of buildings, since occupants' practices can vary to a great extent (Fabi et al., 2012; Socolow, 1978). Evidence shows that intended energy reduction outcomes in buildings may not be achieved as initially planned and in some cases any attained energy savings are short lived (Van Dam et al., 2010). This performance gap in energy consumption suggests that any possible benefit from the use of domestic technology solutions may be significantly reduced, or even invalidated as a consequence of occupants' practices (Pilkington et al., 2011).

Similarly, it is important not to assume that sufficient ventilation will be provided in passive houses as long as they are provided with an efficient, and in good working order, MVHR system. It is also important to understand how home occupants, living and interacting with MVHR technology and other ventilation and home technologies (e.g. windows, house appliances) in passive houses or other highly energy-efficient dwellings may contribute to the quality of their indoor environment.

Among many theoretical approaches to understand individuals and their behaviours (Wilson & Dowlatabadi, 2007), social practice theory offers a suitable framework for the understanding of how the routinised practices of everyday life, including those which involve interactions between building occupants and domestic technologies, may affect their immediate environment (Foulds et al., 2013; Strengers & Maller, 2011). Whilst behaviour theories from both the psychology and economic disciplines place the individual, their attitudes, behaviours and choices at the centre of discussion (Wilson & Dowlatabadi, 2007), social practice theory focuses on the practice itself, rather than on the individuals who perform them (Shove & Walker, 2010). This theoretical approach however, does not invalidate the individual, their beliefs, attitudes and values, as these are cultivated within and arising from the practices themselves (Strengers, 2012). As argued by Schatzki (2001, p. 12) "practices are the source and carrier of meaning, language, and normativity".

Therefore, the objective of this thesis is to determine whether passive houses provide their occupants with a healthy indoor environment, and to understand how occupants' practices may contribute to the indoor climate and indoor air quality in their homes.

There are many studies investigating the indoor environment of passive houses and other highly energy-efficient dwellings from an energy efficiency or occupant comfort viewpoint. There is also a well-established relationship between domestic energy consumption and occupants' practices. However, there are few studies investigating the indoor environment of passive houses from a health perspective. There is also very limited research exploring the role of occupants in contributing to the quality of their indoor environment and consequently, to their health.

It is from this position that the thesis has the following research aim, followed by three research objectives:

Research Aim:

To investigate the possible health implications of passive houses and to understand how occupants' practices may contribute to the quality of their indoor environment, and their health.

Research Objectives:

1. **To investigate the indoor climate and indoor air quality of passive houses, from a health perspective.**
2. **To analyse whether passive houses provide a healthy environment to their occupants.**

3. **To understand how occupants' everyday practices may contribute to the indoor climate and indoor air quality in their passive houses, and consequently how these may affect their health.**

In trying to achieve the aim and objectives, this research study makes three main contributions to the research field of the indoor environment of highly energy-efficient dwellings: empirical, methodological and theoretical. Empirically, it shows possible differences in the indoor environment quality of different rooms in the same passive houses, taking into consideration possible variations following changes in the weather season. It also shows how the indoor environment quality of passive houses compare with conventional, less airtight houses. It provides a new viewpoint for empirical analysis as indoor environmental data are collected and analysed from a health perspective. Methodologically, it uses a mixed method research approach which not only aims to investigate the indoor climate and indoor air quality in passive houses but also attempts to understand how the findings observed there may be influenced by occupants' everyday practices. Although a mixed method research approach has been previously used by researchers investigating the indoor environment of highly energy-efficient dwellings, the approach used here, and further explained in the Methodology Chapter, is potentially the first one, which explores the indoor environment of passive houses and occupants' everyday practices from a health viewpoint. Theoretically, it makes a contribution by applying social practice theory concepts to the social context of the indoor climate and the indoor air quality of passive houses. Again, although social practice theory approaches have been previously used within the domestic environment of highly energy-efficient dwellings, this is the first time, that this theoretical lens has been used to gain insights into the social context around the indoor climate and indoor air quality of passive houses from a health perspective.

Accordingly, this thesis is divided into the following chapters:

Chapter 1: Introduction to the thesis

Provides the overall direction of the thesis and explains how it is structured.

Chapter 2: Research Context

Explains the context of the study being undertaken, establishing a research gap within the published literature exploring passive houses and other highly energy-efficient dwellings.

Chapter 3: Methodology

Presents the methodological design used in the thesis and discusses the merits of a mixed methodology approach as well as the reasoning behind the use of a case study design. It follows by presenting the case study used as well as the methods of data collection and analysis.

Chapter 4: The indoor climate and indoor air quality in passive house rooms: an investigation from a health perspective

Investigates the indoor climate and indoor air quality of different rooms (main bedroom, living room and kitchen) in passive houses and control houses during three weather seasons (winter, spring and summer) from a health viewpoint, aiming to fulfil the first objective of the thesis.

Chapter 5: The health of passive house occupants

Aims to fulfil the second objective of the thesis, by analysing whether passive houses provide their occupants a healthy indoor environment. This is attempted by analysing the indoor climate and indoor air quality data findings from the previous chapter in conjunction with the findings from the review of the epidemiological, toxicological and other health related published literature.

Chapter 6: Indoor environment quality in passive house rooms: understanding the possible influences of occupants' practices

Aims to fulfil the third objective of the thesis. It starts by introducing how social practice theory is applied within the context of the indoor environment of passive houses. It follows by analysing the different social practices undertaken by five families in three different passive house rooms may have contributed to differences in indoor climate and indoor air quality. It also analyses how the four interconnected elements of practice have shaped the practices they are part of, and in turn, how they have influenced the findings from the indoor environment monitoring.

Chapter 7: Conclusions

Integrates the three separate conclusions from Chapters 4 to 6, aiming to answer the central research question. The chapter also provides a reflection on the methodology used as well as on the constraints encountered during the research process. Additionally, the applicability of the findings to housing providers, MVHR manufacturers, passive house designers and building codes is considered. The potential for future research is also discussed.

Chapter 2 – Research context

This chapter provides the background context to this thesis, and in particular, the context which underpins the research aim and objectives. It begins by presenting a definition of the term 'passive house', followed by an introduction of the passive house common design characteristics. It also presents the four main drivers which are encouraging the construction and refurbishment of dwellings to passive house standards.

This chapter follows by presenting and discussing the main concerns associated with these highly energy-efficient dwellings and by clarifying the current gap in the literature. Finally, drawing from the domestic energy consumption literature, it is argued that there could be a gap between the predicted and the actual indoor environment quality of passive houses and that variances in occupants' everyday practices could help to explain this possible gap.

2.1. Passive house: definition, common design characteristics and drivers

2.1.1. Definition

Passive house is the term used in the UK which refers to the German 'Passivhaus', an internationally acknowledged building standard for thermal comfort and energy efficiency (International Passive House Association, 2010). The passive house was developed in Germany by Wolfgang Feist during the late 1980's, with the first passive house building built in central Germany in 1991 (Feist & Schnieders, 2009). The main objective of the passive house standard is to create buildings with minimal requirements for space heating and cooling, and consequently minimal overall energy consumption (International Passive House Association, 2010). Passive house standard buildings require no more than 15 kWh to heat each square metre of living space, which can correspond to a 90% reduction of heating energy consumption when compared to a conventional building (Feist & Schnieders, 2009). The passive house concept also aims at the provision of "an acceptable and even improved indoor environment in terms of indoor air quality and thermal comfort" (Feist et al., 2005, p.1187).

2.1.2. Common design characteristics

Since the main objective of the passive house building standard is to minimise the overall energy consumption of building, there are some well-established common design principles employed by designers to achieve these minimum requirements for energy efficiency. The list below shows some of these:

a) High levels of thermal insulation

Passive house design seeks to minimise energy consumption by reducing energy losses through the building fabric. In helping to achieve this, passive houses use high levels of thermal insulation within the building envelope. The passive house guidelines recommend that U-values[3] of walls, floor and roof should be equal or lower than 0.15 watts per square metre kelvin (W/m^2K). Such low U-value requires the use of exceptionally high levels of thermal insulation, a technique which has become known as superinsulation (Smith, 2005).

b) Triple-glazing windows

Since high thermal insulation within the building envelope is vital in maximising the building thermal performance, the passive house building standard dictates the use of low-e (or low emissivity), triple-glazing windows with insulated frames, which have a U-value less than 0.85 W/m^2K (International Passive House Association, 2010).

c) Minimal air permeability

Air permeability, measured in m^3/m^2 hours at a pressure of 50 Pascal (Pa), is the physical property used to measure airtightness of the building fabric (HM Government, 2010b). Air permeability could also be referred to as 'air leakage index' (Stephen, 2000). However, this is different from 'air leakage rate' (calculated at air flow rate at 50 Pascal and divided by the internal volume of the dwelling) expressed in units of air changes per hour (ACH) (Pan, 2010). Airtightness within the building fabric is considered an essential factor for the reduction of energy losses in energy efficient buildings (Kalamees, 2007). This is based on the fact that heat losses can be significantly minimised by the avoidance of uncontrolled air flows through the external envelope of the building. This includes holes and cracks in the building external fabric as well as air gaps in the junction between external building elements (e.g. wall and window) and service penetrations. The current 'Approved Document Part L – Conservation of fuel and power' of the Building Regulations sets a maximum allowance for air permeability in new residential buildings of 10 m^3/m^2 hour at 50 Pa, or approximate 10 ACH (air changes per hour) (HM Government, 2010b). However, the passive house standard dictates a much lower air permeability rate of less than 0.6 ACH (International Passive House Association, 2010).

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[3] "A U-value is a measure of the overall rate of heat transfer, by all mechanisms under standard conditions, through a particular section of construction"(McMullan, 2002, p.43).

d) Mechanical Ventilation with Heat Recovery (MVHR) system

MVHR are continuous mechanical supply systems which provide both extract and whole house ventilation. They work by extracting moist and stale air from bathrooms and kitchens, passing it through a heat exchanger, immediately ducting it outside. Meanwhile, fresh outside air is drawn in, filtered, warmed up through the heat exchanger and ducted to internal rooms, such as bedroom and living spaces. The heat recovery element recycles the energy which would be otherwise lost, using it to heat the incoming air (Mardiana-Idayu & Riffat, 2012). Research shows that domestic energy efficiency can be remarkably improved with heat recovery technology (Jokisalo et al., 2003). The passive house standard prescribes a heat recovery efficiency equal or higher than 75% for MVHR systems. Some systems will also provide an option for the external ducted air to bypass the heat exchanger. This feature is called 'summer by-pass'. The use of summer by-pass is recommended during the summer season, as it overcomes the issue of hot air being returned to the dwelling, causing possible overheating.

e) Passive solar design

Passive solar design refers to the use of the energy from the sun to heat living spaces. The design aims to heat parts of the building during the winter months and to limit solar gains during the summer months. Passive house building standards recommend designers to optimise solar gains entering the building through glazed areas (International Passive House Association, 2014). This involves consideration of the building location, solar orientation and size of glazed areas.

During warm periods, it is recommended that solar gains are minimised by the use of shading devices, such as roof overhangs, blinds, shutters and horizontal shading, to avoid internal overheating. Passive solar heating is a carbon neutral technology (Pilkington et al., 2011), which does not require the use of any mechanical equipment for its functioning.

2.1.3. Passive house drivers

There are many drivers for the rise of the passive house standard and other highly energy-efficient dwellings worldwide. However, in the UK, there are four main drivers which are encouraging the construction and refurbishment of dwellings to passive house standards. First, due to concerns over the negative effects of climate change, the UK government is committed to reduce greenhouse gas (GHG) emissions by at least 80% below base year levels by 2050 (HM Government, 2011). With the residential sector contributing to around 25% of GHG emissions, home energy efficiency is seen as a vital part of the national emissions reduction targets (HM Government, 2011). Second, the national

Fuel Poverty Strategy has been targeting to improve the energy efficiency of dwellings, aiming to provide warm, comfortable and healthy homes as well as eradicating domestic fuel poverty, especially among the more vulnerable population (HM Government, 2015). Third, concerns related to energy security in the UK have highlighted the need to reduce the demand for imported energy from fossil fuels. Achieving significant improvements in the energy efficiency of the UK's housing sector would help in reducing energy imports and, therefore, would contribute towards national energy security (Aldous & Whitehead, 2016). Fourth, the uncertainties surrounding the possible increase in energy costs, which would particularly affect the affordability of energy in vulnerable households, have placed home energy efficiency as the most logical way to turn the problem around (Hoggett et al., 2011).

2.2. What are the concerns associated with passive houses and other highly energy-efficient dwellings?

2.2.1. Airtightness and ventilation

Buildings are now being designed and constructed with greater airtightness following the latest requirements of the Building Regulations (HM Government, 2010; Jaggs & Scivyer, 2009). The passive house standard and highly energy-efficient domestic buildings demand even greater airtightness to be able to deliver highly energy efficient performance (Kalamees, 2007). However, increasing concerns have been raised regarding the impact of airtight dwellings on the quality of the indoor environment, and consequently, possible effects on the health of the occupants (Bone et al., 2010; Howieson, 2014; Yu & Kim, 2012). These concerns are based on the fact that airtight dwellings do not provide (or provide minimum) ventilation through air infiltration gaps in their external building fabric. This shows a great contrast with many standard homes in the UK, where ventilation rates are also introduced by uncontrolled air leakage in the building envelope. For instance, a BRE database shows that the UK dwellings are very air-leaky (Stephen, 2000). A sample of 471 dwellings of different size, age and type of construction was used. The mean air permeability was calculated as 11.5 m^3/m^2hour at 50 Pa with the air permeability of individual dwellings ranging significantly (from 2 to 29 m^3/m^2hour at 50 Pa). Similar findings were obtained by Dimitroulopoulou et al. (2005), where in a sample of 37 homes built since 1995, 70% of them had air permeability rates greater than 10m^3/m^2 hour at 50 Pa. Although these studies cannot be claimed to be representative of all UK housing stock, they show that many existing UK homes have air permeability rates over the current maximum mandatory requirement of 10m^3/m^2 hour at 50 Pa, set by the Building Regulations.

Therefore, there has been a step-change in building airtightness from the existing UK housing stock to the more energy-efficient schemes being currently designed and constructed. Traditional UK housing has high levels of air permeability, being ventilated by a combination of purpose-provided[4] ventilation and air infiltration. However, with stricter mandatory requirements regarding air permeability rates (HM Government, 2010b) and high fabric energy efficiency performance targets (Zero Carbon Hub, 2013), new buildings following such standards, can no longer depend on air infiltration through joints and cracks in the building fabric for their ventilation supply. As a consequence, passive houses and other highly energy-efficient dwellings are being designed and built with full reliance on purpose-provided ventilation devices, such as MVHR systems.

The significant increase in airtightness and the great dependence on MVHR systems for the provision of adequate ventilation generates two types of concerns. The first concern is related to the fact that homes are becoming sealed structures, which raises fears over the quality of the indoor environment. The second concern regards the ability of the MVHR system in maintaining adequate ventilation and therefore, providing good indoor climate and indoor air quality. Specific concerns over the ability of the MVHR system in providing an adequate indoor environment will be discussed in section 2.3.

Regarding the first point, airtight buildings generate immediate concerns over insufficient ventilation supply and the possible negative consequences on the indoor environment. This is due to the fact that adequate ventilation is an effective means of protecting building occupants from indoor pollutants (Wargocki et al., 2002). Ventilation is considered essential for the dilution and removal of indoor-generated air pollutants (Seppänen & Fisk, 2004) and important for the comfort and health of home occupants (Sundell et al., 2011). Research assessing the role of ventilation in buildings show consistent association between low ventilation rates and adverse health effects (Bornehag et al., 2005; Øie et al., 1999; Stenberg et al., 1994; Sundell et al., 1994).

In the UK the 'Approved Document Part F' of the Building Regulations provides guidance on the requirements for the provision of adequate ventilation (HM Government, 2010a). In addition, it has been accepted that a whole house ventilation rate between 0.5 and 1.0 ACH is adequate in energy efficient homes (DETR, 2005). Although there is little information available regarding the health effects of measured ventilation rates, the recommended minimum of 0.5 ACH is supported by studies concluding that rates below this figure are a health risk in Nordic residences (Sundell et al., 2011; Wargocki et al., 2002). This conclusion was based on the ventilation rates necessary to provide

[4] Purpose-provided ventilation refers to the controlled exchange of indoor and outdoor air in a building via purpose-built devices such as background ventilators, passive stack ventilation, extract fans, mechanical ventilation, etc. (HM Government, 2010b).

homes with a low relative humidity to reduce house dust mite infestation, which are linked with asthma and allergies.

However, while minimum requirements for ventilation rates do exist, and are an integral part of the Building Regulations, there has been much uncertainty about the ventilation rates achieved in practice in passive houses and other highly energy-efficient dwellings and the possible consequences of any shortfall (Bone et al., 2010). These concerns are not only shared by the scientific community, but they are also held by the general public. For instance, research conducted by Davis and Harvey (2008) explored the views of homeowners and house builders on energy efficient housing. It highlighted the concerns of both groups over the possible adverse effects of increased airtightness on the quality of the indoor environment. While home owners feared that airtightness could restrict access to fresh air and ventilation, house builders expressed concerns over possible adverse health effects caused by the lack of ventilation and potential condensation. Similar worries were also demonstrated by others (Hemsath et al., 2012; Bone et al., 2010; Offermann, 2010). Bone et al. (2010) questioned whether occupants' health would be harmed by the drivers for energy efficient homes, whereas Hasselaar (2008) investigated complaints made by passive house residents about perceived health risks in their homes.

Many studies exploring the concerns associated with airtightness and insufficient ventilation in buildings have linked these issues with possible indoor climate and indoor air quality problems and the possible consequent adverse health effects.

The following two sections will discuss in detail these areas: Section 2.2.2 will identify and describe the most common types of air pollutants found in homes and their sources. Section 2.2.3 will explore concerns associated with the indoor climate in dwellings. Subsequently, section 2.2.4 will explore the current knowledge on indoor climate and indoor air quality and health in passive houses and other highly energy efficient homes to help to identify existing gaps in knowledge and subsequent research questions.

2.2.2. Indoor air quality

Although for a long time, air quality concerns were strongly related to the outdoor environment, as air pollution was perceived to be higher outdoors than indoors (LHEA, 1997), this trend has now changed. During the past few decades, there has been increasing interest within the scientific community over the quality of the indoor environment (Jones, 1999). The attention given to the indoor environment may be attributed to two important findings. First, research shows that people in developed countries spend on average 87% of their time indoors (Leech et al., 2002; Klepeis et al., 2001). Second, air quality reports show that air pollution is consistently two to five times higher indoor than outdoors (Hess-Kosa, 2012). As a result, personal exposure to indoor airborne pollutants began to be considered very significant to human health (Dales et al., 2008), and consequently, research exploring indoor air quality in buildings and possible health outcomes started to rise (Raw et al., 2004; Daisey et al., 2003; Ferng & Lee, 2002).

Researchers are now concerned with whether buildings are maintaining appropriate levels of indoor air quality, or as defined by Rousseau (2003, p.A-3) whether indoor environments are "absent of air contaminants which may impair the comfort and health of buildings occupants". Since people spend most of their time in their homes (Klepeis et al., 2001), residential buildings are considered a highly important contributor to personal air pollution exposure (Liu et al., 2007). Accordingly, studies on IAQ and pollution exposure have explored three important areas. First, they have identified the most common types of pollutants found in homes and their possible sources. Second, they have identified possible health consequences of human exposure to these pollutants. Third, research has tried to establish safe threshold levels to indoor pollution exposure.

Regarding indoor air pollution, there are three categories of pollutants/exposure: 1. chemical exposure; 2. biological contaminants exposure and; 3. carcinogens exposure (Dales et al., 2008). Whereas the source of indoor air pollution can be classified into another main three categories: 1. materials; 2. occupants' activities and life styles; and 3. outdoor pollutants. These are detailed in table 2.1.

Although allergen, dampness and mould are included in table 2.1 of indoor pollutants, since their occurrence is largely determined by the indoor climate condition (e.g. level of indoor air relative humidity and/or temperature) (Fletcher et al., 1996), these contaminants will be further explored in the next section 2.2.3 under the heading 'indoor climate'.

Main pollutants			Sources
Chemical	**Biological**	**Carcinogens**	
Carbon Monoxide (CO)			Combustion of fuel, tobacco smoke
Carbon Dioxide (CO_2)			People, indoor plants
Nitrogen Dioxide (NO_2)			Combustion of fuel, tobacco smoke
Formaldehyde			Off- gassing from wooden based products, cleaning products, cosmetics, tobacco smoke
Volatile Organic Compounds (VOC)			Tobacco smoke, consumer products, building materials, wood-based furniture/furnishings
Particulate Matter (PM)			Tobacco smoke, cleaning and cooking activities
	Allergens		Furry pets and dust mites
	Dampness and mould		Mould growth caused by leaks in the building fabric, condensation)
		Radon	Contaminated soil

Table 2.1 Indoor pollutants and their sources

a. Carbon monoxide (CO)

Carbon monoxide is a toxic odourless and tasteless gas emitted by the incomplete combustion of fuel (Jones, 1999). It is a poisonous gas because it prevents the blood from transporting oxygen around the body, by binding itself to the blood haemoglobin (Horner, 1998). The main sources of CO in homes are from water and gas heaters, gas stoves and tobacco smoke. When these emissions sources are absent, concentrations of CO are generally lower indoors than outdoors (Jones, 1999).

b. Carbon dioxide (CO_2)

Carbon dioxide is a colourless, odourless gas, being naturally present in the air. It is also widely used as an indicator of ventilation rate (Bekö et al., 2009), providing information on the adequacy of fresh air supplied to occupied spaces. Building occupants are the main sources of CO_2 in homes (Seppänen & Fisk, 2004) as they inhale oxygen and expel carbon dioxide as a waste product. In airtight buildings, the exhaled CO_2 from occupants can build up, making indoor concentrations greater than outdoors (Hess-Kosa, 2012). CO_2 is normally a harmless gas, unless concentrations reach levels well in excess of those typically found in indoor air quality assessments (Hess-Kosa, 2012). The typical indoor air concentration of CO_2 is between 500 and 1500ppm (Seppänen & Fisk, 2004). However, minimum ventilation rate standards and guidelines list a maximum acceptable indoor carbon dioxide concentration of 1000 ppm (ASHRAE, 1989). It is suggested that when CO_2 concentrations in the air are increased up to 3000 ppm, human capacity to concentrate is reduced (Kajtar et al., 2003). In the indoor environment plants were found to reduce CO_2 concentrations to a certain extent during the day (Cetin & Sevik, 2015).

c. Nitrogen Dioxide (NO_2)

Nitrogen dioxide is a water soluble gas, red to brown in colour, with a pungent acrid odour (Jones, 1999). Because it is formed by a combination of nitrogen and oxygen during combustion at high temperatures, the sources of NO_2 in homes have been frequently associated with gas appliances, such as gas stoves and gas heaters. NO_2 is a predominantly indoor pollutant, known for being an airway irritant especially dangerous to vulnerable groups such as asthmatics, young children and the elderly (Nitschke et al., 1999).

d. Formaldehyde (H_2CO)

Formaldehyde is a very volatile organic compound (VVOC), which is often considered separately from other VOCs since it is not detected by the gas chromatographic methods typically applied to the analysis of volatile organic compounds (Maroni et al., 1995). At room temperature, formaldehyde is a colourless gas with a pungent odour. The most common sources of formaldehyde in homes are from off-gassing emissions from building materials and furnishings containing formaldehyde-bonded resin (Dales et al., 2008). This includes plywood, particle board, floor boards and wall panels. Other sources of formaldehyde are tobacco smoke, certain paints, varnishes and floor finishes. Formaldehyde is also used in personal hygiene products (perfume, deodorant , etc.) and cleaning products (detergents, disinfectants, etc.) (Hess-Kosa, 2012). This gas is widely known to be an irritant to the eye and to the upper and lower respiratory airways (Wolkoff & Nielsen, 2010).

e. Volatile Organic Compounds (VOCs)

The World Health Organization's definition of volatile organic compounds include all organic compounds (substances made up of predominantly carbon and hydrogen) with a melting point below room temperature and a boiling point ranging from 50°C to 260°C (WHO, 1989). Thousands of chemicals belong to this group, with over 900 different compounds identified in indoor air (Maroni et al., 1995). Major sources of VOCs are tobacco smoke, personal hygiene and cleaning products and room deodorisers (Torén & Hermansson, 1999). Other sources are wet paints and new carpets (Hodgson, 2000). Home and office environments can contain VOC concentrations 2 to 100 times higher than those found outdoors (Hess-Kosa, 2012). Exposure to volatile organic compounds in homes have been linked to respiratory symptoms (Norback et al., 1995).

f. Particulate Matter (PM)

Particulate matter consists of a mix of organic and inorganic substances such as aromatic hydrocarbon compounds, trace metals, nitrates and sulphates (Maroni et al., 1995). These particulates range in sizes, but the most common within indoor air quality studies are $PM_{2.5}$ and PM_{10}. $PM_{2.5}$ and PM_{10} can be defined as a particulate with mass that passes through a size-selective orifice with a 50% collection efficiency cut-off at 2.5µm and 10µm aerodynamic diameter respectively (Crump et al., 2002). Particulate matter can be generated from occupants' activities at homes such as cleaning, smoking tobacco and cooking (Zero Carbon Hub, 2012). PM generated indoors tend to be inhaled and deposited in the nasal, pharyngeal and laryngeal regions of the respiratory system, contributing to respiratory diseases (Bernstein et al., 2008).

g. Radon

Radon is an odourless and colourless radioactive noble gas which is produced from the natural breakdown of the uranium found in rocks and soils. This gas emerges from soil and rocks, entering homes mainly through openings and cracks in the building foundation (Fuller-Thomson et al., 2000). When radon gas emerges from the ground, it produces decay products in the air, which when inhaled, may contribute to adverse health effects, such as the development of lung cancer (Yamada, 2003). The amount of radon is measured in becquerels per cubic metre of air (Bq/m^3) (WHO, 2000). Although in the past it was believed that radon exposure was a problem only for uranium and phosphate miners (Jones, 1999), today it is recognised that most people are exposed to low and moderate radon concentrations in their homes (WHO, 2000). Indoor radon surveys show that the average of radon concentrations in dwellings is between 20 and 150 Bq/m^3. For England and Wales, the target level of 100 Bq/m^3 is the threshold for remedial works in existing buildings and protective measures in new buildings (Public Health England, 2010). Therefore, indoor air pollution from radon is less likely to occur in newly constructed dwellings, as these are normally provided with protective measures (e.g. radon barrier) when the risk of radon contamination is detected.

2.2.3. Indoor Climate

Research exploring the indoor climate of buildings and its possible associations with the health and comfort of occupants are not a new trend. There are many studies dating back to the 1980's and 1990's which investigate building occupants' health and comfort complaints and their associations with poor indoor climate in office buildings (e.g. Mølhave, 1989; Mølhave, 1991; Skov et al., 1990). In regards to indoor climate in dwellings, research has shown that temperature and relative humidity are important indoor parameters when considering the health and comfort of home occupants (Howieson et al., 2003; Strachan & Sanders, 1989; Ormandy & Ezratty, 2012). For instance, Collins (1986) has shown that very low indoor temperatures in dwellings can contribute to morbidity in the elderly, whilst a literature review undertaken by Baughman & Arens (1996) shows that high indoor relative humidity can contribute to the proliferation of biological agents in homes. This consequently contributes to allergic diseases such as asthma and rhinitis (Andersen & Korsgaard, 1986).

The main biological pollutants and other agents associated with indoor climate conditions are the following:

a. Allergens

The most common source of allergens in homes are furry pets and dust mites (Dales et al., 2008). House dust mites can develop in environments with relative humidity (RH) as low as 55%, however they will reproduce more rapidly when RH is over 75% and internal temperature is in the region of 25°C (Crump et al., 2002). Therefore warm and moist conditions favour the development and increase in the number of dust mites in homes, whereas dryer and cooler conditions will tend to lower the levels of mites (Crump et al., 2002). House dust mite allergen is considered one of the most important factors related to the development of asthma worldwide (Niven et al., 1999).

b. Dampness and mould

Environments with high relative humidity are ideal for the growth of mould, a type of fungi. Thus, it is accepted by some authors that relative humidity in homes should be kept below 60 to 70% to avoid the mould growth (Crump et al., 2002). Mould growth can be caused by water leaks in the roof, pipes and in the building envelope, as well as from condensation in the building. Many studies provide an association between the presence of dampness and mould in homes and the occurrence of respiratory conditions (Peat et al., 1998; Niven et al., 1999). These associations may be explained by home occupants' allergies to fungi (Fuller-Thomson et al., 2000).

c. Bacteria and virus

The survival and infectivity of respiratory viruses are especially dependent on indoor climate parameters such as temperature and relative humidity (Hersoug, 2005). For instance, findings from Myatt et al. (2010) show that the influenza virus in the air and on surfaces is controlled by moisture levels, with the lowest level of survival in the range of 40% to 60% of relative humidity. Similarly, other studies have shown a consistent association between the survival of air-borne bacteria and relative humidity levels (Dunklin & Puck, 1948; Mancinelli & Shulls, 1978).

Since indoor temperature and relative humidity levels have been associated with the survival and proliferation of biological agents, which in turn can contribute to ill health, there has been some concerns over the quality of the indoor climate of passive houses and other highly energy-efficient dwellings (Hemsath et al., 2012; Howieson, 2014). These concerns are based on the uncertainty of very airtight indoor environment providing to the occupants adequate levels of relative humidity and adequate temperature.

Furthermore, in more recent years, the indoor climate of highly energy-efficient dwellings (including passive houses) became the centre of much attention and concern as many studies have reported that the indoor environment of these well-insulated buildings may overheat during warmer weather seasons (Artmann et al., 2008; Badescu et al., 2010; Mlakar & Strancar, 2011), which could not only adversely affect the thermal comfort of occupants but it could also potentially harm their health.

2.2.4. Indoor environmental quality (IEQ) and comfort

The quality of the indoor environment in buildings has been identified as a great influence on occupants' comfort (Frontczak & Wargocki, 2011). In relation to indoor climate, thermal comfort stands out as one of the most important parameters of IEQ (Al horr et al., 2016).

Other comfort parameters (e.g. visual, acoustic, and perceptual) are also discussed within the literature. However, although visual and acoustic comfort can be influenced by IEQ, they are less characterised by the indoor climate parameters or any other parameters (e.g. indoor air quality) explored in this thesis. For instance, visual comfort, "a subjective condition of visual wellbeing induced by the visual environment" (EN 12665, 2002, in Frontczak & Wargocki, 2011, p. 925), is characterised by luminance distribution, illuminance and its uniformity, glare, colour of light, amongst others (EN 12464-1, 2002). Acoustic comfort, “a state of contentment with acoustic conditions” (Navai & Veitch, 2003, p. 655) is characterised by sound pressure level and sound frequency, which is influenced by physical building properties such as sound insulation and sound absorption (Cowan, 1994). Therefore visual and acoustic comfort are not discussed as part of this literature review.

In relation to thermal comfort, it has been defined by ASHRAE Standard 55 as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (in Frontczak & Wargocki, 2011, p. 925). As such, the majority of studies on thermal comfort are undertaken when building occupants are awake, performing certain activities and able to answer a questionnaire (Rupp et al., 2015). Nevertheless, some studies assessing thermal comfort during sleep were also found within the literature (e.g. Lin & Deng, 2008; Dongmei et al., 2013).

Currently, there are two different approaches for the definition of thermal comfort: the rational or heat-balance approach and the adaptive approach.

The rational or heat balance approach is based on the works of Fanger (1970), which uses climate chamber studies to support its theories of heat balance combined with the physiology of thermoregulation. According to this model, the human body uses physiological processes such as sweating and shivering to maintain heat balance, which is the first step to achieve a neutral thermal sensation (Charles, 2003). The works of Fanger (e.g. Fanger, 1970; 1967) which aimed to predict conditions where thermal neutrality would occur, contributed to the development of the seven-point ASHRAE thermal sensation scale, known as ‘Predicted Mean Vote’ (PMV) index and the ‘Predicted Percentage of Dissatisfaction’ (PPD) index.

PMV is used by thermal comfort standards in order to recommend acceptable thermal comfort conditions. It is calculated by using six variables: metabolism, clothing, indoor air temperature, indoor mean radiant temperature, indoor air velocity and indoor air humidity. Subjects in climate chambers are asked to give their opinions according to a seven-point scale of thermal comfort (-3 to +3). The mean vote (MV) is then obtained for a certain variable by calculating the mean value of the feeling expressed by all the subjects. PMV is related to the imbalance between the heat flow required for optimum comfort at a specific activity and the actual heat flow from the human body in a particular environment. PMV is expressed by the following equation, where L is the thermal load on the body (the difference between internal heat production and heat loss to the environment) and α is the sensitivity coefficient:

$$PMV = [0.303 \exp(-0.036M) + 0.028]\, L = \alpha L$$

PPD is used for the prediction of the percentage of people who felt uncomfortable about the environment. Using the thermal comfort scale (-3 to +3), Fanger (1970) considered those who responded ±1 and 0 comfortable whilst considering those who responded ±2 and ±3 as uncomfortable. The percentage of subjects who were considered uncomfortable is calculated for each variable of PMV. The relationship between PPD and PMV is given by the following formula:

$$PPD = 100 - 95 \exp [0.03353\ PMV^4 + 0.2179\ PMV^2)]$$

The PMV-PPD model has been widely accepted and used within the field of thermal comfort in the built environment (Lin & Deng, 2008).

The adaptive approach is based on the works of Nicol & Humphreys (1973; 2002; 2010), Dear et al. (1997), Dear & Brager (1998) and Auliciems (1981). Their methodology moves away from the climate chamber studies by adopting a field study approach, where the acceptability of the thermal environment is strongly dependent on the context, the behaviour of the occupants and their expectations. In contrast with the heat balance approach, the adaptive model of thermal comfort is based on the assumption that occupants take charge of their own comfort through various adaptive mechanisms. Those mechanisms were classified by Dear & Brager (1998) as physiological adaptation (occupants getting acclimatised), behavioural adjustments (opening windows, drawing internal blinds, using fans) and psychological habituation (comfort expectations being adjusted according to indoor/outdoor climate conditions). As pointed out by Halawa & van Hoof (2012), the main contribution of the adaptive approach to thermal comfort has been the criticism towards the heat balance approach, exposing some inadequacies of the ASHRAE thermal comfort scale to express the preferred thermal sensation of building occupants.

Studies have used one or a combination of both when exploring the thermal comfort of passive houses and other highly energy-efficient buildings. For instance, Rohdin et al., (2014) have used the PMV-PPD model combined with post-occupancy survey to assess the indoor thermal environment of nine passive houses in Sweden. The authors found the indoor thermal comfort to be generally good in the passive houses. However, they also reported that there was a high degree of complaints related to high temperatures during the summer.

A number of other studies on thermal comfort have also reported overheating in passive houses dwellings (Brunsgaard et al., 2012; Foster et al., 2016; McLeod et al., 2013; Mlakar & Strancar, 2011; Ridley et al., 2013). A common finding among those studies is that occupants in passive house dwellings often report better thermal comfort in winter when compared with the summer season. As pointed out by Mlakar & Strancar (2011), when compared with conventional dwellings, higher indoor temperatures can occur more easily in passive houses if they are experiencing hot summers. The authors explain that on hot summer days, passive houses are exposed to extensive solar radiation and high external temperatures, which prevent them from releasing energy via heat conduction due to the high levels of insulation. In addition, internal heat gains from appliances can also contribute to higher indoor temperatures.

Evidence from the literature suggest that overheating risks in passive houses are greatly dependent on the context and strongly influenced by occupants' practices, including the use of shading and night ventilation strategies (Larsen et al., 2012; Mlakar & Strancar, 2011). Interestingly, many of the studies found in the literature point out the importance of external solar shading in passive houses to prevent overheating problems.

In contrast, there are also studies based on Post-Occupancy Evaluation (POE) which indicate high levels of occupancy satisfaction with the thermal environment in passive houses during the summer (e.g. Feist et al., 2005; Schnieders, 2003; Schnieders & Hermelink, 2006). For instance, using detailed measurements and POE questionnaires in 11 passive house projects with more than 100 dwellings, Schnieders (2003) found that occupants (88%) were satisfied or very satisfied with the indoor climate during the summer. The scale of satisfaction used by Schnieders (2003) ranged from 0 to 6, with 0 representing very dissatisfied and 6 representing very satisfied.

Regarding perceived comfort, studies exploring this area usually involve occupants' perceptions of the indoor environment quality assessed by self-administered personal questionnaires (Zagreus et al., 2004). Perceived comfort is normally evaluated by several criteria, including thermal and indoor air quality. Those criteria usually assess the perceived comfort of occupants during the winter and summer months using a seven-point scale which usually goes from satisfactory to unsatisfactory (Roulet et al., 2006).

Studies exploring occupants' perceived indoor air quality comfort in passive houses and other highly energy-efficient dwellings were also found within the literature (McGill et al., 2015; Roulet et al., 2006; Schnieders & Hermelink, 2006). Indoor air quality comfort has been mainly linked with the lack of discomfort due to odour and sensory irritation (Frontczak & Wargoki, 2011). ASHRAE Standard 62.1 (2007) defines acceptable air quality as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" (in Frontczak & Wargocki, 2011, p. 925).

Many of the studies on perceived indoor air quality suggest that overall, passive house occupants were satisfied with the indoor air quality in their homes. For instance, Schnieders & Hermelink (2006) found that within the 100 passive house dwellings they studied, 95% of the occupants surveyed perceived the indoor air quality in their passive house as good to very good. Unfortunately, there is no detailed information from the authors regarding the satisfaction scale they used to investigate the occupants' perceptions of indoor air quality.

In a study undertaken by McGill et al. (2015) where indoor air quality perceptions were obtained from passive house occupants during the winter and summer seasons, the authors found that generally, passive house occupants perceived the indoor air quality as satisfactory. Nevertheless, McGill and colleagues also found that in some cases, occupants perceived the air in their passive houses too humid during the summer months. In their study, the authors used a few criteria to investigate occupants' perceptions regarding the indoor quality in passive houses. These include odour (odourless-odorous), sensation of freshness (fresh-stuffy), sensation of humidity (dry-humid) and satisfaction with the air (e.g. too still-too draughty). A seven-point scale was used to measure occupants' perceptions for each of the criteria investigated.

There are also many studies exploring occupants' perceived thermal comfort in passive houses and other highly energy-efficient homes (e.g. Derbez et al., 2014; McGill et al., 2015; Rojas et al., 2016; Udrea et al., 2016). Most of these studies report on occupants' overall satisfaction with their thermal comfort, albeit some highlight complaints regarding thermal dissatisfaction during summer months as previously reported from studies discussing thermal comfort and overheating in passive houses (e.g. Brunsgaard et al., 2012; Foster et al., 2016).

2.2.5. The indoor environment and the health of occupants of passive houses

Despite people spending most of the time in their homes (Klepeis et al., 2001), a very small number of studies have investigated a comprehensive range of indoor environment parameters, including indoor air quality in dwellings. For instance, only two UK studies exploring indoor air quality, ventilation rates and airtightness in dwellings (Dimitroulopoulou et al., 2005; Raw et al., 2004) were found from the published literature.

Research on the indoor environment of passive houses is also scarce. Although passive houses have received much attention in recent decades, studies investigating these highly energy-efficient buildings have mainly focused on their thermal performance and energy efficiency (e.g. Feist & Schnieders, 2009; Feist et al., 2005; Ridley et al., 2013) and far less on their indoor climate and indoor air quality from a health viewpoint. Furthermore, some studies which address the indoor climate aspects of passive houses, seem to use indoor environment parameter data (e.g. temperature and relative humidity) to investigate the durability of buildings materials (e.g. Mlakar & Štrancar, 2013), rather than considering aspects related to health. Nevertheless, a few studies have investigated the indoor climate and/or the indoor air quality of passive houses and other highly energy-efficient dwellings in the UK and worldwide, from a health viewpoint.

For example, a longitudinal study of seven, newly built, energy-efficient homes in France (with MVHR systems) measured several indoor air quality parameters and compared the results with indoor air quality parameters of standard French homes (Derbez et al., 2014). The results show that some concentrations of air pollutants ($PM_{2.5}$ and radon) were low compared with standard houses whereas other pollutant concentrations were similar (CO_2 and formaldehyde). In contrast, concentrations of some VOCs and aldehydes (e.g. acetaldehyde, hexaldehyde, n-decane, n-undecane, oxylene) exceeded the levels of the traditional French dwellings by more than 50%.

Another study in the Netherlands investigated the indoor environment of four passive house standard dwellings (Balvers et al., 2008). Indoor air pollutants (CO_2, CO, H_2CO) as well as temperature, relative humidity and air flow were measured over a period of several weeks. Balvers and colleagues found that on some occasions insufficient ventilation was provided causing high levels of indoor pollutants (CO_2 and CO). Nevertheless, the authors concluded that these houses are potentially healthy and comfortable and that air quality is significantly dependent on the behaviours of the occupants, especially on the understanding and use of the MVHR system.

In the UK, two studies were identified within the published literature, which investigated indoor climate and/or indoor air quality in passive houses from a health viewpoint. Sharpe et al. (2014) monitored the bedroom of 26 energy efficient houses in Scotland. These houses included both naturally ventilated houses and houses with a MVHR system, although only five of those had MVHR systems. Indoor temperature, relative humidity and carbon dioxide data were collected for a period of eight months. The authors show that consistently high temperatures were observed in the majority of the dwellings (summer indoor temperature > 21^{o}C in 94% of dwellings and > 23^{o}C in 68% of dwellings). Unfortunately, this study does not specify the indoor temperatures observed in the monitored bedroom of the houses with the MVHR systems. Additionally, the authors also show that although CO_2 levels were lower in houses with MVHR systems (average winter CO_2 of 858 ppm for MVHR houses compared with 1292 ppm for the naturally ventilated houses), there were exceptions. For example, three of the five houses with MVHR systems had winter CO_2 levels over 1000 ppm for over 50% of the time.

In the second study undertaken in the UK, McGill et al. (2014) investigated the indoor air quality of three passive house standard houses in the UK. Indoor temperature, dew point, relative humidity and carbon dioxide levels were monitored in the open plan living room during the summer and winter seasons and in the main bedroom during the summer season only. Study findings show that high levels of carbon dioxide (above 1000 ppm) were observed in all passive houses, whilst relative humidity and temperature remained below 60% and between 21.0-23.2^{o}C respectively.

A third relevant study identified within the published literature investigates the health of occupants of energy-efficient homes in Canada (Leech et al., 2004). Although this study does not investigate physical indoor climate and indoor air quality parameters in these airtight homes, the authors do explore the possible health effects of living in very airtight residences with heat recovery ventilation. Through the use of questionnaires, 128 home occupants reported their health status at approximately one year of occupancy and the data obtained were compared with the occupants' self-reported health status in the year before occupancy. The questionnaires included health symptoms and general health related to poor indoor quality such as diagnosis of asthma, chronic obstructive pulmonary disease (COPD), respiratory symptoms, etc. The authors concluded that there was nothing in their study that would suggest that occupants of these energy-efficient homes have poorer health compared with traditional homes.

These very few studies investigating the indoor climate and indoor air quality of passive houses from a health viewpoint as well as other studies exploring the health status of energy-efficient housing have been considered insufficient. This is very problematic and an issue that raises concerns as national carbon policies are increasingly driving mainstream house building towards energy-efficient housing standards (Osmani & O'Reilly, 2009).

Furthermore, these few studies identified within the published literature offer very limited information on possible differences on the indoor climate and indoor air quality between distinct rooms in the same house (e.g. bedroom and living room). Most of these studies also fail to take into account seasonal weather variations which may alter the indoor climate and indoor quality of the environment, which as a consequence, may have an impact on the health of dwelling occupants. Finally, although four studies have investigated the indoor climate and/or indoor air quality of passive houses and other highly energy-efficient dwellings from a health viewpoint, they do not clearly state what their findings (e.g. high levels of CO_2, >1000 ppm) mean in relation to the health of building occupants. Or in other words, these studies do not provide clear information on what specific health risks dwelling occupants were exposed to when inadequate indoor climate or indoor air quality was observed.

In addition, there is a strong consensus among the majority of studies investigating ventilation, air tightness, indoor climate and indoor air quality in passive houses and other highly energy-efficient dwellings. Research in these areas show that occupants' practices (or behaviours) play a significant role in determining the quality of their indoor environment (Balvers et al., 2008; Hasselaar, 2008). For instance, a study comparing the performance of ventilation systems in energy-efficient homes in

Germany (Maier et al., 2009) identified a strong relationship between indoor CO_2 concentrations and window opening behaviours. The results of the study show a significant influence of occupants' everyday habits and behaviours on the relationships obtained. Similar conclusions were reached by Iwashita & Akasaka (1997), when they investigated the effects of human behaviour on the natural ventilation rate and indoor air quality in homes in Japan. Ventilation rates in eight dwellings were measured using a tracer gas technique and residents were interviewed to assess their behaviours and the indoor environment. The study identified that 87% of the total air change rates in the dwellings were caused by the behaviours of occupants.

Within the energy-efficient housing (including passive house) and indoor climate/indoor air quality literature, this trend has a particularly strong relationship with MVHR systems. Although mechanical ventilation systems are expected to provide adequate ventilation and maintain appropriate indoor climate and indoor air quality in homes (Zero Carbon Hub, 2012), research shows that the performance of such systems relies on many factors (Balvers et al., 2012). Occupants' practices (and behaviours) appear to have a significant importance among them (Gill et al., 2010).

The next part of the literature review aims to understand the role of MVHR technology in dwellings and to explore how these systems are performing in passive houses and other highly energy-efficient dwellings.

2.3. Mechanical Ventilation with Heat Recovery (MVHR) system

2.3.1. The role of ventilation technology in passive houses and other highly energy-efficient homes

Increasingly stringent air tightness standards in new dwellings have reduced air infiltration through the building fabric, therefore compromising ventilation rates in internal spaces. As a consequence, mechanical ventilation systems were developed to provide buildings with adequate controlled ventilation. This technology aims to provide constant fresh air, ensuring that harmful levels of air pollutants and allergens do not accumulate indoors, maintaining a healthy and comfortable indoor environment.

Some studies suggest that if working correctly, mechanical ventilation systems could have a positive effect on the quality of the indoor environment (Zero Carbon Hub, 2012).

A study by Lowe & Johnston (1997) explored the effectiveness of MVHR systems in 12 local authority, 1970's refurbished UK dwellings. The air permeability of these homes was reduced to an average of

10.9 ACH at 50 Pa. The results show that air quality was significantly better in the dwellings with the mechanical ventilation system compared with the control homes with extract only ventilation.

Another research study showing the possible benefits of MVHR systems was undertaken by Howieson et al. (2003). They investigated allergen levels, indoor humidity and changes in lung function in 32 dwellings of asthmatic occupants living in UK homes installed with MVHR systems. They concluded that the ventilation system significantly reduced moisture content in the air, diminishing dust house mite allergen reservoirs in carpets and beds by about 96%. Additionally, significant improvement in asthma was also confirmed from the self-reported health status of the occupants.

In contrast, similar studies evaluating the benefits of mechanical ventilation systems in homes in the UK, have failed to present equivalent benefits in terms of mite population and mite allergen reduction, despite apparent adequate control of temperature and humidity levels (Niven et al., 1999; Fletcher et al., 1996).

Such discrepancies are difficult to explain, however, there are some confounding factors that may have influenced the overall results of these studies. For example, pressure tests were not undertaken in all studies, as a result air permeability rates were unknown for many of the dwellings involved. In addition, certain activities and their frequency (e.g. window opening and closing) which may have influenced the results were not taken into account.

Some may argue that the effectiveness of the MVHR technology, in terms of reducing air pollutants and allergens to acceptable levels, strongly depends upon the design of the systems, its installation and maintenance (Crump et al., 2009). Although this statement is true to some extent, evidence shows that there are other factors which may affect the ability of MVHR systems to perform as initially intended (Balvers et al., 2012). Other studies show that this technology is failing to perform in dwellings (Dengel, 2013; Kurnitski et al., 2007). The next part of this review will explore these issues in more detail.

2.3.2. Unintended shortcomings of MVHR systems

MVHR systems have been widely used in many countries and it is becoming the dominant ventilation technology in passive houses and other highly energy-efficient homes (Zero Carbon Hub, 2012). In the UK alone, sales figures show that over 18,000 MVHR units were sold between April 2010 and March 2011 (Zero Carbon Hub, 2012). The increasing interest and use of these systems in airtight homes also raises much awareness regarding their performance. Consequently, several studies have started to investigate the effectiveness of mechanical ventilation technology in highly energy-efficient dwellings (Balvers et al., 2008; van der Pluijm, 2010; Wendt et al., 2004). The attention was focused on whether these systems were able to provide and maintain adequate ventilation rates in airtight buildings.

Research in this area has established that the ability of the mechanical ventilation systems to provide and maintain adequate ventilation depends on many factors. These range from the design of the product, installation and maintenance, to how users operate them. For example, Balvers et al. (2012) investigated the performance of mechanical ventilation systems (including MVHR) in 299 Dutch homes. The results of this study show that shortcomings are common in many dwellings. Problems related to the design, construction, performance, maintenance and usage of the system greatly affect its efficiency. The most common shortcomings with the installed MVHR system were insufficient control options for the users (81% of the dwellings), dirty air supply ducts due to poor maintenance (77%), and improper use of control switches where they were mostly used in a lower setting than recommended by manufacturers (96%). Additionally, only half of the houses using MVHR were equipped with a bypass system.

Specific design inadequacies in the ventilation technology were found by a study exploring the usability of 'touchpoint' controls in low-carbon housing (Stevenson et al., 2013). The study shows that within a large housing scheme in the UK (42 homes), many residents found that the MVHR system contained confusing labels and information which was not intuitively understandable. Home occupants also stated that the control panel was difficult to use with little indication of the system response or whether the system was faulty. This resulted in occupants not understanding some of the environment control systems in their homes and therefore not using them as recommended.

Possible MVHR installation and commissioning problems were examined by Lowe & Johnston (1997) in a study of 12 refurbished UK dwellings. This study found discrepancies between the manufacturer's installations and commissioning intentions and the actual observed condition of the installed MVHR. The greatest problem found by the authors, was that the MVHR system was originally intended to be installed and commissioned by the manufacturer in order to ensure that installations procedures were being followed according to the manufacturers manual. However, for many reasons, the ventilation system was installed by third parties unfamiliar with it, resulting in errors and omissions (e.g. ductwork junctions were not insulated and ducts were connected the wrong way round).

The operation and use of the MVHR systems by homes occupants were also considered as a critical issue in several studies. A Finnish study carried out on 102 new built homes (Kurnitski et al., 2007) showed that only 57% of the houses complied with national regulations on minimum ventilation rates. The reason for the non-compliance from the other 43% of residences was due to occupants turning down fan speeds to reduce noise levels. Similar findings were presented by Mlecnik (2013) in a study exploring end-users experiences with MVHR systems in 16 passive house standard dwellings in Belgium. The results show that occupants regularly shut down the entire ventilation system aiming to stop the disturbing noise emitted by the equipment, particularly in the bedrooms. In this instance, however, the design of the system appeared to be accountable for excessive noise production as the heat exchanger and fan unit were positioned close to bedrooms and with no appropriate acoustic insulation to avoid sound transfer.

In another study investigating MVHR performance in 28 Dutch dwellings, van der Pluijm (2010) found that the noise nuisance from the ventilation system proved to be a problem which affected the behaviour of the occupants regarding their ventilation control. To avoid the disturbing noise levels, occupants were ventilating their homes at capacity level 1 for 93% of the time, providing not more than 15% of the required ventilation in the living room and less than 50% in the bedrooms.

Several studies also show that home occupants may not be using the ventilation system as prescribed for many different reasons. For instance, a study of 139 apartments using mechanical ventilation systems in Seoul, South Korea (Park & Kim, 2012) shows that 70% of the home occupants did not operate the mechanical fan at all during the summer period and one quarter of the older respondents (over 40 years) were unaware of the needs of the ventilation system. The results of this study also show that most of the occupants were mainly concerned about possible increases in heating cost associated with the use of the mechanical ventilation, which in turn affected the way they managed their ventilation.

Similar behaviour from home occupants was found in a study of 3 passive house standard homes in the Netherlands (Balvers et al., 2008). The installed mechanical ventilation system used three different control settings. The lowest setting (1) which should only be used when no one was in the home; setting (2) used for standard operation and setting (3) used when pollution reaches high levels. Residents, however, were leaving the ventilation control on setting 1 on a regular basis, even when the homes were occupied. Some home occupants were further reducing the ventilation rates in their homes, aiming to reduce their energy consumption.

With the Sigma home prototype at BRE Innovation Park, occupants were left confused with the room thermostat controls, which showed no indication of what the numbers displayed on them related to (Stevenson & Rijal, 2008). Although the occupants were given a home user guidebook prior to occupation, the study shows that the guidebook used generic information extracted from the manufacturers' manual. This failed to provide specific adequate information for those particular homes, causing residents to reject the user guidebook, preferring to test the technologies for themselves as a trial and error exercise.

Other studies similarly pointed out the importance of providing householders with users' manuals containing better and more specific information about their ventilation system as many home occupants seem to be unaware of the ventilation requirements in their homes (Mlecnik, 2013; Bone et al., 2010; Leech et al., 2004). A good example of this trend was reported by Macintosh & Steemers (2005) when investigating ventilation strategies on a new housing scheme of 59 units in central London. They found that 47% of the occupants made no adjustment to their MVHR system controls throughout one year of occupancy, whereas one occupant had it permanently disabled and 42% did not know what setting the switch was at the time of the interview. It was also reported that the number of windows opened over the monitoring period was significantly higher than expected for a housing scheme with MVHR. The study suggests that the misuse of the MVHR system by the occupants was caused by a lack of understanding about the ventilation technology.

Lack of maintenance of the ventilation system was a very common problem found by Balvers et al. (2012) in a Dutch study of 150 dwellings using MVHR. They reported that 77% of the dwellings had the air supply duct contaminated with dust and dirt and 43% of the air filters were dirty enough to warrant filter replacement. Longer maintenance intervals (more than the annual inspection of the overall functioning of the ventilation unit) were reported for 66% of the dwellings. Other studies have reported similar trends (e.g. NHBC, 2012; Zero Carbon Hub, 2012).

All these reported studies on the performance of MVHR technology show that there are several inefficiencies which need to be overcome if the ventilation system is to function as intended. Although it is clear that the design, installation and commissioning of the MVHR are important technical factors associated with its performance (Balvers et al., 2012; Lowe & Johnston, 1997), these factors alone do not guarantee the provision of good indoor air quality in passive house and other highly energy-efficient homes. To be able to understand the actual performance of the ventilation system, one must take into account not only the technical aspects related to its functioning (design, installation, commissioning), but also the human aspect of performance. The literature on the MVHR system and its shortcomings has strongly suggested that it is crucial that home occupants' practices (or behaviours) are also accounted for when analysing the effectiveness of such systems.

However, despite the recognition of the importance of occupants' practices as a significant influential factor in contributing to the performance of MVHR systems, there is a lack of research exploring how practices related to the use of the MVHR system and other ventilation technologies (e.g. windows) may influence the quality of the indoor environment in passive houses and other highly energy-efficient dwellings. Additionally, little is known about the possible impact of occupants' everyday practices on the quality of the indoor climate and indoor air quality in their highly energy-efficient homes, and how these in turn may affect their health.

Although information on the consequences of occupants' practices on the indoor air climate and indoor air quality in passive houses and other highly energy-efficient homes is scant, other areas of research have strongly demonstrated that human behaviour can significantly influence actual performance of low-carbon technologies in dwellings (Hargreaves et al., 2013; Firth et al., 2008; Owens and Driffill, 2008). For instance, the literature on 'behaviours and domestic energy consumption' has thoroughly explored and discussed similar relations regarding the conflict between physical systems and human interaction as well as the disjunction between predicted and actual building performance (Tweed et al., 2013; Steemers & Yun, 2009). Therefore, reviewing the literature on 'practices/behaviours and domestic energy consumption' may provide interesting insights on relevant trends regarding home occupants' practices and the indoor environment, which could be very useful when investigating occupants' practices and the possible consequences on indoor climate and indoor air quality.

2.4. Occupants' behaviours in residential settings

2.4.1. Domestic energy consumption, indoor comfort and occupants' practices and behaviours

There is a large body of literature exploring the relationships between building occupants' practices or behaviours and energy consumption (e.g. Hargreaves et al., 2013; Guerra-Santin & Itard, 2010; Owens & Driffill, 2008; Tweed et al., 2013; Wood & Newborough, 2003). Many of these studies established the need to better understand occupants' practices regarding indoor comfort, showing how these can significantly influence building energy consumption (Gill et al., 2010; Maier et al., 2009; Steemers & Yun, 2009).

Research shows that there is a large gap between the predicted and the actual energy performance of dwellings since occupants' behaviours can vary to an extent that energy consumption in similar homes may differ by a factor of two or higher (Fabi et al., 2012). Palmborg (1986) confirms this argument with a study of 76 similar single-family homes, where the total variation in energy consumption (water consumption, around 50%; ventilation habits, around 35%; indoor temperature, around 15%) was explained by differences in social habits among households. Similarly, Gill et al. (2010) attributed to occupants' behaviours the significant variation in heat and electrical energy consumption (51% and 37% respectively) in a study of 26 energy-efficient dwellings in Sweden.

Other studies explored the possible differences in domestic energy consumption in identical dwellings, in order to explore and highlight occupants' behaviours. For example, Socolow (1978) investigated the energy consumption of 29 identical town houses, including identical floor plans, heating/cooling systems and appliances. He found that the highest energy consumption was more than two times higher than the lowest energy consumption. Additionally, Sonderegger (1978) further examined the same housing scheme studied by Socolow (1978) by collecting energy consumption data from another 205 dwellings in the same housing scheme. His research showed a variance by a factor of three between the lowest and the highest gas consumption. Although there was some attribution of energy consumption variance to house features (e.g. window area), the author concluded that 71% of the unexplained differences in energy consumption was related to occupants' consumption patterns and social habits.

In a more recent study Maier et al. (2009) compared the heat consumption of 22 houses in Germany over a two year period. The houses were identical apart from the different types of ventilation systems used. Maier and colleagues found that among the 12 houses using identical ventilation systems, the heat consumption varied by a factor of 2.8 between the lowest and highest consumption. The study also shows that the house with the lowest heat consumption had the lowest average air temperature, suggesting that these occupants presented a behaviour pattern aimed towards energy conservation, by lowering the internal temperature of their homes.

Studies like these show how researchers used comparisons in domestic energy consumption to explain the effects of occupants' behaviours on energy demand. Mainly quantitative data (energy consumption metering) were collected and used for the purpose of such studies. Other scientists, however, have tried to investigate the reasons why home occupants behave the way they do (Fabi et al., 2012). There are several different theoretical and methodological approaches in the literature which have been used to investigate and explain occupants' behaviours and energy consumption in dwellings. Methodologically, some studies have made great use of quantitative data, by conducting questionnaire surveys combined with energy data from utilities and using statistical methods of analysis (Andersen et al., 2009; Sardianou, 2008), while others have opted for qualitative methods, such as interviews combined with energy metering data (Gram-Hanssen, 2010a).

Most quantitative studies have tried to identify the determining factors which contribute to home occupants' behaviours and decisions regarding their energy consumption (Fabi et al., 2012). Examples can be found in the work of Guerra-Santin & Itard (2010), where a questionnaire survey was conducted in 313 homes in the Netherlands. This study aimed not only to investigate the effects of occupants' behaviours on energy consumption, but also any possible relationships between behaviour and building characteristics and behaviour and household characteristics. Statistical analysis of the data showed that the number of hours the heating system was left on had the strongest effect on energy consumption. Building characteristics such as the type of temperature control (e.g. households with a programmable thermostat) seemed to have a great effect on the use of heating and ventilation systems. In addition, regarding household characteristics, the presence of elderly persons in the household proved to be a determining factor in the use of heating and ventilation, as the heating system appeared to be on for more hours while the ventilation system was used for fewer hours in households with elderly persons.

A similar method was also employed by Sardianou (2008) who used extensive data from a questionnaire survey of 586 households in Greece, together with measurements of energy consumption for the domestic space heating. Consumption models and regression techniques were used for data analysis. The author found that demographic and economic variables such as the age of the respondent, family size, household's annual income, dwelling size and ownership status explained differences in oil consumption for space heating. Other studies using demographic and economic variables have reported similar and contrasting findings. Similarities were reported by Schuler et al. (2000) showing that household annual income was a determining factor for energy consumption as rising income resulted in rising energy demand for space heating. Regarding age, Liao & Chang (2002) also reported that energy consumption is determined by the age of household members, as more energy is needed for space heating for elderly households. However, regarding dwelling characteristics, while Nesbakken (2001) estimates that energy demand increases as the number of occupants and dwelling size increase, Schuler et al. (2000) reported that energy demand for space heating did not rise linearly with the dwelling size. Because of some inconsistencies encountered in studies using demographic and economic variables (Faiers et al., 2007), and due to the argument that those variables alone do not take into account other important facets of occupants' behaviours, such as price, awareness, sense of moral obligation, routine habits/practices, lifestyles and cultural norms (Owens & Driffill, 2008), researchers have opted for alternative approaches.

Other scholars exploring the reasons why homes occupants act the way they do in relation to their energy consumption have used a combination of qualitative research methods (e.g. interviews and occupants' diary) and quantitative methods (e.g. energy metering) aiming to produce insights beyond those already known. Although this combination of research methods has not been widely used within the domestic energy consumption and indoor comfort areas, some examples can be found within the published literature. For instance, the work of Gram-Hanssen (2010) shows how users regulate their indoor climate, exploring the reasons why they act in particular ways. A combination of questionnaire survey methods, energy and water consumption metering and open question interviews were used to gather the data. Another example is given by Foulds et al. (2013) who investigated the performance of domestic practice by monitoring the energy consumption of passive house standard dwellings in the UK and interviewing home occupants. Reflecting upon the mixed methods employed in their study, the authors described that "these often deemed incommensurate data types can actually mutually guide, inform, critique and create opportunities for one another" (Foulds et al., 2013, p.634).

2.4.2. Relating the findings from the domestic energy consumption studies to domestic indoor environment studies

The primary purpose for reviewing the published literature on 'practice/behaviours and domestic energy consumption' was to explore relevant trends related to indoor comfort and the role of occupants in contributing to the energy consumption in their homes. This was considered an important part of the literature review, as findings on domestic energy consumption could offer rich insights on relevant trends regarding occupants' practices/behaviours and the indoor environment, which in turn could be useful when investigating the relationships between occupants' practices and the indoor climate and indoor air quality of passive houses. There was a need to explore other literature, in this case, practices/behaviours and domestic energy consumption, as only a very small number of studies exploring occupants' practices/behaviours and their influence on domestic indoor climate and the indoor air quality have been found within the published literature.

However, although domestic energy consumption studies and domestic indoor environment studies are two distinctive areas for research, they do present similarities which could be explored and discussed, aiming to provide future indoor environment studies with some insightful and relevant trends which could be further investigated. It is important to note that whilst the reviewed studies on domestic energy consumption investigated dwellings more generally, this PhD research uses passive house standard dwellings as the context which frames practices and indoor environment enquiry.

Regarding domestic energy consumption, the consensus among scholars and researchers appears to follow the argument of Janda (2011 p.15) that "buildings don't use energy, people do". On the other hand, some may also argue that people (householders) do not use energy, but instead they use the technologies provided in their homes, which in turn, consume energy (Kirsten Gram-Hanssen, 2012). In this case the way households use and interact with their domestic technologies, including home appliances (e.g. cooker, fridge, freezer, shower, heating system, etc.), and the way they develop their routines (Gram-Hanssen, 2008) contributes to the energy consumed in their homes. Whilst some studies have investigated the use of domestic technologies and its relation with energy consumption (Hinnells & Lane, 1996; Lebot et al., 1995; Wood & Newborough, 2003), others have explored how the practices related with the use of domestic technologies (e.g. cooking, freezing, showering, heating, etc.) are intertwined with energy use (e.g. Gram-Hanssen, 2008; Shove, 2003).

In the context of indoor climate and air quality in passive house standard dwellings, technology is also employed in order to provide homes with adequate indoor air quality and a comfortable indoor environment. This would mainly include the use of a MVHR system, which provides ventilation inlets and outlets for the provision of fresh air and the extraction of stale air respectively, but it also includes other components of the house design, such as windows and doors which could also contribute towards home ventilation. Some conclusions could be drawn by analysing studies from the domestic energy consumption literature and linking these with the findings from the literature on domestic MVHR systems. For example, it seems appropriate to consider how the interactions of home occupants with their ventilation technology (or any other technology related to ventilation, indoor climate and indoor air quality) may affect their indoor environment.

Energy consumption studies reveal that there is a large gap between predicted and actual energy performance in domestic buildings (Fabi et al., 2012), and that this gap can be explained by variances in occupants' practices and behaviours. Indoor environmental studies, in particular studies exploring the use of MVHR systems, agree that occupants' practices and behaviours, including their interaction with the ventilation technology is crucial to the performance of the system. However, little investigation has been undertaken on the possible performance gap between predicted (or expected) and actual indoor climate and indoor air quality in passive houses, from a health perspective. The assumption is that this gap could exist, as research on MVHR technology shows that these systems are failing to perform as initially intended (Balvers et al., 2012).

Using a variety of theoretical and methodological frameworks, domestic energy consumption studies have clearly documented the ways occupants' practices and behaviours contribute to energy consumption, also exploring the consequences of such behaviours (Firth et al., 2008; Steemers & Yun, 2009; Tweed et al., 2013). However, studies on the quality of the indoor environment of dwellings, and especially highly energy-efficient dwellings, appear to be following far behind in these areas. There is a lack of knowledge on how the home occupants' everyday practices (including practices related to their ventilation system) may contribute to the quality of their indoor environment.

Another emergent trend found in the literature on domestic energy consumption was the criticism from many scholars on the current acceptance of techno-economic assumptions in energy research and policy. Techno-economic models view energy efficiency as a technical issue, which can be amended with scientific methods of enquiry. Although this model recognises the importance of occupants' behaviours in shaping technological performance, it interprets social processes as market arenas, where a rational energy user, when equipped with perfect information and definable utility maximising logic, will behave according to energy policy goals (Shove & Guy, 2000). "This model sets the scene for understanding both success and failure. Success follows where technologies are proven and consumers are rational. Failure, or significant delay in achieving success, is the result of inadequate technical expertise or irrational consumer behaviour, perhaps relating to market imperfections or a breakdown in the necessary flow of information" (Shove & Guy, 2000, p.59). Although techno-economic assumptions have dominated energy consumption research and policy, some academics have criticised this model for its failure to recognise the routine complexities of energy related decision making, and for its inability to consider the extent to which energy-efficient choices are embedded in the routines and practices of domestic life (Shove & Wilhite, 1999; Shove et al., 1998). This criticism and the search for an alternative model of inquiry led energy researchers to leave behind the focus on individual decision makers and the linear model of technological change, which concentrates on rational logic, attitudes and beliefs of end users. Instead, emergent energy research has started to emphasise the social contexts in which choices and options are defined and made (Gram-Hanssen, 2013).

Similarly, the mainstream assumption that well developed technologies will produce the intended results if end users are rational and well informed, seems to dominate the rather limited literature on the domestic indoor environment and MVHR systems. Drawing examples from the studies exploring the common shortcomings of MVHR systems, they seem to agree that technical factors (design, installation, maintenance) as well as 'human dimensions' (user interaction) contribute to the underperformance of the system (e.g. Balvers et al., 2012; Mlecnik, 2013). The human dimension described in these studies relate to the economic and psychological perspectives, which assumes that individuals (or users) behave according to the information available to them (economic) or in line with their attitudes and values (psychological). However, as already pointed out by critics from the domestic energy consumption studies, such behavioural assumptions do not take into account broader social contexts in everyday domestic life, which are considered by many scholars and researchers as an essential framework for the understanding of practices of everyday life (Gram-Hanssen, 2013; Shove et al., 1998; Shove, 2010; Warde, 2005).

2.5. Research aim and objectives

Research Aim:

To investigate the possible health implications of passive houses and to understand how occupants' practices may contribute to the quality of their indoor environment, and their health.

Research Objectives:

1. To investigate the indoor climate and indoor air quality of passive houses, from a health perspective.
2. To analyse whether passive houses provide a healthy environment to their occupants.
3. To understand how occupants' everyday practices may contribute to the indoor climate and indoor air quality in their passive houses, and consequently how these may affect their health.

Chapter 3 – Methodology

This chapter begins by advocating the use of a mixed methods research strategy. It aims to elucidate what mixed methods research entails and the debates involving the use of a combination of quantitative and qualitative data. The chapter also provides an explanation of the rationale for using this particular research approach. It follows by presenting the case study research method and advocating its use as a suitable research approach for achieving the thesis core objectives. Subsequently, the research methods of data collection and data analysis are presented, together with the rationale for using those. Finally, the chapter presents the ethical considerations of the research design.

3.1. Using quantitative and qualitative enquires: Advocating a Mixed Methods Research approach

Mixed methods research (MMR) can be defined as “a research in which the investigator collects and analyses data, integrates the findings and draws inferences using both qualitative and quantitative approaches or methods in a single study” (Tashakkori & Creswell, 2007, p.4). Creswell (2009, p.4) has added that mixed methods “is more than simply collecting and analysing both kinds of data; it involves the use of both approaches in tandem so that the overall strength of a study is greater than either qualitative or quantitative research”.

Nevertheless, discrepancies exist among researchers in trying to define what constitutes a mixed methods research (Doyle et al., 2009). Whilst some researchers may interpret mixed methods as the collection and analysis of quantitative and qualitative data, others may argue that discussions around what it is should be kept open since mixed methods research is still an evolving approach (Tashakkori & Creswell, 2007).

Mixed methods research has been increasingly employed as a technique to expand the scope and improve the analytical power of research studies (Sandelowski, 2001). It has been used as a useful frame for interdisciplinary and complex research, offering researchers the best chance of fulfilling their research objectives (Johnson & Onwuegbuzie, 2004).

As explained by Onwuegbuzie & Leech (2006), quantitative research inquiry tends to be very specific in nature, attempting to describe, compare and associate phenomena. This type of research mostly aims to answer ‘*what is*’, ‘*what’s the difference*’ and ‘*what’s the relationship between*” questions. In contrast, qualitative research inquiry attempts to obtain insights into social phenomena. Qualitative research tends to address ‘how’ questions, providing an informative and detailed account of reality. Thus, a mixed methods research approach might be necessary when the researcher attempts to answer a research question, or a set of research questions, which combines both qualitative and quantitative elements.

Fulfilling the aim and objectives of an interdisciplinary research was indeed the rationale behind the use of mixed methods research. This thesis attempts to answer a set of research questions, which are interdisciplinary. They involve the use of both quantitative and qualitative enquiries. The objective of the first part of the research is to investigate the indoor air climate and indoor air quality of passive houses. This investigation requires the physical monitoring of indoor environment parameters (e.g. CO_2). It also involves questions such as 'what is the difference between the indoor environment of passive houses and the indoor environment of conventional houses?' This type of enquiry requires the use of quantitative research methods, such as indoor environment monitoring. In contrast, the second part of the research aims to understand how occupants' everyday practices may contribute to the indoor climate and indoor air quality in their passive houses. This research objective addresses understanding individuals and their practices, and also understanding how these practices may vary in different passive houses. This type of enquiry requires the use of qualitative research methods, such as participant interview, use of detailed diary and participant observation.

However, as pointed out by Bryman (2012) there are many ways in which quantitative and qualitative enquiries can be combined in a mixed methods research. For instance, combinations may occur for the purpose of triangulation or greater data validation. Alternatively, a combination of different enquiries may be necessary for sampling (e.g. when one approach is used to facilitate the sampling of participants).

The thesis has combined qualitative and quantitative enquiries with a twofold purpose. The primary purpose for the quantitative-qualitative combination was for explanation. In other words, the qualitative enquiry was used to explain the findings generated by the quantitative enquiry. Bryman (2004) also makes a valid point when he argues about the usefulness of mixed methods in explaining phenomena. He explains that although quantitative research allows the researcher to establish relationships among variables, it is often weak in exploring the reasons for those relationships. Still, "a qualitative study can be used to help explain the factors underlying the broad relationships that are established" Bryman (2004, p.507).

The secondary purpose for the combination of quantitative and qualitative enquiries was for triangulation. Thus, quantitative findings from participants' activity diaries were combined with qualitative findings from participants' interviews in order to better validate the results (Bryman, 2012). The benefits of triangulation was noted by other researchers (Abowitz & Toole, 2010; Jick, 2008; Yin, 2014), where they explain that the collection of a rich and strong array of evidence from both sets of enquiry may strengthen the validity of the research findings.

Although mixed methods research has been widely used and accepted in many areas of research (Sale et al., 2002), there are arguments against it. These arguments tend to be based on the idea that researchers should locate their research in a selected paradigm (Bryman, 2012). Paradigm can be defined as “a set of shared beliefs among the members of a specialty area about both which questions are most important and which methods are most appropriate for answering those questions” (Morgan, 2007, p.69). Its elements - ontology (nature of reality), epistemology (how we know what we know) and methodology (the process of research) influence how the researcher view the world and how they interpret it (Doyle et al., 2009).

Traditionally, researchers have chosen between two research philosophies – the constructivist paradigm, which underlies the use of qualitative methods of enquiry, and the positivist paradigm, which underlies the use of quantitative methods (Guba & Lincoln, 1994). Many have argued that these paradigms are incompatible and therefore it is not possible to combine them (Howe, 1985; Sandelowski, 2001). This is due to positivist researchers viewing the world as a single reality and therefore they identify causal relationships through objective measurement and quantitative analysis (Firestone, 1987). On the other hand, constructivist researchers seek to examine the context of human experience (Schwandt, 2000). They propose that there are multiple realities, which are researched through subjective enquiry, resulting in different interpretations (Appleton & King, 2002). The enquiry focuses on a deeper understanding of the phenomena and normally uses smaller samples.

More recently, there has been much debate regarding these two positions and their possible incompatibility (Bryman, 2007; Howe, 1985; Smith & Heshusius, 1986). Some theorists and researchers in the social sciences have come to accept the use of both paradigmatic positions, recognising that they can indeed be compatible (e.g. Brewer & Hunter, 1989).

For instance, Onwuegbuzie & Leech (2005) have argued that research purists (researchers who exclusively adopt either qualitative or quantitative research) relentlessly focus on the differences between the two orientations, ignoring their many similarities. Onwuegbuzie & Leech pointed out that both quantitative and qualitative enquiries involve the use of observation to address a research question. They also agree that both quantitative and qualitative researchers may attempt to triangulate their data, using either multiple quantitative or multiple qualitative methods respectively. Both positivists and constructivists have to make subjective research decisions before they finalise their research design (e.g. selecting the most appropriate equipment that yield empirical data, selecting an appropriate case study) (Onwuegbuzie & Leech, 2005).

Drawing on the argument addressing the reasons why quantitative and qualitative methods can be combined despite their basic philosophical assumptions, Sale et al., (2002, p.46) points out that the two approaches can be combined because they not only share the goal of understanding the world we live in, but they also "share a unified logic, and that the same rules of inference apply to both".

Similarly, Newman & Benz (1998) have recognized that quantitative and qualitative research can represent an interactive continuum, rather than represent bi-polar opposites. The authors agree that although the most common purposes in qualitative research are those related to theory initiation and theory building, whilst for quantitative enquiry the most common purposes are theory testing and theory modification, the two research approaches are not independent and using both can be useful to gain a more complex understanding of a phenomena.

However, one of the main issues around mixed methods research is related to its philosophical assumptions (Johnson & Onwuegbuzie, 2004). In other words, what is the paradigmatic stance held by mixed methods researchers? A positivist purist stance views the world as a single reality, where the only truth is out there waiting to be discovered by objective enquiry. In contrast, a constructivist purist stance views the world as socially constructed, where truth, which is constantly changing, is discovered by subjective enquiry. Thus, which of those paradigmatic stances, or any other, does a mixed methods researcher hold when they mix both objective and subjective enquiries?

Teddlie & Tashakkori (2010) have produced a list of six paradigmatic stances used in mixed methods research. These include a-paradigmatic stance, substantive theory stance, complementary strengths stance, multiple paradigms, dialectic stance and single paradigm stance. Refer to table 3.1 for an overview of each of them.

Paradigmatic Stances	**Position taken**
a-paradigmatic	For many studies conducted within real world settings paradigms or conceptual stances are unimportant.
Substantive theory stance	Theoretical orientations (e.g. critical theory, attribution theory) relevant to the research study being conducted are more important than philosophical paradigms.
Complementary strengths stance	MMR is possible but different methods must be kept as separate as feasible so that the strength of each paradigmatic position (e.g. constructivism, positivism) can be realised.
Multiple paradigms	A single paradigm may does not apply to all MMR research designs.
Dialectic stance	Assumes that all paradigms have something to offer and that the use of a multiple paradigms in a single study contributes to greater understanding of the phenomenon under investigation.
Single paradigm stance	It was initially formulated to provide a philosophical underpinning for MMR. It has been described as one that 'welcomes or even requires a mix of methods' (Greene, 2007). Examples include pragmatism, critical realism and transformative paradigm.

Table 3.1 Paradigmatic stances in mixed methods research (Adapted from Teddlie & Tashakkori (2010, p.14-15))

Understandably, not all of these six paradigmatic stances can be applied to any mixed method research as some may be more suitable than others in underpinning the worldview of a particular research problem. Similarly, a researcher may argue against some of these paradigmatic stances by addressing their possible weaknesses related to some specific research questions.

In the case of this thesis, the single paradigmatic stance, pragmatism has been adopted as the most appropriate paradigmatic stance to be used when conducting this particular mixed methods research study. The rationale behind this choice will be presented shortly. First, the reasons why the other five paradigmatic stances have been rejected will be discussed.

The a-paradigmatic stance, which deals with the research stance by ignoring it, has been considered unsuitable as no research is paradigm free. Although a researcher may not explicitly declare their world view when writing up their study, it does not mean that they don't have one. Researchers were still influenced by their undeclared philosophical positioning during the entire duration of their research (Hall, 2013).

The substantive theory stance advocates that "what matters most in guiding enquiry decisions are the substantive issues and conceptual theories relevant to the study being conducted, not philosophical paradigms in and of themselves" (Teddlie & Tashakkori, 2010, p.5). The problem in using this stance in an interdisciplinary research is that some theoretical lenses may be appropriate when used within one discipline, but may be less pertinent when trying to apply to another (Teddlie & Tashakkori, 2010).

The multi paradigmatic approach allows the researcher to choose more than one paradigm. The researcher chooses the most appropriate paradigms for their research design and determines when and how to mix them. This paradigmatic stance has been criticised for the problems inherent to it: how does one know which paradigms are to be mixed and how the mixing is to be done (Hall, 2013).

Similarly, the dialectic stance proposes the use of multiple paradigms. However it also involves consideration of opposing viewpoints and interactions with 'tensions' caused by their juxtaposition (Teddlie & Tashakkori, 2010). This stance presents the same difficulties described by the multi paradigmatic stance and therefore was considered unsuitable for this research.

The complementary strengths stance proposes that different methods are kept as separate as feasible. Because of the nature of the research problem being investigated and the questions it attempts to answer in this research, methods can't be completely separated. On the contrary, in some parts of the research, different methods are integrated aiming to explain phenomena in detail. For example, findings from the monitoring quantitative data are integrated with the findings from interview qualitative data, attempting to understand how occupants' everyday practices may contribute to their indoor environment quality.

As previously stated, a single paradigm, pragmatism, has been adopted as the philosophical stance for this mixed methods research. Pragmatism originates from the work of Peirce, James, Mead and Dewey (Cherryholmes, 1992). The use of a pragmatic approach in a mixed methods research appears to be broadly acceptable within the field of mixed methods (Greene, 2008). The pragmatic approach offers an alternative worldview to those held by positivists and constructivists, focusing on the problem to be researched and the consequences of the research and not on the research paradigm (Creswell & Clark, 2007). Therefore, rather than holding assumptions of the nature of reality to determine what kinds of knowledge are possible, pragmatists replace this abstraction by emphasising on experiences as the continual interaction between beliefs and actions (Morgan, 2013). As Morgan (2013, p.1049) puts it, "knowledge is not about an abstract relationship between the knower and the known; instead, there is an active process of enquiry that creates a continual back-to-forth movement between beliefs and actions". As further explained by Feilzer (2010, p.8), pragmatism "sidesteps the contentious issues of truth and reality, accepts, philosophically, that there are single and multiple realities that are open to empirical inquiry and orients itself toward solving practical problems in the *real world*". Pragmatism could be related to a world with different layers, where some are objective, some are subjective, and some are a mixture of the two (Dewey, 1925).

In some ways, pragmatism acts as a new paradigm (Johnson & Onwuegbuzie, 2004), by not only replacing the positivist and constructivist argument that the nature of reality is an essential criterion for undertaking different research approaches but also by recognising the values of those different approaches in guiding the choices of different enquiries (Morgan, 2013).

Therefore, as argued by Creswell (2014, p.11) "pragmatists do not see the world as an absolute unit … Truth is what works at the time and it is not based in a duality between reality independent of the mind or within the mind… Pragmatists believe in an external world independent of the mind as well as lodged in the mind". Therefore mixed methods pragmatic researchers use both quantitative and qualitative enquiries because they work to provide the best understanding of a research problem (Creswell, 2014).

Johnson & Onwuegbuzie (2004) argue that in order to mix different approaches, pragmatic researchers need to consider the different characteristics of quantitative and qualitative research, gaining understanding of their strengths and weaknesses, so that they are in a position to combine strategies. The authors believe that using this principle in mixed methods research, it is likely to produce studies with "complementary strengths and non-overlapping weaknesses"(Johnson & Onwuegbuzie, 2004, p.18).

Johnson and Onwuegbuzie (2004, p.17) refers to the pragmatic view in the mixed method research as “a movement that moves past the recent paradigm wars by offering a logical and practical alternative”. The authors add that the pragmatist “logic of enquiry includes the use of induction (or discovery of patterns), deduction (testing of theories and hypotheses) and abduction (uncovering and relying on the best of a set of explanations for understanding one’s results)” (Johnson & Onwuegbuzie, 2004, p.17).

Nevertheless, others theorists (e.g. Biesta, 2010) argue that pragmatism should not be understood as a philosophical position among others, but should be used as a set of philosophical tools which aim to address problems.

Yet, since pragmatism focuses on the need to address the research problem and the necessity to answer the research questions, this mixed methods research paradigm was considered appropriate for this interdisciplinary research study. As explained by Johnson & Onwuegbuzie (2004, p.17-18) for pragmatists “what is most fundamental is the research questions – research methods should follow research questions in a way that offers the best chance to obtain useful answers”.

3.2. Advocating a case study research design

As previously discussed, a mixed methods research frame, using both quantitative and qualitative methods of inquiry was considered necessary to fulfil the thesis aim and objectives. Accordingly, a suitable research design, which permitted those two forms of enquiry, within a contemporary setting, had to be selected.

After a review of the different research designs, the case study was considered a suitable and useful design frame for the thesis. The rationale behind this choice will be discussed shortly, after a brief explanation of what a case study is and what it entails.

Thomas (2011, p.513) defines case studies as “analyses of persons, events, decisions, periods, projects, policies, institutions, or other systems that are studied holistically by one or more methods. The case that is the subject of the enquiry will be an instance of a class of phenomena that provides an analytical frame – an object – within which the study is conducted and which the case illuminates and explicates”. Thomas sees the case study as a form of enquiry which gives primacy to the case (the subject) while attempting to offer an analytical frame within which the case is viewed (the object).

Case study research aims to gain a rich and detailed understanding of what is being studied and analysed (Thomas, 2013). Yin (2014, p.16) explains that a case study is usually undertaken when the researcher wants “to understand a real-world case and assume that such an understanding is likely to involve important contextual conditions pertinent to the case”.

For this reason, case study research involves an in-depth research into either one case or multiple cases (Thomas, 2013). It looks at the complex interactions of many factors in a single case or multiple cases, rather than looking at a few variables in a large number of cases (Thomas, 2011). As explained by Thomas (2011b, p.23) “a case study is about seeing something in its completeness, looking at it from many angles”. The benefit of an in-depth, detailed examination of phenomena lays on the fact that some research studies may require a research method which allows a deeper level of contextual insight (e.g. Yin & Davis, 2007).

Case studies examine contemporary phenomena, which can be investigated through qualitative enquiry or quantitative enquiry alone, or through a combination of both. Indeed, the opportunity to use many different sources of evidence is a major strength of case studies (Yin, 2014). Therefore, when utilising a case study design, the researcher can use a combination of methods to help understand and explain the different facets of what is being examined. This combination of methods, enables the case study in assisting with more complex investigations, where the boundaries between phenomena and context are not sharply distinguishable (Yin, 2014).

Anderson (1993; in Noor, 2008, p.1602) noted that by exploring the *how* and *why* of phenomena, case studies allow the examination of contextual realities and the differences between what was planned and what actually occurred. Furthermore, Yin (2014, p.19) argues that one of the most important applications of the case study is its ability to “explain the presumed causal links in real-world interventions that are too complex for survey or experimental methods”.

Reflecting on what a case study design is and what it entails, this was considered by the researcher as a suitable and useful research design for the thesis. The aim of the research is to investigate the indoor environment of passive house from a health perspective, which are contemporary phenomena and thus, supported by a case study design.

Additionally, these phenomena were not being investigated in isolation. Other methods of enquiry were used to provide a detailed context and an explanation for the phenomena. And that is exactly what a case study design facilitates. It allows the researcher to investigate phenomena in detail, within their context, and to explore the *how* and *why* of them.

Researchers can also select the use of a single case or multiple cases, depending on the research objectives and the questions they are trying to answer. The researcher has opted to use a single case since it is the most appropriate to be used in a longitudinal study. In the case of the thesis, it was considered inappropriate and very difficult to use multiple cases when collecting and analysing large datasets from three different points in time (Yin, 2014).

Although the benefits of case studies have been discussed, this research design has been criticised by some for its bias towards verification, lack of scientific value and for its weakness in allowing generalisations (e.g. Campbell & Stanley, 1966).

On the other hand, proponents of case study research, such as Flyvbjerg (2006), argue that the perceived weaknesses of such methods are misunderstandings or oversimplifications about the nature of such research, which need to be discussed and clarified. Indeed, that is what Flyvbjerg does in his paper. He presents the five common misunderstandings of case study research and refutes them in turn. In short, Flyvbjerg argues that a case study is a valid and important method for social enquiry as it takes into account the context dependent knowledge, which is an integral part of human affairs. It also reiterates that case studies contain a substantial element of good narrative which best capture the complexities and contradictions of real life, holding no greater bias towards verification of preconceived ideas than other forms of research inquiry.

After concluding that a case study would be the most appropriate research frame to be used in this research study, the next step involved finding a suitable case. This proved to be challenging as this study requires a case which consists of passive houses or other similarly highly energy-efficient dwellings. Although they are a desirable building standard for reaching CO_2 emission reductions within the housing industry, currently, they are not a mandatory standard in the UK housing sector. Homes built following passive house standards or similar are constructed mostly by social housing providers, although, again this is not a mandatory requirement in the UK. Following this insight, social housing schemes in the UK, designed and constructed following passive house standard, were identified. This was possible by a variety of means: by undertaking internet searches into national social housing providers, by searching into the 'Passivhaus Trust' website and looking for passive house standard housing schemes in the UK and by talking to personal contacts within the housing industry about the research and the desirable case study.

After identifying a few housing schemes which were considered suitable cases for this research study, and considering the difficulties in travelling to and from them on a regular basis, the housing provider and/or the architectural firm responsible for the projects were contacted.

The first step was to send these organisations an email explaining the research study aim and objectives. It was also important to explain to these organisations the need to find an appropriate case study and that it was believed that that particular housing scheme was a suitable case. It was also explained how the researcher planned to collect the data. Finally, the organisations were asked whether a meeting could be arranged to discuss the possibility of using that housing scheme as a case study for the research study. If there was no reply to the first email in five days, a follow up email was sent, followed by a phone call. In total, seven social housing providers and architects were contacted.

Five organisations replied to the first email or talked to the researcher over the phone. From those five, two housing providers indicated their passive house schemes were already ‘over-researched’ and they did not think it was appropriate to invite residents to take part in another study.

The third social housing provider explained that there was currently another university undertaking research in their housing scheme and they did not want other researchers accessing the homes and being a possible nuisance to the residents.

The fourth contact was from the architectural firm responsible for the design of the passive house standard homes in this particular housing scheme. The researcher was informed that there were long delays within the design/construction/procurement process and the construction of the passive house scheme had not yet started. Thus, this passive house scheme was considered unsuitable due to the thesis completion deadline.

After many negative responses, or no responses at all, Amber Housing[5], the social housing provider of passive house standard homes, and the fifth organisation contacted by the researcher, agreed to arrange a meeting to discuss it further.

During the meeting, Amber Housing agreed to support the research by allowing the researcher to use David’s Court[6], a passive house standard housing scheme as the case study for the research. However, because David’s Court would also be researched by Spire Group[7], a private research company employed by Amber Housing, the access to the passive house housing scheme was restricted by a few conditions imposed by the social house provider: First, the research had to be conducted alongside Spire’s research. This meant that although the two research projects had different aims and objectives (this one exploring the indoor environment and occupants’ practices from a health perspective, and Spire’s research exploring energy consumption and occupants’ behaviours), the collection of data from the passive house scheme should be coordinated and done concurrently. Second, any visits made or appointments booked with the residents of David’s Court homes had to be arranged through Spire Group only, which meant that the timings for any field

[5] To protect the anonymity of the social housing provider and the home occupants, I have used the pseudonym ‘Amber’ throughout this thesis.

[6] To protect the anonymity of the home occupants, I have used the pseudonym ‘David’s Court’ throughout this thesis.

[7] To protect the anonymity of the social housing provider and the home occupants, I have used the pseudonym ‘Spire Group’ throughout this thesis.

work, had to be agreed between the two sets of researchers. Limiting disturbing the residents was the justification behind the conditions imposed by Amber Housing.

It is very important to explain the restrictive conditions inherited with this case study, as they also have contributed in shaping the methodological design of the research. It is also vital to point out that although using a case study with no restrictive conditions attached to it, would had been more appropriate (as it would had given the researcher more freedom in designing the research), the lack of access to other suitable case studies (for the reasons explained above), meant that the research design had to be planned alongside those restrictions.

3.2.1. David's Court

David's Court is a passive house standard housing scheme located in East London. The scheme has 51 housing units including houses and apartments distributed within four blocks. Block A is a 3 storey building comprising of 1, 2 and 4 bedroom flats. Blocks B and D are both a 3 storey building containing 4 bedroom houses. Block C is a 2 storey building consisting of 3 bedroom houses.

David's Court had faced construction delays which presented some constraints, which also shaped the research methodological design. Although Amber Housing had planned a phased handover[8] starting in September 2014 and finishing in December 2014, delays in construction changed the planned dates. The first houses to be constructed, in block C and block D were handed over to occupants in October and November 2014 respectively. The houses in block B and the flats in block A were handed over in March/April 2015.

3.2.2. The selection of participants at David's Court and the selection of control houses

All 51 households at David's Court were invited to take part in this research. A leaflet[9] explaining the research and inviting their participation was posted to households. The leaflet also informed residents that there was a financial incentive of £150[10] for taking part in the research. However, because of very low responses received from the leaflets, residents were then contacted by phone and once again invited to take part in the study. From these telephone calls, nine households agreed

[8] Phased handover here refers to a housing scheme completed in sections and handed over to the occupants following a particular sequence.
[9] Refer to Appendix 1 for a copy of the leaflet. Please note that any names related to the social housing provider, the research company or the housing scheme have been concealed from the document to protect the anonymity of the participants.
[10] The financial incentive was to be paid in three instalments of £40, £40 and £70.

to take part in the study. It was agreed with the participant householders that the data collection process (and gaining access into their homes) would only start from four to six weeks after they first moved in. That would give residents time to get settled in their new homes, before accessing them.

The selection process for the control houses had two phases. Initially, a leaflet explaining the research and inviting participation was posted in the letterbox of 100 houses on roads near David's Court site (refer to Appendix 2). The selected houses were of a conventional construction and less airtight. However because there was no response from any of the selected houses, and due to time and the financial constraints of the need to make regular trips to site, other houses were selected.

In the second phase, an advert was posted on a local (to the researcher) neighbourhood social network website. The advert explained the research and invited households living in 3 or 4 bedroom terraced houses, with conventional ventilation system[11] (not MVHR) to take part in the research. Participants were offered a financial incentive of £50[12] for their participation. In total, 10 households expressing interest contacted the researcher. A brief telephone interview was conducted with the 10 households, aiming to establish whether the houses followed the following criteria: (1) they should not be classified as a passive house or an energy-efficient home or similar, (2) they should not have a MVHR or similar ventilation system, (3) they should have three or four bedrooms, matching as closely as possible the studied passive houses, (4) the number of occupants should match as closely as possible the number of occupants in the passive houses, (5) the houses should be terraced and with the same number of storeys as the passive houses, (6) control houses should have similar footprint size as the passive houses, (7) if possible, the houses should be located in a targeted urbanised location, away from busy main roads. This condition attempted to match the location of the control houses as closely as possible the location of the passive houses.

Following these criteria, two 3 bed conventional houses (CH3 and CH4) were used as a control group for the identical 3 bed passive houses (PH1 and PH2), whilst two 4 bed conventional houses (CH1 and CH2) were used as the control group for the identical 4 bedroom passive houses (PH3, PH4 and PH5). These control houses were located in Bury St. Edmunds, Suffolk, in close proximity to one another (maximum 800 metres apart).

Additionally, because the control house site and the passive house site were located in different areas: Bury St. Edmunds (Suffolk) and Rainham (East London) respectively, outdoor weather data (daily mean temperature, relative humidity and wind speed) were obtained from the nearest

[11] Conventional ventilation system refers to houses with trickle ventilation over the window frame and/or extractor fans in the bathrooms. However, many houses in the UK (especially those built before 1985), might not have these items, relying on air gaps within the building fabric or on residents opening the windows for the provision of ventilation.
[12] The financial incentive was to be paid in three instalments of £10, £10 and £30.

MetOffice weather station from both sites[13], so external weather variations between these two sites could be controlled for. The outdoor weather data downloaded correspond to the three periods of monitoring (two weeks during the winter, spring and summer, totalling six weeks of external weather data).

Figures 3.1, 3.2 and 3.3 show a comparison of outdoor temperature, outdoor relative humidity and wind speed between the two sites (studied and control) during the two weeks of monitoring, in winter, spring and summer season respectively. It was noted many similarities between the passive house site and the control house for all the three outdoor parameters analysed. The most evident variation between the passive house site and the control house site was found during the spring season, when outdoor relative humidity was compared (figure 3.2). However, statistical analysis tests (Mann-Whitney U test) indicated that there were no statistical significant difference (P<0.05) between any data sets, when the outdoor parameters from the passive house site and the control house site were compared.

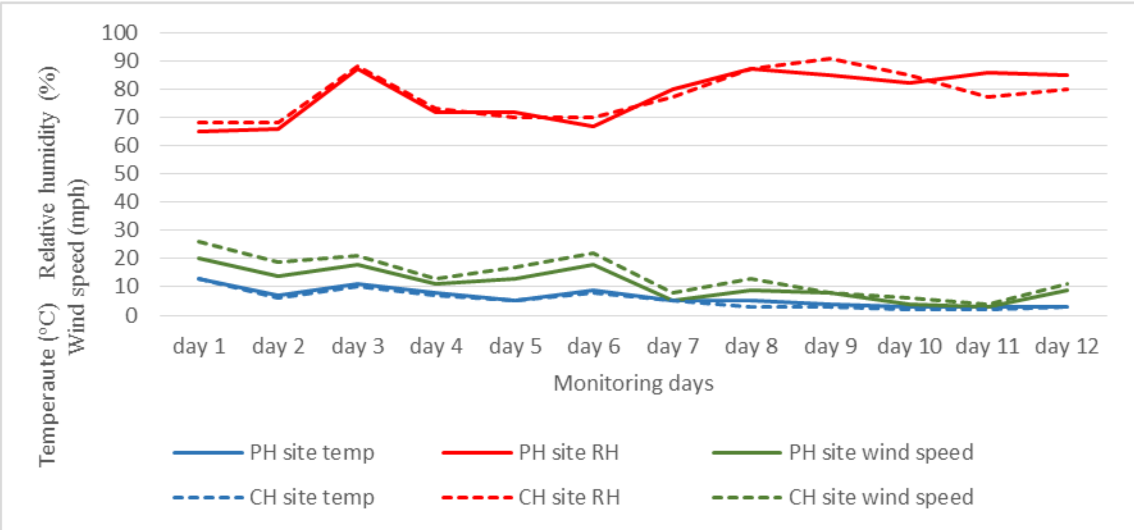

Figure 3.1 Winter outdoor temperature (temp), relative humidity (RH) and wind speed obtained from the nearest weather station to the passive house site (PH) and control house site (CH)

[13] The data were downloaded from https://data.gov.uk/metoffice-data-archive for Dagenham weather station (351142) and Bury St Edmunds weather station (324050), the closest weather station to the passive house site and the control house site respectively.

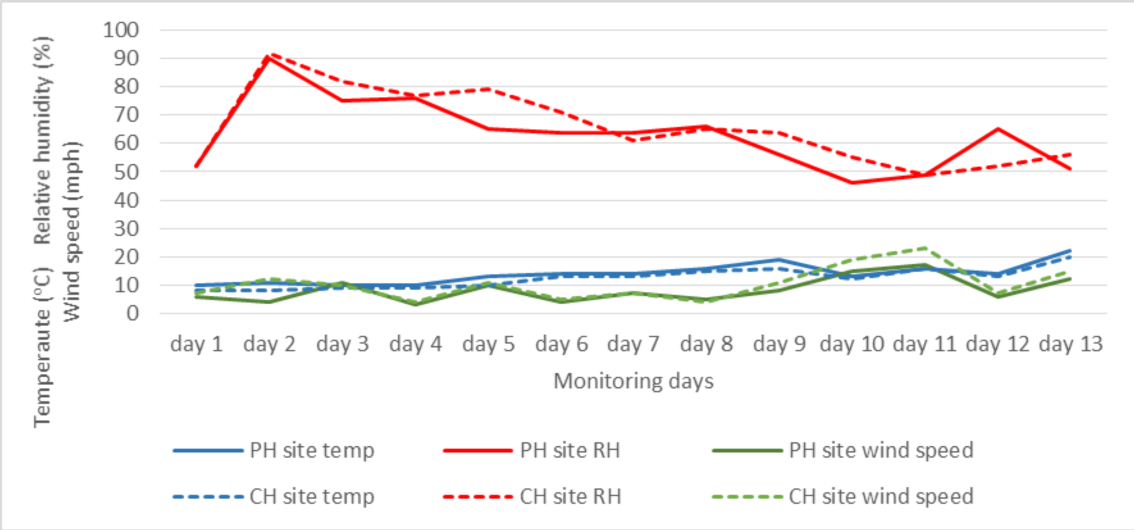

Figure 3.2 Spring outdoor temperature (temp), relative humidity (RH) and wind speed obtained from the nearest weather station to the passive house site (PH) and control house site (CH)

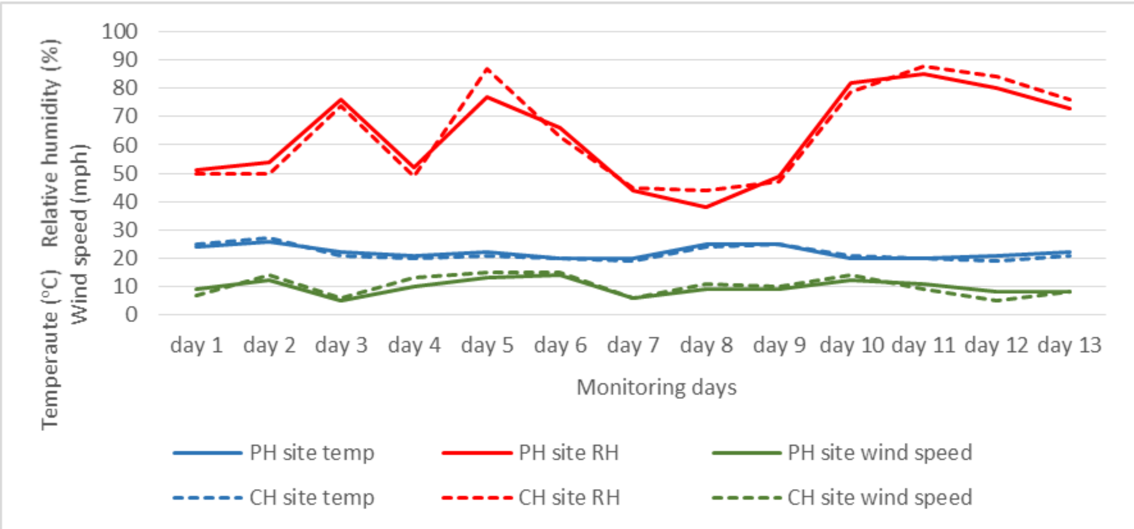

Figure 3.3 Summer outdoor temperature (temp), relative humidity (RH) and wind speed obtained from the nearest weather station to the passive house site (PH) and control house site (CH)

Table 3.2 shows the participant dwellings at David's Court and at the conventional houses, used as a control group for the first part of the research, together with information regarding the house type, ventilation details and the number of occupants in each dwelling.

Household code	Household type	Dwelling type	Year built	Building block	Number of occupants	Type of ventilation
PH1	Passive house	3 bed 2 storey terraced house	2014	C	4	MVHR system
PH2	Passive house	3 bed 2 storey terraced house	2014	C	4	MVHR system
PH3	Passive house	4 bed 3 storey terraced house	2014	D	5	MVHR system
PH4	Passive house	4 bed 3 storey terraced house	2014	D	5	MVHR system
PH5	Passive house	4 bed 3 storey terraced house	2014	D	5	MVHR system
CH1	Conventional	4 bed 3 storey terraced house	2003	N/A	4	Ceiling extractor fans in bathrooms and trickle ventilation on window tops
CH2	Conventional	4 bed 3 storey terraced house	2009	N/A	5	Ceiling extractor fans in bathrooms and trickle ventilation on window tops
CH3	Conventional	3 bed 2 storey terraced house	2009	N/A	3	Ceiling extractor fans in bathrooms and trickle ventilation on window tops
CH4	Conventional	3 bed 2 storey terraced house	1985	N/A	4	No ventilation mechanisms, apart from opening windows and doors

Table 3.2 Participant households at David's Court passive houses and at the conventional, control houses

3.2.3. Design and construction characteristics of David's Court and control sample houses

All five studied passive houses are Passivhaus certified dwellings. In terms of design, the case study dwellings included many of the common design characteristics found in UK passive houses. They have high levels of thermal insulation (as shown by the low U-values on table 3.3). The construction type used was the 'ecoTECH Passive House Build System', which is a structural insulated panel (SIP) manufactured off-site for the inner skin of the wall combined with facing brick for the outer skin. The cavity external walls have an overall thickness of 454 mm. Triple glazing windows were used in all dwellings.

Passive solar design was also a feature in the dwellings, which had large glazed areas (windows) in some of the rooms. However, external shading devices (e.g. overhangs, external shutters), especially to south facing rooms, were not part of the design of the five studied houses.

All studied passive houses had a MVHR unit located inside a cupboard on the second floor. The control panel for the MVHR was located on the ground floor, on the kitchen wall.

Table 3.3 shows the energy performance of the studied UK passive houses and the minimum requirements of energy performance for the UK conventional houses, as set by the UK Building Regulations in force at the time of construction. The build year of the UK traditional houses on the table 3.3 refers to the period in which the four control houses were built (between 1985 and 2009). Therefore, these should reflect the minimum standards of energy performance achieved by the control house dwellings.

Energy performance and design components	UK Passive House	3 bed David's Court passive houses	4 bed David's Court passive houses	UK traditional house (built between 2003 and 2009)	UK traditional house (built in 1985)
	Minimum requirements	Achieved performance	Achieved performance	Minimum requirements	Minimum requirements
		PH1 & PH2	PH3, PH4 & PH5	CH1, CH2 & CH3	CH4
Specific heating demand ($kWh/m^2/yr$)	≤ 15	15	14.5	No limit	No limit
Specific cooling demand ($kWh/m^2/yr$)	≤15	9.6	9	No limit	No limit
Specific heating load (W/m^2)	≤ 10	Not known	Not known	No limit	No limit
Specific primary energy demand ($kWh/m^2/yr$)	≤ 120	105	101	No limit	No limit
Air changes per hour (@50 Pa)	≤ 0.6	0.6	0.5	≤ 10 (introduced in 2006)	No limit
Walls, roof, floor (U-values) (W/m^2K)	≤ 0.15	0.15	0.15	≤ 0.35 walls ≤ 0.25 floors; ≤0.25 roofs	≤0.6
Glazing unit	≤ 0.8 W/m^2K	0.8	0.8	N/A	N/A
Installed glazing	≤ 0.85 W/m^2K	0.8	0.8	≤ 2.2	≤ 5.7
Doors	≤ 0.8 W/m^2K	0.8	0.8	≤ 2.2	No limit

Table 3.3 Energy performance achieved by the studied passive houses and the minimum requirements of energy performance for UK traditional houses

3.2.4. Users' manual and information given to passive house occupants

All passive house occupants were provided with an induction pack, which included a users' manual, explaining all the main features of the passive house and how to use them. Table 3.4 below summarises some of the instructions contained in the users' manual for the passive houses at David's Court. Further information on the passive house operation was also provided verbally by the Housing Association representative and by the Mechanical and Heating (M&E) engineer through visits to householders.

Windows	**In winter** •Do use the windows like a 'solar panel' to collect as much 'solar gain' (heat from the sun) as possible. Keep the curtains open and let the sun light into the room. •Do not leave windows and doors open for long in winter. The available heating in a passive house is relatively small so the heating will take longer to heat up your home. •Avoid losing heat through open windows, (it shouldn't be necessary anyway), and don't leave external doors or windows open for longer than necessary. **In summer** •When you do not want the solar gain (heat from the sun) coming through the windows, close your blinds or curtains to stop the house heating up and keep your house cooler. •Use the windows to ventilate especially when it is cooler at night. The windows can be opened fully or tilted inwards. •Summer cooling - Do use the windows to ventilate. You can ventilate your house in the morning with cool air. It is then best to keep the windows shut during the day when temperatures become higher. This should also help with security. You can then open them during the evening and night when you are at home, allowing cooler fresher air to circulate. **Generally** •If you live in a house do use the windows at the top of the staircase which can be tilted electrically to further ventilate the house. •Do use the windows with high solar gain (facing the sun) as part of the heating System. •Can I open my windows for ventilation? Yes of course you can open your windows in a passive house. This shouldn't be needed especially in winter as open windows lose heat from the home.
MVHR	• Do leave ventilation running on normal level all year round. • Do boost the ventilation when you feel you need to - this can be done by the control panel in the kitchen, the boost function should not be left on all the time • Do reduce the ventilation level (trickle) when leaving the house unoccupied for longer periods of time • Don't change the filters; this service is provided by the Housing Association. • Don't block the room and ceiling vents, the supply grills, the extract grill on the outside wall of your property or the gaps under the doors • Don't run the MVHR unit without filters. Running without filters causes dust to collect in the fan unit and in the ducts inside the walls and ceilings which will be very difficult to clean • Don't switch the ventilation unit off – even in the summer. The rate of ventilation is something you can control. The control panel has minimal control functions. Occasionally you might need rapid ventilation, if you burn the toast perhaps. In the kitchen you can boost from the main control panel which will give you a timed boost. You should not leave the system constantly in boost mode as this is not an efficient use of energy.
Bypass	In the Summer when the MVHR doesn't need to recover the heat from your home, the summer by-pass function will automatically activate at 24°C. A motorised valve closes and re-directs the air directly (from outside) without going through the exchanger. This will only happen however when the outside air being drawn in is cooler than inside the house.
Cooker hood	A recirculation type cooker hood (with charcoal filter) has been fitted in your kitchen. This is because a direct extract vent through the walls would remove too much heat. The recirculation cooker hood is designed to clean the air and allow the heat to be recovered via the ventilation system. The charcoal filter in the cooker hood will need regular replacing. Your extractor hood is recirculating through a charcoal filter. The filter should be replaced periodically.
Heating	The MVHR recycles some of the heat back into the house • Any additional heating is provided via your gas boiler and radiators. The heating and hot water programmer is on the boiler.

Table 3.4 Summary of the instructions contained in the users' manual for the passive houses at David's Court

3.3. Using theory to understand occupants' everyday practices

The understanding of occupants' everyday practices and the analysis of the ways these practices may contribute to the indoor climate and indoor air quality in their passive houses is the focus of the third research objective. Although there are many theoretical lenses which aim to understand and explain human behaviour (e.g. rational choice theory, theory of planned behaviour), social practice theory has been considered an appropriate and useful theoretical framework in helping the researcher to fulfil the third research objective.

Before explaining the merits of social practice theory and the rationale for using it in the thesis, a brief explanation and a critique of other theoretical frameworks will be presented.

3.3.1. Behaviour theories from the disciplines of psychology and economics

Research across all disciplines of the social sciences have created different theoretical models to understand individuals and their behaviours. Boundaries within these disciplines serve to demarcate the definition of behaviour, the types and contexts of the behaviour being analysed, and the methodology used to study them (Morris et al., 2012).

Research exploring human behaviour within residential settings have made great use of linear behavioural theories, such as the ones found in the disciplines of economics and environmental psychology, to explain the reasons why home occupants act the way they do (e.g. Faiers et al., 2007; Gill et al., 2010). Both disciplinary categories focus on the individual, assuming a consistent behaviour pattern based on external determinants.

Economic behavioural models, for instance, assume that behaviour is the outcome of a linear and rational process where individuals are regarded as utility-maximizers who make rational choices based on the available information (Wilson & Dowlatabadi, 2007). Individuals having full information about the alternatives and the consequences of their choices, will make cost benefit calculations to rationally decide on the best course of action (Geels, 2010). Research following this theoretical framework has often focused on the role of information (e.g. Ueno et al., 2006; Wood & Newborough, 2003) or pricing (Faruqui & Sergici, 2010; Thorsnes et al., 2012) as determinants for behaviour.

However, economic behavioural models have been considered by some as inappropriate, as evidence shows that individuals do not make constantly rational decisions (Camerer & Loewenstein, 2004), and limited, since they fail to account for the influence of other factors such as the attitudes and values of an individual (Martiskainen, 2007).

Other behavioural models from the discipline of psychology have also been extensively used in research in residential settings. Psychological behavioural theories focus on the role of psychological constructs – values, attitudes and norms – to predict and explain behaviour. Similarly to the behaviour theories from the economic discipline, psychological models view individuals as rational beings who are able to make systematic use of information to behave consistently (e.g. Abrahamse et al., 2007; Brandon & Lewis, 1999). However, this framework does not focus on utility-maximization, but instead it emphasises the role of individual's values, attitudes and norms as determinants of behaviour (Wilson & Dowlatabadi, 2007).

The most widely used and cited model in this category is the theory of planned behaviour (TPB) which was conceptualised by Ajzen (1991) but developed as an extension of the theory of reasoned action (TRA) (Ajzen & Fishbein, 1980; Fishbein & Ajzen, 1975). The theory of planned behaviour posits behavioural intention as the best predictor for actual behaviour. In this model, intention is an outcome of the combination among three constructs. These include individual's *attitudes* towards a particular behaviour, the *subjective norm* (referring to the perceived social pressure to perform or not to perform a behaviour) and the *perceived behavioural control* (referring to the perceived ease or difficulty in performing a particular behaviour). As pointed out by Hargreaves (2011), this model offers the benefit of the possible inclusion of other variables when analysing behaviour. For instance, Conner & Armitage (1998) argued that TPB could be further extended to incorporate additional variables, such as past behaviour/habit, moral norms, self-identity and affective beliefs. However, the addition of other variables has been further criticised based on the possibility that the model's predictive capability may be diminished as a result (Jackson, 2005). Although TPB has been successfully used by researchers in the domestic field (e.g. Faiers et al., 2007; Wilson & Dowlatabadi, 2007), critics argue that this model fails to measure actual behaviour since it only focuses on measuring the relationships among behavioural constructs (Martiskainen, 2007).

Behaviour theories from the economics and psychology disciplines share the behavioural approach which places the individual at the centre of the analysis, considering them as autonomous decision makers, whose behaviour is subject to external pressures. However, this linear and simplistic cause-and-effect relationship embedded in theoretical models from both disciplines has been criticised under the argument that "individuals do not exist in a social vacuum" (Hargreaves, 2011, p.81). Critics have argued that these approaches are not only very individualistic but they also fail to take into account the meaningful interrelations among context, infrastructures and social beings (Sandberg & Tsoukas, 2011; Schatzki, 2002; Shove & Guy, 2000; Shove, 2010). As argued by Shove & Guy (2000), these linear behavioural views fail to recognise the routine complexities of decision making in everyday domestic life. Based on similar critiques, philosophers such as Bourdieu (1977,

1990) and Giddens (1979) sought to overcome the assumptions rooted in these ontologies by proposing the use of theories of practice as an alternative approach.

3.3.2. Social practice theory

Social practice theory is a fragmented body of theories predominantly focused on the performance of practices. Attention is diverted away from the individual decision making and centred on the 'doings' of social practices (Shove & Warde, 2002). However, social practice theory does not disregard the role of individuals in the doings of practice but instead it acknowledges that individuals are 'carriers' of social practices (Reckwitz, 2002; in Hargreaves, 2011, p.83).

Early concepts of social practice theory emerged from the works of Giddens (1984) and Bourdieu (1977, 1990). Despite some differences, similarities were also observed on the conceptualisation of social practice between the two authors: Giddens views individuals as continually performing practices and at the same time reproducing the social structures of society, whilst Bourdieu sees 'habitus' as unconsciously rooted in human action, therefore shaping social practices and structures. However, as explained by Shove & Pantzar (2005), although these two social practice theorists powerfully argue that practices are recognised entities made through their routine reproduction, their theories are social theories since material artefacts, infrastructures and products are hardly discussed.

On the other hand, the more recent work developed by Shove & Pantzar (2005) takes on board the views of Reckwitz, who defines social practices and makes a distinction between practice and practices:

> *"Practice (Praxis) in the singular represents merely an emphatic term to describe the whole of human action (in contrast to 'theory' and mere thinking). 'Practices' in the sense of the theory of social practices, however, is something else. A 'practice' (Praktik) is a routinized type of behaviour which consists of several elements, interconnected to one another: forms of bodily activities, forms of mental activities, 'things', and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge. A practice … forms so to speak a 'block' whose existence necessarily depends on the existence and specific interconnectedness of these elements" (Reckwitz, 2002, p.249).*

For Reckwitz and other theorists, practices require the existence of interconnected elements for the production and reproduction of practices (Warde, 2005). Because social practice theory concepts are indeed derived from a rather fragmented body of theories, the naming of these elements and therefore, the framework used for the analysis of social practices vary as different theorists offer different concepts. There is no agreement among social theorists on the naming of the elements which guide social practices (for a comparison of the different elements used by Schatzki, Warde, Shove & Pantzar and Reckwitz, see Gram-Hanssen (2009, p.154)), therefore researchers have based their analysis on different approaches according with their suitability in achieving the objectives of the study.

The latest body of social practice theories, which focuses on the collective structures of practices (social, physical and cultural) and also on the elements which guide the practices that people routinely perform (e.g. Shove & Pantzar, 2005; Schatzki, 2002, 2001; Reckwitz, 2002) has been arguably successfully used in studies exploring domestic practices of everyday life (e.g. Galvin, 2013; Strengers & Maller, 2011; Hargreaves et al., 2013; Gram-Hanssen, 2012).

Social practice theory has been particularly important in producing new insights into routinized everyday activities and their consequences for the indoor domestic environment (e.g. Foulds et al., 2013; Galvin, 2013; Gram-Hanssen, 2011; Strengers & Maller, 2011). The benefit of using social practice theory for the analysis of social enquiry in domestic settings is that this theoretical lens does not focus on the individual's decision making rationalities and choices, as the behavioural theories from the disciplines of economics and psychology do, but instead, it centres the analysis on the mundane and routinized practices of everyday life. Selecting a theoretical framework which focuses on the analysis of "a routinized type of behaviour" (Reckwitz, 2002, p.249) of everyday life was important in trying to achieve the third objective of the thesis for two reasons. First, it would be very difficult to imagine that many everyday activities which may influence the indoor environment quality of passive houses (e.g. cooking, drying clothes, opening windows/doors, smoking) are the result of informed rational action on the part of the occupants or solely attributed to causal factors. Second, the third research objective requires the adoption of an analytical frame which emphasizes the context of social enquiry and the emergent dynamics of everyday life. It would be insufficient to utilise linear theories of behaviour, which focus on causal factors and external drivers, in attempting to explain the dynamic and messy practices of everyday life.

Therefore, for the purpose of the thesis, there was a need to use a more holistic theoretical framework which has been 'tested' by previous studies, therefore, demonstrating its capability to provide guidance in the investigation of empirical data. Although different social practice frameworks have been developed, used for empirical studies and are now reflected in a number of publications, the framework developed by Gram-Hanssen (2010a, 2010b, 2011) has been used for the purpose of the thesis.

Gram-Hanssen's framework has been considered suitable for the thesis as it emphasises the role of routines and technological structures in contributing to the performance of practices while simultaneously taking into consideration how the other elements (habits, knowledge and engagement) hold practices together. It is argued that the routinised and technologically structured parts of everyday domestic social practices are a central part of the analysis if practices which may influence the indoor climate and indoor air quality of passive house dwellings are to be understood. This is due to the fact that technologies which may influence the indoor environment quality of passive houses are not only part of the building structure (e.g. MVHR ventilation, windows, super insulation) but they are also in the dwellings (e.g. cooker, dish washer, washing machine, and kettle appliances).

Drawing from the work of Gram-Hanssen (2010a, 2010b, 2011,), there are four elements holding practice together – technologies (and artefacts), institutionalised knowledge, embodied habits and meanings and engagements.

Technologies (and artefacts) are considered very important in the context of this study. While Gram-Hanssen's framework only explores the role of technologies as the material element when examining domestic energy consumption related practices, artefacts have also been included for the purpose of the thesis. Although technologies are the central material element when analysing practices related to the indoor climate and indoor air quality of passive houses, they were not considered the only ones. Artefacts, such as cleaning products and cigarettes (used for tobacco smoking), for example, may also have a part to play when considering the indoor air quality of passive houses.

Nevertheless, technologies are the central material element when analysing indoor climate and indoor air quality related practices in passive house dwellings. Because passive houses are very airtight, they greatly rely on the use of ventilation technologies (e.g. MVHR system, windows and doors) for the provision of fresh air. Therefore, it is vital that these technological structures are taken into account when analysing occupants' everyday practices in the studied dwellings. Furthermore, since there are many other technologies used indoors which can contribute to the quality of the indoor environment (e.g. electrical appliances) it is also important that those are also part of the analysis.

Institutionalised knowledge refers to the knowledge of how to do things. It includes not only technical knowledge itself (e.g. information from the user manual) but also knowledge obtained from cultural myths of the indoor environment, indoor air and ventilation as well as rules of how to regulate them.

Embodied habits refers to the routinised practices that people perform in their everyday lives. These practices are often subconsciously performed as it's hard to imagine that people would constantly think about every small thing they do at home, such as waking up, getting dressed, making a coffee, etc. However, peoples' conscious decisions may also influence their practices. For example, home occupants may receive information on the importance of using their ventilation system as prescribed by the manufacturers, and this information or knowledge may influence their ventilation practices. However, although social practice theory recognises the role of information, it does not offer a simple correlation between knowledge and practice.

The meanings and engagement element implies that the practices performed have a meaning to the people who perform them. For example, ventilation practices and other practices which may affect indoor air quality, such as, opening the window, using the extractor fans and cooking may have as the ultimate goal freshness, extracting strong smells and serving a meal respectively.

3.4. Methods of data collection

In order to investigate the selected case study and with the purpose of fulfilling the research aim and objectives of this thesis, a variety of methods were employed. As case study research does not prescribe the use of a particular method of data collection (Yin, 2014), a variety of methods were selected according to their ability to answer the research questions, while also taking into consideration the many constraints involved when undertaking indoor environment monitoring and other research tasks in occupied dwellings. The nature of the constraints encountered and how they influenced the research design will be discussed further as part of this section. The researcher has used the following methods of data collection:

1) Monitoring indoor climate (IC) and indoor air quality (IAQ)
2) Conducting semi-structured interviews
3) Using occupants' activity diaries
4) Completing a field diary

1) Monitoring indoor climate (IC) and indoor air quality (IAQ)

The investigation of the indoor climate and indoor air quality of passive houses from a health perspective is the heart of the first results chapter. Therefore, it became clear from the beginning of the research process that monitoring the indoor climate and the indoor air quality of passive houses would be imperative for this research. Many studies (Crump et al., 2002; Dimitroulopoulou et al., 2005; Möhle et al., 2003; Richardson et al., 2006) have monitored a range of indoor environmental parameters to investigate the IC and IAQ in buildings. These include temperature, relative humidity (RH), allergens, particulates (PM), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), volatile organic compounds (VOCs) and formaldehyde (H_2CO). However, monitoring this long list of indoor environmental parameters in multiple homes and in multiple rooms proved impracticable for two reasons. First, it was not financially feasible to obtain the necessary monitoring equipment to investigate many indoor environmental parameters in multiple locations. Second, some of the most common monitoring equipment currently available are sampling devices which provide a mean value of pollutant concentration over a period of time (e.g. Crump et al., 2002). Although such a sampling device would suffice in the investigation of the indoor environmental quality in passive houses, when faced with the third research objective (analysing possible associations between indoor environmental parameters and occupants' practices), it became clear there was a need for additional monitoring devices capable of continuously recording data at certain intervals, during a certain period of time. For this reason, two types of data logger were employed, together with a passive sampler device for indoor air quality data collection. The data loggers used were Wöhler model CDL 210 (accuracy ±50ppm CO_2, ±0.6^{o}C temperature and ±3% RH) and HOBO model UX100-003 (accuracy ±3.5% temperature/RH). Wöhler is a mains powered data logger, which uses a USB cable for data transfer. It records temperature, relative humidity and carbon dioxide data at specified intervals. HOBO is a battery powered data logger which also uses a USB cable for data transfer. It records temperature and relative humidity data at specific intervals. Additionally, a volatile organic compounds (VOCs) passive sampler was employed to gather further indoor air quality data. The passive (time weighted average concentrations) sampler consists of a stainless steel tube filled with a solid polymer absorbent (Tenax TA), sourced from Gradko International®.

Indoor climate data, such as temperature and relative humidity are useful in this research as they can provide guidance relating to the quality of the indoor environment in relation to human health and comfort (e.g. Arundel et al., 1986; Howieson et al., 2003; Ormandy & Ezratty, 2012). Temperature and relative humidity data have been used by many researchers investigating the indoor climate of buildings (e.g. Ferng & Lee, 2002; Godwin & Batterman, 2007; Tweed et al., 2013). In addition, it was considered vital to investigate the indoor air quality of passive houses, since IAQ related data could help the researcher to further examine the indoor environmental quality of passive houses, from a health perspective. For that reason, two IAQ parameters, CO_2 and VOCs, were selected for monitoring.

Although CO_2 is not considered an air pollutant, its concentration in occupied rooms has been shown to be a significant predictor of some air pollutants (Chatzidiakou et al., 2015), and a good indicator of adequacy of ventilation since elevated CO_2 levels can reflect the deficiency of outdoor/indoors air flow (Hess-Kosa, 2012; Scheff et al., 2000). Some studies have successfully used CO_2 as a proxy for adequacy of ventilation and/or indoor air quality (Chatzidiakou et al., 2015; Ferng & Lee, 2002; Guo & Lewis, 2007; Hui et al., 2008). There is a general acceptance that CO_2 levels above 1000 ppm are indicative of inadequate ventilation (Daisey et al., 2003). On the other hand, VOCs are classified as air pollutants, which depending on the type of VOC, its concentration and length of human exposure, could be associated with negative health effects (Maroni et al., 1995). Studies investigating air quality in buildings have also employed VOCs monitoring data when attempting to analyse whether specific indoor environments posed any health risks to its occupants (e.g. Lu et al., 2015; Norback et al., 1990; Weschler et al., 1990).

Wöhler monitoring loggers were placed in the main bedroom and in the living room of each dwelling (case and control), at a height between 0.75m and 1.8m (Mahyuddin & Awbi, 2012) on a horizontal surface near a power socket, away from the reach of children when possible. Because the monitoring equipment has a display screen which shows real time CO_2, temperature and humidity levels, the display screen was covered during the monitoring period to conceal the displayed data. This was to minimise the risk of occupants changing their behaviours due to information. The equipment was calibrated before every use by following the manufacturer's instructions. Furthermore, HOBO monitoring loggers were placed in the kitchen of each passive house (case houses only), over the internal door frame at a height of 2.1 m. This equipment was not placed in the control houses due to restrictions imposed by Amber Housing, who owned the equipment. HOBO data loggers were also calibrated before every use following the manufacturer's instructions. In addition, VOCs passive samplers were placed in the main bedroom of each dwelling (case and control), fixed to the wall, at a height of approximately 2.0 m, out of the reach of children, and away from windows and room corners (to avoid the possibility of sampling outdoor and stagnant air respectively).

CO_2, temperature and relative humidity monitoring data were collected at 15 minutes intervals. These indoor environmental parameters were monitored in five passive houses and in four control houses for two weeks in three different seasonal periods: during winter 2014/2015, spring 2015 and summer 2015, equating to a total of six weeks of monitoring. There were, however, some minor omissions of environmental quality data sets, due to residents unplugging the equipment during the monitoring period. VOCs data were collected during the spring monitoring stage only, for a period of two weeks, in the five passive houses and in the four control houses. It was not financially feasible to collect VOC data for every house, for more than one season. Additionally, constraints with the funding application deadline dictated the approximate time (spring season) of VOCs monitoring, since the VOCs samplers had to be ordered and delivered by a particular day (i.e. the last day of the financial year) and used within 10 weeks. VOC data were also collected from the outdoor environment, at a specific location, located as closely as possible to case and control houses. For the passive houses, the VOC sampler was placed at high level (approximate 1.8 m), in the garden of passive house PH1. This location was considered appropriate for collecting data representative of all five passive houses since passive house PH1 garden was located within a few metres of the other four passive houses. For the control houses, the VOC sampler was placed at high level (approximate 1.8 m), in the garden of a property located centrally to the 4 control houses.

Table 3.5 shows the orientation of each room monitored in passive houses and corresponding control houses.

Household code	Orientation of the rooms monitored		
	Bedroom	**Living room**	**Kitchen**
PH1	South	North	South
PH2	South	North	South
PH3	West	East	West
PH4	West	East	West
PH5	West	East	West
CH1	East	East	N/A
CH2	West	East	N/A
CH3	South	North	N/A
CH4	West	East	N/A

Table 3.5 Orientation of the rooms monitored in passive houses and corresponding control houses

2) Conducting semi-structured interviews

Face-to-face, semi-structured interviews were a prominent research instrument in this thesis. It allowed the collection of data which deeply explored the questions raised by the third research objective. This type of interview was suitable as it encourages participants to provide more information, giving researchers more in-depth knowledge as it offers the opportunity to ask follow-up questions related to the participants' responses to previous questions (Vanderstoep & Johnston, 2009). Riessman (1993, p.2; in Hoggart et al., 2002, p.205) notes that with this type of interview technique "it is possible to search, clarify and probe, effectively to ask why a story was told 'that' way". (Refer to Appendix 3 for the interview topic guide).

Interviews were carried out with one adult from each participant household. There were three rounds of interviews with an adult from each participant household. The first round of interviews took place at around six weeks after the occupants moved to their new homes, from November 2014 to February 2015. The second round of interviews took place in May 2015 and the third round of interviews took place in August 2015. The first round of interviews aimed to gather information on the householders, the home occupancy patterns as well as specific details on the residents' interactions with MVHR controls, windows, vents and other form of ventilation. The interviews also explored home occupants' everyday ventilation practices and other practices associated with ventilation (e.g. smoking and opening windows). The interviews also explored energy consumption and related behaviours, following the agreement with Amber Housing to conduct research alongside another researcher (as explained above). The second and third round of interviews were very similar to the first, but with some differences. First, although they explored the same themes as the first interviews, attention was directed towards any changes that may have occurred and the reasons behind such changes. Second, because some monitoring data were available during the second and third round of interviews, it was possible to use part of those interviews to clarify and further explore any issue which emerged from the monitoring data.

Interviews were carried out inside the homes, either in the kitchen or in the living room. They had two parts which included sit-down questions and a walk-around. The walk-around offered the opportunity to gain a detailed understanding of how each of the rooms was used, how they were ventilated and how everyday practices were being performed and their possible connections with ventilation. The interviews lasted between 35 minutes and one hour. They were recorded and fully transcribed. The questions included in the interview were also piloted by research colleagues and some alterations were made following their comments. (Refer to Appendix 4 for an extract of the interview transcript).

3) Using occupants' activity diary

The use of a diary in this thesis was seen as a complementary yet key research instrument. It was used to gather information related to occupants' everyday practices (refer to Appendix 5 and 6)[14] in their social context. Indeed, the opportunity for the recording of events in their natural, social context, has been identified as one of the great benefits of using diaries in social research (Hawkes et al., 2009; Reis, 1994).

For the purpose of this thesis, a structured, time-based, activity diary was given to all the five households during each monitoring period. The households completed three diaries during the two weeks of winter, spring and summer monitoring periods, equating to six weeks of diary keeping. One to two weeks has been considered the optimal time for keeping a solicited diary. A study carried out by Jacelon & Imperio (2005) shows that keeping a diary for less than one week may not present sufficient depth of data whilst keeping it for more than two weeks may make participants tired of making regular entries. The diary was an A4 size structured format (Alaszewski, 2006), spiral bound, with one page per day entry. Each page had a list of possible everyday practices carried out in the house. This included changing the ventilation settings on the MVHR, opening windows, smoking and cooking, among others. Occupants were asked to fill in the diary by indicating if any of the listed activities had been carried out in their homes. They were also asked to indicate the locations (which room) and time the activity was carried out, together with other relevant details (e.g. reasons why

[14] Appendix 5 shows a blank copy of the occupants' activity dairy whilst Appendix 6 shows an extract of the occupants' activity diary filled in by a passive house householder.

occupants engaged with that particular activity). Therefore, occupants' activity diaries contained both sets of data: quantitative and qualitative data.

The first page of the diary provided an example of how the diary should be filled in. Occupants were also given face-to-face information on how to complete the diary, together with the researcher's telephone number as a mechanism of support in answering occupants' queries about the diary. Additionally, in order to maximise responses, occupants were reminded to fill in their diaries (Jacelon & Imperio, 2005) by regular text messages. The diary was piloted by three households living in dwellings that were not low-carbon as there were difficulties in recruiting low-carbon homes residents. The diary was also reviewed by other social researchers within the university. The use of a diary served three purposes. First, it provided details regarding occupants' everyday activities, which could have influenced the IAQ parameters being monitored. This information was valuable when analysing the context around the monitoring data. Second, it also helped in gathering additional information about the everyday practices performed in the dwellings and their frequency (e.g. were occupants using MVHR controls? If so, how often?). Third, the information obtained from the diary entries were also used in data triangulation, allowing the cross-checking (Bryman, 2012) of qualitative and quantitative findings from occupants' activity diaries and qualitative data findings from interviews.

4) Completing a field diary

A field diary was used throughout the monitoring and interview periods. It was used to record information on "what was happening to and in the research setting" (Lofland, 2004, p.232). Field diary notes involved descriptions of the physical environment, changes within the physical environment and details on indoor and outdoor conditions. For instance, field notes included room orientation, whether internal doors were open/closed, whether windows were open/closed, whether a room changed use/purpose during the research period. In addition, field notes also contained details of the MVHR ventilation settings used by the households during each field visit.

Although field notes primarily captured physical observation in the field, diary entries also contained analytical thoughts (refer to Appendix 7) regarding what the researcher had observed and heard during the interviews with home occupants. These entries were very fruitful as they acted as a first step towards data analysis (Bryman, 2012; Lofland, 2004).

3.5. Methods of data analysis

Because the thesis employed a mixed method research approach, which involves the collection of multiple sources of data, there was a need for a robust analytical strategy when undertaking data analysis (Yin, 2014). As previously explained, the thesis aims to investigate phenomena within their context, and not in isolation. Likewise, the various sources of data gathered for this research, although initially individually analysed, are also part of a broader, interconnected analysis. For details on the various methods of data collection and analysis and how these were linked to the research objectives and sub objectives, please refer to table 3.6.

After capturing the emergent themes from the various data sources and using construct mapping techniques to establish links and connections among themes, there was a need to attain *meaningful explanations* (Thomas, 2011b) regarding the research findings. For this reason, social practice theory was a vital analytical tools used in this thesis. The same theoretical propositions that shaped the data collection, also shaped the data analysis. Through the lenses of social practice theory, it was possible to draw explanations on the many relationships found.

After discussing the analytical strategy used in this thesis, the sections below aim to explain the methods for data analysis of individual sources of data. These include:

1) Descriptive statistical analysis
2) Laboratory analysis
3) Criteria based analysis
4) Coding textual data
5) Coding occupants' activity diary
6) Qualitizing descriptive statistical data
7) Analytical framework

Research objectives	Sub objectives	Methods for data collection	Methods for data analysis
1. To investigate the indoor climate and indoor air quality of passive houses, from a health perspective	1. To investigate indoor climate and indoor air quality parameters in passive houses in different seasons. 2. To compare the indoor climate and indoor air quality parameters found in passive houses with those found in conventional houses.	IC and IAQ monitoring, semi-structured interviews, occupants' diary, field diary	Descriptive statistical analysis, laboratory analysis, coding textual data, coding occupants' activity diary, analytical framework
2. To analyse whether passive houses provide a healthy indoor environment to their occupants.	1. To reveal, through a literature review, any known health concerns related to the indoor environment parameters found in the passive houses as well as known safe threshold levels. 2. To compare the data from the literature review with the findings from the indoor environment of passive houses, attempting to find out whether passive houses occupants are at risk of exposure to any known health effect.	IC and IAQ monitoring, semi-structured interviews, occupants' diary, field diary	Descriptive statistical analysis, criteria based analysis, coding textual data, coding occupants' activity diary, analytical framework
3. To understand how occupants' everyday practices may contribute to the indoor climate and indoor air quality in their passive houses, and consequently how these may affect their health.	1. To understand occupants' everyday practices, especially practices related to changes in the indoor air climate and indoor air quality. 2. To understand how these everyday practices may contribute to the indoor environment in passive houses, and how these may vary following seasonal variations.	Semi-structured interviews, occupants' diary, field diary	Coding textual data, coding occupants' activity diary, qualitizing descriptive statistics, analytical framework

Table 3.6 Research objectives and methods

1) Descriptive statistical analysis

Descriptive statistics were used in this thesis to organise and summarise large amounts of monitoring data allowing a better analysis and interpretation of those data (Triola, 2015). This was indeed the reason why this analytical tool was considered appropriate for this research. Since there was a large number of numerical data to be analysed (a total of six weeks of monitoring in two/three rooms, in nine houses), descriptive statistics helped the researcher to organise and summarise the data, which were then more easily visualised and interpreted. As explained by Thomas (2013, p.250), "descriptive statistics are about the simplification, organisation, summary and graphical plotting of numerical data".

The IC and IAQ data collected using the monitoring loggers Wöhler and HOBO were statistically analysed using SPSS® software. The non-parametric ANOVA, Kruskal-Wallis test was considered the most appropriate statistical analysis for the type of data employed in this part of the thesis. The Kruskal-Wallis test can be used to compare the medians of three or more groups (in this case five passive houses and four control houses), following the assumption that "the distribution of values in the population being compared should all be the same shape, but not necessarily normal" (Townend, 2002, p.196). Indeed, this particular analytical test seems to be appropriate when analysing the monitored, not always normally distributed, quantitative parameters (CO_2, temperature and RH), in order to compare the data sets from several houses, and attempting to answer the research questions set above. Kruskal-Wallis tests were performed on all available indoor climate and indoor air quality data collected from the two logging devices. The statistical significance level (P-value) was set at 0.05, which is the standard level of significance used to justify a claim. P-values greater than 0.05 indicate insufficient evidence to say that the populations differ or have no significant difference whilst P-values equal or lower than 0.05 indicate enough evidence to say that the populations do differ or have a significant difference (Townend, 2002).

All monitoring data were converted into boxplots graphs, which showed the distribution of the data. This includes the central tendency (median) or the middle score numbers in a dataset and the spread of the data (range), the lowest and the highest score in the dataset.

2) Laboratory analysis

The indoor air quality data collected by the VOCs passive sampler, were sent to the equipment manufacturers' laboratory and analysed by them. The analysis was carried out in accordance with Gradko's in-house method GLM 13. The laboratory was asked to analyse the samplers and to identify the top 10 most abundant VOCs[15] found in the main bedroom of all houses monitored, as well as the top 10 most abundant VOCs found outdoors, at specific locations, for the case and control houses. VOCs which were marked by the laboratory as 'compounds may be an artefact due to reaction of ozone with the Tenax sorbent' were excluded from the dataset. The identification of the 10 most abundant indoors VOC concentrations in the case and control houses has a twofold purpose. First, the data were used to compare VOCs and their levels among the studied and the control houses. Second, knowing the type of VOCs and their concentrations could be helpful in finding associations between these parameters and any known health outcomes, which is part of the second research objective of this thesis.

3) Criteria based analysis

The second research objective aims to analyse whether passive houses provide their occupants with a healthy indoor environment. It was considered important to identify any known risk factors or health consequences which may have been associated with the indoor environment parameters

[15] The top 10 VOCs refers to the 10 highest concentrations (μgm^{-3}) of VOCs found in the main bedroom.

observed in the different rooms of the passive house dwellings. In order to obtain possible risk factors and/or adverse health consequences associated with indoor climate and indoor air quality, as well as evidence of a safe threshold for the indoor environment, a literature review was carried out and a criteria based analysis was established.

The literature review followed the following criteria: the literature was searched to identify peer reviewed articles from epidemiological, toxicological and other health related research studies that reported any possible health impacts of the indoor climate and indoor air quality parameters monitored in the passive houses. These included the following four parameters: temperature, relative humidity, carbon dioxide and VOCs (including the specific VOCs observed in the monitored bedroom of passive houses and control houses). PubMed, Ovid, Medline and Scopus databases were searched using a combination of terms as shown in table 3.7.

Primary search term	Secondary search term
'temperature',	OR heat OR hot OR cold
'relative humidity',	OR CO_2
'carbon dioxide',	OR VOCs
'volatile organic compounds' AND	OR limonene OR alpha-pinene OR 3-carene OR decane OR undecane OR tetradecane OR pentadecane OR heptadecane OR teracosane OR naphthalene OR docosane OR acetic acid OR 1,4 dichorobenzene OR xylene
Indoor AND	OR room OR inside OR home OR dwelling OR house OR housing OR lounge OR bedroom OR building
Health AND	OR threshold OR heart attack OR stroke OR asthma OR respiratory disease OR COPD OR chronic obstructive pulmonary disease OR blood pressure OR dementia OR influenza OR flu OR mental health OR depression OR vulnerability OR infirm OR bronchitis OR hypothermia OR coronary OR death OR effect OR mortality

Table 3.7 Literature review search terms

The literature search only included papers written in English from inception to 2016. Relevant articles were then selected by reading the abstracts. Many papers reported on the health risks attributed to at least one of the four parameters analysed. However, only papers which reported on possible health risks associated with a specific concentration of one of the four indoor parameters were selected. In addition, papers that offered an evidence base for possible safe indoor thresholds for any of the indoors parameters investigated was also included in the review. The paper selection criteria aimed to bring to light and assess research studies which provided evidence of possible health risks, as well as indoor thresholds related to the range of indoor parameters found in passive houses.

4) Coding textual data

The textual data obtained from interview transcripts and the field diary were analysed using a coding method. Coding is a useful technique which facilitates a thorough examination of textual data, by defining categories in each distinct text and creating relationships between them (Basit, 2003). As Grbich (2007, in Saldaña, 2009, p.8) puts it, coding is a process that permits data to be "segregated, grouped, regrouped and relinked in order to consolidate meaning and explanation". Among the various techniques used for coding textual data, the researcher has adopted the following four, based on the work of Ryan & Bernard (2003):

a) Repetition: Coding "topics that occur and reoccur" (Bogdan & Taylor, 1975).
b) Similarities and differences: This is a "constant comparison method" (Glaser & Strauss, 1967), which aims to compare multiple texts from the same or different transcripts, questioning the similarities and differences between them. The abstract similarities and differences generated by questioning texts, generates themes.
c) Metaphors and analogies: As people often express their thoughts and experiences with analogies and metaphors (Lakoff & Johnson, 1980), their analysis and coding may reveal important themes.
d) Linguistic connectors: Certain words used by interviewees often have the ability to carry meaning in a text. For instance 'because', since' and 'as a result' can indicate casual relations, whereas 'if', 'instead of' and 'rather than' can indicate conditional relations. Other examples are time-oriented words such as 'before', 'after', 'then' and 'next', and words related to negative characteristics, such as 'not', 'no' and 'none'. As noted by Ryan & Bernard (2003, p.92), "investigators can discover themes by searching for such groups of words and looking to see what kind of things the words connect".

Furthermore, the coding of textual data was completed in two cycles, drawing on Saldaña (2009). The first cycle is part of the initial process, where codes were created. These codes included words, sentences, fragments of sentences and complete paragraphs. The second cycle involved the reorganisation and reconfiguration of the codes created in cycle one, aiming to develop a smaller and more specific list of themes, categories and concepts. The two cycles of coding were carried out using NVivo® software.

5) Coding occupants' activity diary

As explained above, the use of a structured, time-based, activity diary served three general purposes: (1) to provide a context around the monitoring data; (2) to help gather information on specific everyday practices and their frequency and (3) to triangulate or cross-check data. On this basis, the data obtained from the occupants' activity diaries were coded in three different ways. First, aiming to provide context around the monitoring data, some quantitative data obtained from the diaries (e.g. number of people sleeping in the monitored bedroom, number of people in the house during the day, window open or closed) was tabulated into an Excel spreadsheet for each monitoring day (refer to Appendix 8). Second, after gathering data about households' everyday activities and their frequency (e.g. how often occupants cooked in the kitchen, what appliances were used), this information was scrutinised using the 'analysis of the content of diaries' (Alaszewski, 2006). This method involves converting diary data into text, which can then be coded and grouped into themes, aiming to produce a narrative which could complement and enrich the narratives produced from qualitative interviews. This complementary information could shed light on how some practices that were (or were not) practiced every day, changed for one reason or another. For instance, a household may state during the interview that they never interacted with the MVHR control whilst the diary entry could indicate that they have changed the settings twice due to a severe change in temperature. The text extracted from the occupants' activity diaries were grouped in themes (e.g. kitchen practices, bedroom practices, MVHR interactions). They were consequently transferred to NVivo® software to be coded in conjunction with the occupants' interview data.

6) Qualitizing descriptive statistical data

For some pragmatists, mixed methods research involves quantitative data being analysed using quantitative methods and qualitative data being analysed using qualitative methods (Tashakkori & Teddlie, 2010). Nevertheless, at some point during the analysis process, a combined method may be necessary when a particular research question dictates the integration of both sets of data (Onwuegbuzie & Combs, 2010). This is indeed the case with the third research objective, where quantitative data (indoor environment monitoring) and qualitative data (occupants' interviews and occupants' activity diary) were integrated as this was considered necessary for the research objective to be fulfilled. The qualitative data have, however an explanatory purpose. Qualitative data were used in attempting to explain the findings obtained from the quantitative data analysis. Therefore, data from the occupants' interviews and activity diaries aimed to explain the social context of the findings obtained from the monitoring of indoor climate and indoor air quality of passive houses.

This explanation requires comparisons between the quantitative monitored data (analysed by descriptive statistics) and qualitative textual data (analysed by coded texts). Although these two sets of data were analysed separately, they must be integrated if the third research objective is to be fulfilled. The integration takes place when the quantitative data, after being subjected to a quantitative analysis, are "transformed into a narrative data that can be analysed qualitatively"

(Tashakkori & Teddlie, 1998; in Tashakkori & Teddlie 2010, p.414). This narrative data is then further analysed using the same process used for qualitative data sets (e.g. text coding) and where the researcher uses a constant comparison technique which attempts to weave both sets of data, by constantly reviewing them, "comparing each element, phrase, sentence and paragraph" (Thomas, 2013, p.235). This is an interpretative approach which aims to compare the elements of the two sets of data so themes that capture the essence of the data can emerge (Thomas, 2013).

7) Analytical framework

Aiming to provide explanations for possible differences in indoor climate and indoor air quality between different passive houses, an analytical framework (figure 3.4) was designed and used as the basis for analysis in Chapter 4. It provided a set of four explanatory variables for each of the indoor parameters monitored. These explanatory variables are: 1) passive house design and construction; 2) property characteristics; 3) external conditions and 4) occupants' practices. Based on evidence from the literature review, table 3.8 provides a summary of the rationale for the explanatory variables included in the analytical framework.

The concept was to use each one of these explanatory variables to test whether they contributed to specific indoor climate and/or indoor air quality outcomes in passive houses. However, it is reasonable to say that some explanatory variables are more strongly relevant to some outcomes than others. For instance, passive house design (e.g. lack of solar shading) combined with occupants' practices (e.g. cooking, ironing) and seasonality (summer) may contribute to high indoor temperatures. Therefore, the explanatory variables were analysed for each outcome of interest, when they were considered relevant to that particular outcome.

The findings from this analysis are used in Chapter 5, aiming to explain how these variables might contribute to possible health risks to passive house occupants.

It is important to point out that a specific indoor climate and/or indoor air quality outcome (e.g. high temperature in the bedroom) might be considered a hazard[16] if it is outside a recommended safe threshold. Additionally, it might only be considered a health risk[17] for passive house occupants if there is exposure.

Hasselaar (2006) has emphasised this point when explaining the framework for the evaluation of the health performance of houses (figure 3.5). The author explains that for the diagnosis of health risk

[16] "A hazard is a potential source of harm or adverse health effect on a person or persons" (H&SA, 2018, p. 1).
[17] "Risk is the likelihood that a person may be harmed or suffer adverse health effects if exposed to a hazard" (H&SA, 2018, p. 1).

stemming from a particular health hazard, one must also analyse exposure. Therefore, drawing on Hasselaar (2006), it is reasonable to occupants' exposure to health risks in passive houses is dependent on a list of explanatory variables (as shown on the right hand column of figure 3.4).

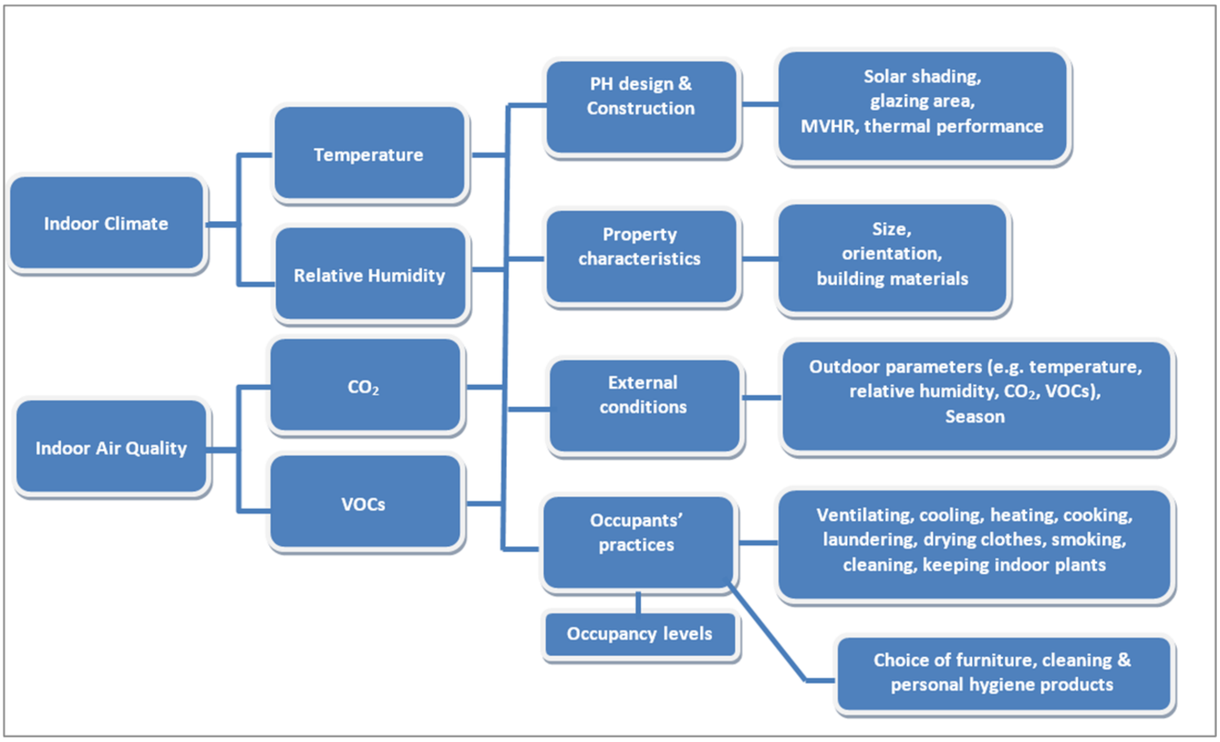

Figure 3.4 Analytical framework

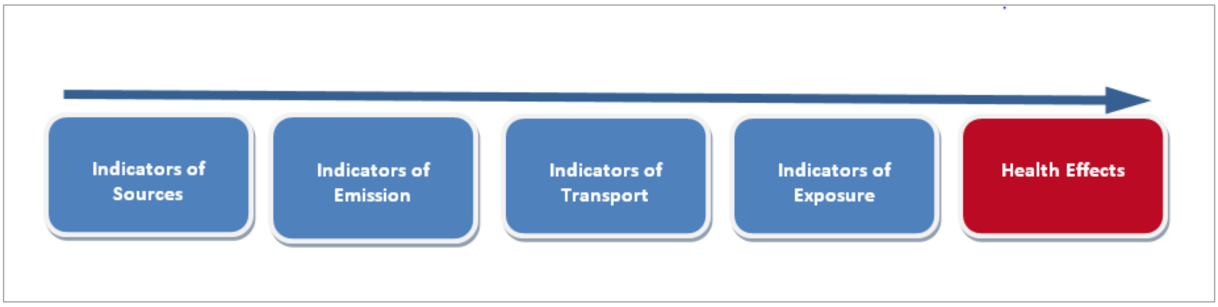

Figure 3.5 Evaluation of the health performance of houses. Adapted from Hasselaar (2006)

	Temperature	RH	CO_2	VOCs
PH design & construction	Indoor heat gains can be influenced by solar shading devices (Larsen et al., 2012; Mlakar & Strancar, 2011) and the size of glazed areas (Csaky & Kalmar, 2015; (McLeod et al., 2013); MVHR system performance can influence indoor temperatures (Zero Carbon Hub, 2012; Lowe & Jonhnson, 1997).	MVHR system (ventilation) can influence indoor RH levels (Howieson et al., 2003).	MVHR system can influence indoor CO_2 levels since they are associated with ventilation rates (Seppanën & Fisk, 2004; Maier et al., 2009).	MVHR system can influence VOC concentrations since they are associated with ventilation rates (Weschler et al., 1990).
Property characteristics	Indoor heat gains can be influenced by the orientation of a building (glazed areas) (Csaky & Kalmar, 2015).	No strong evidence found	Indoor CO_2 is dependent on the size/volume of the room (Seppanën & Fisk, 2004; Batog & Badura, 2013).	Indoor VOC concentrations are usually higher in new buildings when compared with established buildings (Yu et al., 1997). No relationship found between VOC concentrations and room area and volume (Fromme et al., 2008).
External conditions	Correlation between indoor and outdoor temperature only at warmer outdoor temperatures (Nguyen et al., 2014).	Weak association between indoor and outdoor RH (Nguyen et al., 2014). Outdoor RH levels are used on the analytical framework but only to test it in relation to ventilation practices (window opening). E.g. warmer indoor air being replaced with colder and dryer outdoor air.	Atmospheric CO_2 levels are currently around 405 ppm (Earth System Research Laboratory, 2017). Seasonal variation between spring/summer and winter CO_2 levels (generally less than 10 ppm) (Earth System Research Laboratory, 2017).	Some VOCs originate outdoors and can enter the indoor environment through indoor/outdoor air exchange (Hess-Kosa, 2012).
Occupants' practices	Ventilation can influence indoor temperatures (Larsen et al., 2012; Mlakar & Strancar, 2011). Ventilations practices include opening windows and MVHR interactions. Using electrical appliances to cook, clean, wash dishes, etc. can increase indoor temperatures as they convert electrical energy into heat energy (Parsons, 2001).	Practices which emit water vapour: cooking, dishwasher opening, clothes washing and drying (Firlag & Zawada, 2013; TenWolde & Pilon, 2008). Ventilation can introduce or reduce humidity in the indoor air depending on the difference of internal/external humidity levels (Howieson et al., 2003). Ventilations practices include opening windows and MVHR interactions.	Ventilation was associated with CO_2 levels (Maier et al., 2009). Ventilations practices include opening windows and MVHR interactions. Keeping indoor plants can influence CO_2 concentrations (Cetin & Sevik, 2015).	Ventilation - insufficient ventilation is associated with high indoor VOC concentrations (Weschler et al., 1990). Ventilations practices include opening windows and MVHR interactions. Tobacco smoke – VOC concentrations were found to be higher in homes where occupants smoked compared with homes with non-smoking occupants (Kim et al., 2001).
Occupancy levels	Indoor heat gains can be influenced by the metabolism of occupants as people emit heat (Simon et al., 2011).	Indoor moisture gains can be influenced by the metabolism of occupants as people emit water vapour (Firlag & Zawada, 2013; TenWolde & Pilon, 2008).	Indoor CO_2 is dependent on the number of occupants and the duration of occupancy since people inhale oxygen and expel CO_2 as a waste product (Seppanën & Fisk, 2004).	No strong evidence found
Others	N/A	N/A	N/A	The use of cleaning and personal hygiene products, building materials, wood-based furniture and furnishings can influence indoor VOC concentrations (Hess-Kosa, 2012; Toren & Hermansson, 1999).

Table 3.8 Summary of the rational for the explanatory variables included in the analytical framework

3.6. Ethical considerations

As explained by Vanderstoep & Johnston (2009, p.12), “research ethics deals with how we treat those who participate in our studies and how we handle the data after we collect them”. Furthermore, UEA (2012, p.1) states that “ the concept of ethics is taken to define systems of moral principles or values, principles of right or good behaviour in relation to others, integrity and the rules and standards of conduct binding together members of a profession”.

Ethical considerations for the thesis were made according to the University of East Anglia Research Ethics Policy, Principles and Procedures (UEA, 2012), prior to, during and after the completion of the research activities.

Ethical considerations included considering the safety and wellbeing of participants and colleagues, obtaining informed consent from research participants, providing anonymity and confidentiality and protecting data. How each of those elements were considered prior to, during and after the research will be explained in turn.

The safety and wellbeing of participants were considered prior to the research stage. The ethics policy developed by UEA (2012, p.5) states that “people participating in research should not be exposed to risks that are greater than, or additional to, those they encounter in their normal lifestyles”. This was ensured by designing a research methodology where data could be collected from a real world context, where the indoor environment of passive houses was monitored without manipulating indoor conditions, and therefore not exposing occupants to possible risks to their safety and wellbeing.

Prospective participants were also informed that the researcher would carry photographic identification when visiting their homes for interviews or setting up the monitoring equipment. This procedure aimed to ensure that participants felt safe in their homes.

Informed consent of participation in the research was obtained from each participant (refer to Appendix 9). As defined by the UEA Research Ethics Policy (UEA, 2012, p.6), “informed consent is the process whereby a prospective participant, prior to participating in research, is fully informed about all aspects of the research project which might influence their willingness to participate, in a language which the participant understands. In addition, the researcher should normally explain all other aspects of the research about which the prospective participants enquire. The basis of this is to provide free and voluntary consent”.

Therefore, the following actions were taken to ensure that all participants were given informed consent:

1. All prospective participants were sent a leaflet inviting them to take part in the study. This leaflet contained brief information about the research, together with information on when and how the householders would participate.
2. A follow up telephone call to prospective participants was made. Again, this allowed the researcher to inform the prospective participants about the objectives of the research, who was carrying out the research, and how and when they would take part.
3. Research participants were provided with a research information sheet (refer to Appendix 10) which explained in detail the purpose of the research, who was carrying out the research, what taking part in the research involved and gave a brief explanation of the monitoring equipment to be installed in their houses.
4. Research participants were informed that any feedback from the data collected would be given after completion of the third round of data collection. It was explained to the participants that this procedure was followed to ensure that householders did not change their everyday practices as a result of receiving information from the research.
5. Prospective participants were informed that their participation was voluntary and that they did not have to answer questions they did not wish to. They were also informed that they could withdraw from the research at any point in time, and for whatever reason, if they no longer wished to take part in the study.
6. Prospective participants were informed that their information and all the data collected were to be treated with the utmost confidentiality, and would not be shared beyond the few people involved with the research process (e.g. researchers, research supervisors). They were also informed that their identity would be kept anonymous from any other parties (e.g. the housing association, readers of the research findings).
7. Before the dictaphone began recording, research participants were asked whether they were happy to be recorded.

The anonymity, confidentiality and data protection of research participants complied with the Data Protection Act 1998 and subsequent revisions. The purpose of the Act is to ensure that “researchers make arrangements to carefully protect the confidentiality of participants and ensure the security of their data. All personal information collected should be considered privileged information. It should be dealt with in such a manner that it does not compromise the personal dignity of the participants or infringe upon their right to privacy” (UEA, 2012, p.8).

The following steps were taken to ensure the anonymity, confidentiality and data protection of research participants:

1. Randomly assigned codes were used when referring to the studied houses and control houses. These codes have no connection to the house number.
2. Pseudonyms were used when transcribing interview data, and on the thesis. The pseudonyms have no connection with the participants' names, so participants cannot be identified.
3. Any information containing the name, address and other personal details of the participants were kept in a locked cupboard.
4. Participants' names and addresses were not kept on any computer hard drive.

Protecting the identity of the passive house scheme was an additional step taken to protect the identity of the research participants. Any information that could be linked to the passive house scheme was concealed. For instance, the name of the passive house scheme, the name of the passive house housing provider as well as the name of the management company responsible for the researcher's access to the site, were replaced by pseudonyms.

The research had the approval of the General Research Ethical Committee (refer to Appendix 11).

Chapter 4 – The indoor environment of passive house rooms: investigating indoor climate and indoor air quality and explaining observed differences

4.1. Introduction

Policies related to the reduction of both carbon dioxide emissions and energy consumption within the residential sector, have contributed towards a growing number of passive houses and other highly energy-efficient houses being built in many countries. Because passive house standards prescribe the design and construction of well insulated and airtight structures, there has been an increasing concern over the quality of the indoor environment in these homes. Furthermore, it has been questioned, whether the move towards higher standards of energy performance and airtightness is unintentionally compromising the comfort and health of home occupants (Dengel, 2013). Although passive houses are not completely sealed structures, since they are supplied with a MVHR system for continuous ventilation, there has been some scepticism as to whether these systems are performing as expected (Balvers et al., 2012).

Even though passive house supporters advocate that this housing standard creates homes that are comfortable and healthy (International Passive House Association, 2010), little is known about the indoor environment of passive houses, especially in the UK. More information about the passive house indoor environment is therefore necessary to verify whether these houses are healthy.

Although passive houses have received much attention in recent decades, studies investigating these low energy houses have mainly focused on their thermal performance from an energy efficiency perspective (e.g. Feist & Schnieders, 2009; Ridley et al., 2013), whilst rarely addressing their indoor climate and indoor air quality from a health viewpoint. Furthermore, some of the few studies which do address some indoor climate aspects of passive houses, seem to use indoor environmental parameter data (e.g. temperature and relative humidity) in an attempt to investigate the durability of building materials (e.g. Mlakar & Štrancar, 2013), rather than considering aspects related to health.

Nevertheless, a few recent studies have investigated the indoor climate and the indoor air quality of passive houses and other low energy houses worldwide (e.g. Langer et al., 2015; Derbez et al., 2014) and in the UK (e.g. McGill et al., 2014; Sharpe et al., 2014). However, these not only represent a very limited number of studies exploring the indoor environment of passive houses, from a health perspective, but they also offer insufficient information about the possible differences between the indoor climate and the indoor air quality of distinct rooms. For instance, some studies only focus on one area (e.g. Sharpe et al. (2014) investigate bedrooms only). Furthermore, a very limited number of studies have explored how the indoor environment of passive houses may change following seasonal variation.

By investigating the indoor environment of more than one location in the passive house (e.g. bedroom, living room and kitchen), taking into consideration seasonal variations, a research study could not only investigate the indoor environment quality of different rooms in passive houses, it could also attempt to analyse how the study findings may differ due to changes in the season, consequently exploring what the results of the investigation could mean to the health of home occupants. This more detailed examination of the passive house attempts to understand the indoor environment quality of specific rooms, through different seasons.

This approach may produce findings which would not otherwise have come to light when using a more holistic approach. For example, monitoring data from bedrooms may present high levels of CO_2 in the winter and low levels in the summer, whilst CO_2 data from the living room may present the opposite trend.

This study also attempts to explain the reasons for the observed differences in indoor parameters between similar rooms in different passive houses and between different rooms in the same passive house. It does that by applying an analytical framework (discussed in Chapter 3) to a particular outcome variable of interest (e.g. high temperature in passive house kitchens), trying to link it to a set of explanatory variables.

Each of the explanatory variables from the analytical framework is applied systematically to the outcome variable of interest. After the analysis, a variable is either accepted or rejected, depending on its ability to offer an explanation to the outcome variable of interest. It is important to mention that some explanatory variables are more strongly relevant to some outcomes than others. Therefore, if an explanatory variable was considered less relevant in explaining a specific outcome, that variable was not included in that particular analysis. For example, room orientation might offer a strong explanation for high indoor temperature whilst it is less relevant when explaining low indoor relative humidity.

This chapter also aims to analyse how some of the results found in UK passive houses compare with the results found in conventional UK houses. Having a control group is important to this study because without it, one could not know whether the results observed in UK passive houses differ from UK conventional houses.

Furthermore, some of the results found in this thesis chapter will also serve as the basis of analysis in the next chapter. Since the next thesis chapter attempts to analyse whether passive houses provide their occupants with a healthy indoor environment, it is essential that the data presented here are subsequently used.

The chapter is divided into two parts. The first part focuses on the indoor climate of passive houses and conventional houses whilst the second part focuses on the indoor air quality of these houses. Both parts begin by presenting the results obtained from the passive houses, followed by the results obtained from the conventional houses and subsequently, they present a comparison between these two groups.

4.2. Comparing the indoor climate and its seasonal variations in the bedroom, living room and kitchen in passive houses and in conventional houses

Indoor climate data were collected from the living room, bedroom and kitchen, in five passive houses (PH1, PH2, PH3, PH4 and PH5) and four conventional (control) houses (CH1, CH2, CH3 and CH4). The five studied passive houses represent two dwelling types, whereas PH1 and PH2 are identical[18] 3 bedroom houses and PH3, PH4 and PH5 are identical 4 bedroom houses. CH3 and CH4 are the control houses for the passive houses PH1 and PH2 whereas CH1 and CH2 are the control houses for passive houses PH3, PH4 and PH5. Therefore the results presented in the chapter show comparisons between the five passive houses, comparisons between the two groups of identical passive houses, comparisons between different rooms in the same passive house as well as comparisons between passive houses and the corresponding control houses.

Indoor climate data (temperature and relative humidity) are presented using boxplot graphs. The bottom and the top of the boxes represent the 25th and 75th percentiles and the line near the middle of the box represents the median. The end of the whiskers indicates the minimum and maximum temperatures.

4.2.1. Temperature

Figures 4.1, 4.2 and 4.3 display boxplots showing the seasonal variation in temperature in a specific room in the passive houses and control houses. Figure 4.1 shows the data gathered in the monitored bedroom[19] of case and control houses, figure 4.2 shows the data gathered in the living room of case and control houses, whilst figure 4.3 shows the data gathered in the kitchen of the case houses

[18] These identical dwelling types also present identical room orientation. Refer to table 4.1 for details of room orientation for all houses.
[19] The monitored bedroom was the main bedroom in the dwelling, where two adults slept.

only[20]. Because the room solar orientation can also influence indoor temperatures (Ali-Toudert & Mayer, 2006), the figures also show the solar orientation of each of the rooms monitored.

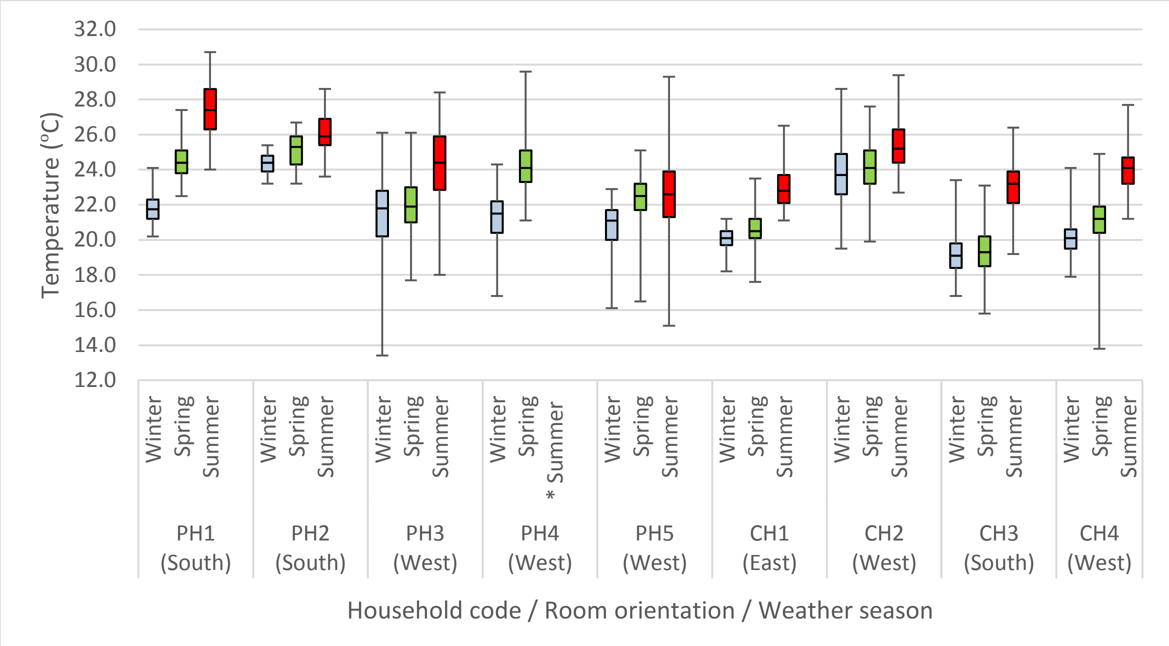

Figure 4.1 Boxplots showing seasonal variation of temperature in the monitored bedroom of passive houses (PH) and control houses (CH). (The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

[20] Data obtained from the kitchen were only collected from passive houses due to constraints related to the case study. Please refer to the methodology chapter for further details.

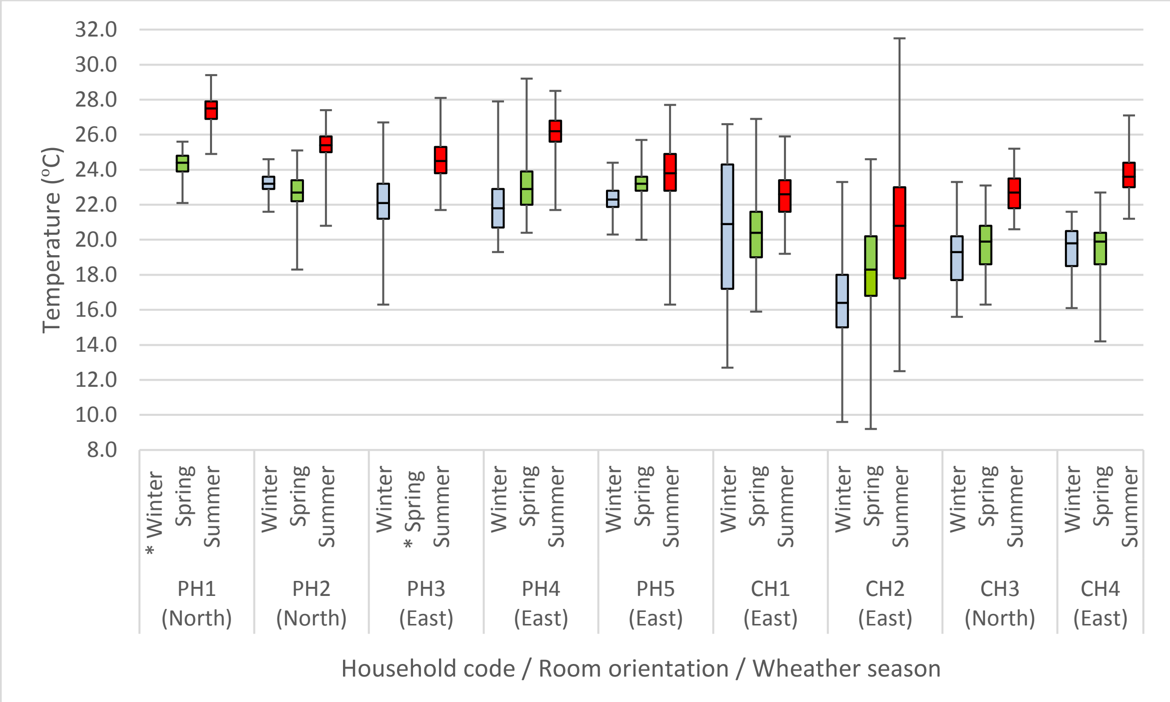

Figure 4.2 Boxplots showing seasonal variation of temperature in the living room of passive houses (PH) and control houses (CH). (The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

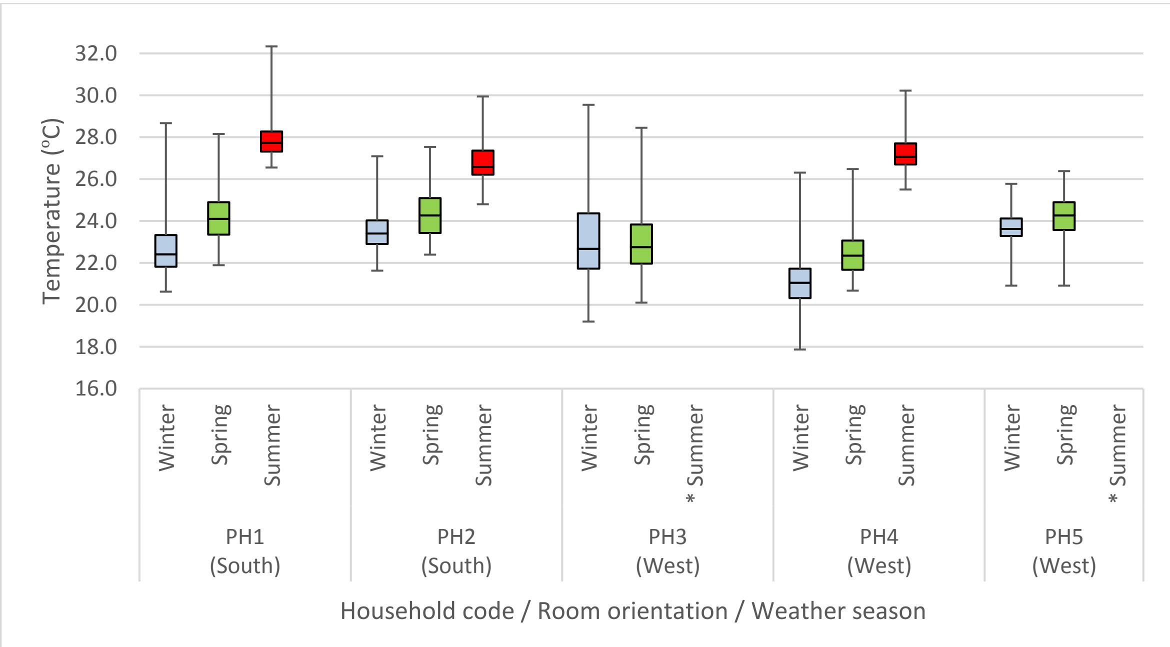

Figure 4.3 Boxplots showing seasonal variation of temperature in the kitchen of passive houses (PH). (The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

a) Passive houses

Overall, temperatures in all passive house monitored rooms were higher in the summer and lower in the winter. Spring temperatures were lower than summer temperatures but higher than winter temperatures, with the exception of the living room of PH2, where winter and spring median temperatures were 23.2°C and 22.7°C respectively.

Although temperatures in the bedroom of passive houses had the highest variation among all three monitored rooms, ranging from 13.4°C in the winter (PH3), to 30.7°C in the summer (PH1), the bedroom of 3 bed houses presented a different trend compared with the bedroom of 4 bed houses. The temperature in the bedroom of the 4 bed passive houses showed the highest variation through all seasons, ranging from 13.4°C (PH3) in the winter to 29.6°C (PH4) in the spring, whereas the temperature in the bedroom of the 3 bed passive houses ranged from 20.2°C (PH1) in the winter to 30.7°C (PH1) in the summer. The temperature in the bedrooms of the 3 bed passive houses was overall higher than the temperature in the bedrooms of the 4 bed passive houses, during all three seasons. During the winter, in particular, very low temperatures were observed in the monitored bedroom of the 4 bed passive houses.

Aiming to provide an explanation for the differences in temperature observed in the monitored bedroom of the studied passive houses, five days[21] were extracted from the total two weeks of monitoring and further analysed. Figure 4.4 shows the indoor temperatures in the monitored bedroom of the five studied passive houses, during the winter season, during those five days of monitoring. The figure shows particularly low temperatures (under 18°C) in the monitored bedroom of the 4 bed passive houses PH3 (at night on day 1, 2, 3, and during the day on day 4) and PH5 (during the day on day 3). In addition, much higher temperatures were observed in the 4 bed passive house PH3 during the day (e.g. over 24°C on days 2, 3, and 4).

[21] To enable a more detailed analysis of the data, five days of monitoring were extracted from the total data set of two weeks. A five day extract was considered appropriate by the researcher, as it provides more clarity over temporal variations in monitoring data, allowing clearer association with explanatory variables (e.g. those recorded in the diaries). A five day extract (first five days of monitoring) is used for further detailed data analysis throughout this chapter.

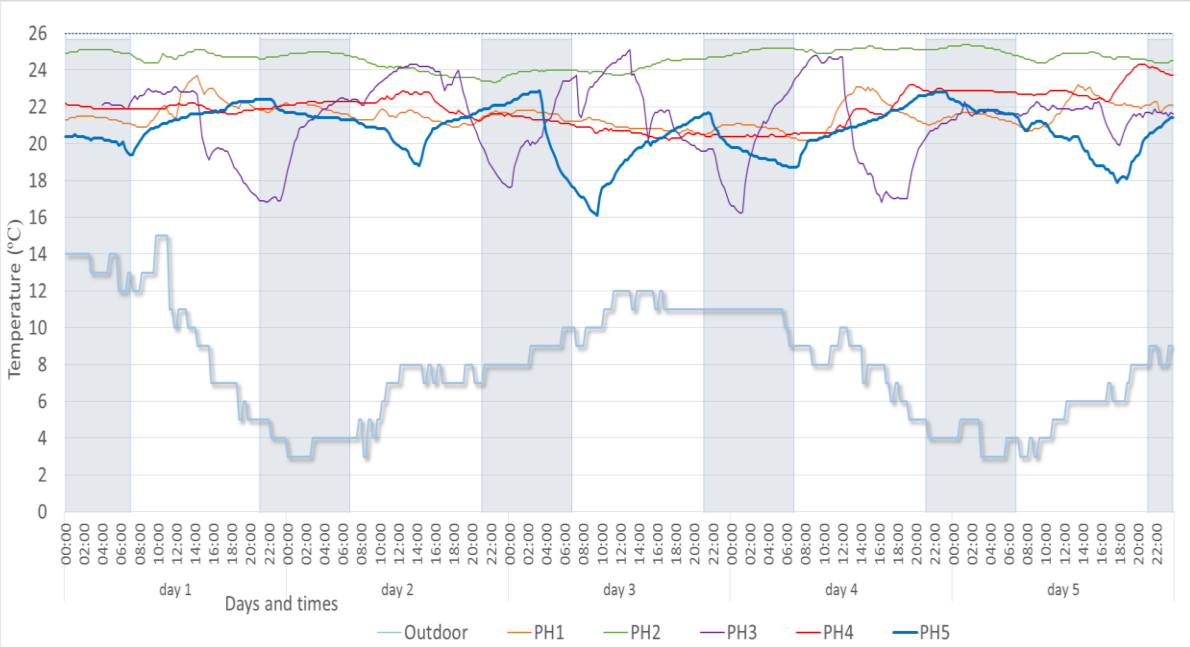

Figure 4.4 Indoor temperature in the monitored bedroom of the passive houses during the winter season, during five days of monitoring. (The grey columns indicate the typical period of bedroom occupancy – from 21:00 to 07:00)

By using the explanatory variables from the analytical framework introduced in Chapter 3, some possible explanations were considered:

1) Passive house design & construction (e.g. energy performance, solar shading, glazing area, MVHR)

The design and construction of the studied passive houses could have contributed to the significant differences in temperatures between the monitored bedroom of the 3 bed and the 4 bed passive houses. In terms of building fabric and energy performance, it was noted that all five passive houses complied with the minimum requirements for UK passive houses (as shown on table 3.3, Chapter 3). However, the researcher did not have access to the results for all elements (e.g. specific heating load). Nevertheless, since all passive houses were compliant with the minimum requirement regarding most elements (e.g. wall, roof, floor, window thermal performance, air permeability), it is not possible to say that the energy performance is a valid explanatory variable for the difference in indoor temperature. Therefore this variable was rejected.

Another design factor considered was heating gains through glazing areas (windows), as the larger the glazing area, the more heating would be gained through that element. Nevertheless, because the two groups of passive houses had identical glazing area in the bedroom (2.85 m^2), this design factor was rejected as an explanatory variable for the difference in indoor temperature between the 3 bed and the 4 bed passive houses.

Solar shading to glazing areas was also considered as an explanatory variable to the temperature differences observed. However, because none of the studied passive houses had any external shading to windows, this variable was also rejected.

The performance of the MVHR system was the third factor to be considered under PH design & construction. It is not possible to know with any certainty how well the MVHR units were performing during the monitoring periods, without testing them (which was not part of the scope of the research). The MVHR commissioning data sheets for each of the passive house dwellings were obtained by the researcher. These documents provide details on the MVHR performance when the units were commissioned (just before occupants moved in). Table 4.1 illustrates the MVHR performance details at the point of commissioning.

Room	Design targets (3 bed)		PH1		PH2		Design targets (4 bed)		PH3		PH4		PH5	
	S (m^3/h)	E (m^3/h)	S (m^3/h)	E (m^3/h)	S (m^3/h)	E (m^3/h)	S (m^3/h)	E (m^3/h)	S (m^3/h)	E (m^3/h)	S (m^3/h)	E (m^3/h)	S (m^3/h)	E (m^3/h)
Bedroom 1	**25**		25		25	-	**23**	**-**	23.1	-	22.2	-	23.2	-
Bedroom 2	**22**	**-**	21.3	-	22.5	-	**23**	**-**	21.3	-	28.6	-	23.1	-
Bedroom 3	**22**	**-**	22.9	-	22.5	-	**23**	**-**	20.3	-	23.2	-	25.6	-
Bedroom 4	**N/A**	**-**	-	-	-	-	**23.4**	**-**	22	-	22.6	-	25.5	-
Living room	**25**	**-**	25.3	-	25.5	-	**30.6**	**-**	30.4	-	32	-	32	-
Dining	**-**	**-**	-		-	-	**27**	**-**	27.2	-	29.2	-	26	-
Kitchen	**-**	**36**	-	35.3	-	35.9	**-**	**43**	-	41.7	-	42.9	-	42.9
Bathroom 1	**-**	**22**	-	20.2	-	21.9	**-**	**27**	-	27.5	-	27.7	-	27.9
Bathroom 2	**-**	**-**	-	-	-	-	**-**	**27**	-	27.3	-	27.6	-	30.1
WC	**-**	**15**	-	15	-	15.9	**-**	**27**	-	27.2	-	31.1	-	27.3
Cupboard	**-**	**21**	-	21.2	-	21.1		**27**	-	26.9	-	29.5	-	30.9
Total	**94**	**94**	94.5	91.7	95.5	94.8	**151**	**151**	144.3	150.6	157.8	158.8	155.4	159.1

Table 4.1 MVHR performance measured during commissioning, showing the air supply (S) and air extraction (E) achieved in each room. The highlighted rows indicate the monitored rooms

Table 4.1 shows the air supply and air extraction rates achieved in the five studied passive houses and compares them to the design target rates. During the commission, the MVHR system in all passive houses was balanced (within a 10% margin as required by the Passivhaus standard) so the total supplied air rate was equal to the total extracted air rate. Additionally, the air supply and air extraction rate was adjusted following the design target rates (within 10% margin) in all rooms in the studied passive houses. Although, the diary data suggest that passive house occupants had very little or no interaction with the MVHR system (e.g. changing settings, turning off the system), there is no certainty that those ventilation rates were achieved during the monitoring period. However it has been assumed that even if there were some differences in terms of the ventilation rates supplied to the monitored bedrooms, it wouldn't be sufficient to cause such significant temperature differences among the passive houses.

2) Property characteristics (size, orientation)

In the case of the monitored bedrooms of passive houses, the orientation of the room can contribute to variations in indoor temperature. As previously discussed, glazing areas on the building envelope (e.g. windows) can contribute to heating gains inside a building during colder seasons, with the glazing size being one of the factors which determines how much heat is gained. The other factor to take into account is the orientation of the glazing area, as for example, south facing windows located within the north hemisphere, may benefit from additional heat gains compared with west facing windows (Csaky & Kalmar, 2015).

However, as explained earlier, because the window glazing area in the monitored bedroom of the two groups of passive houses (3 bedrooms and 4 bedrooms) were identical, this possible explanatory variable was rejected. Nevertheless, the two groups of passive houses have different solar orientation, with the 3 bed passive house monitored bedroom facing south and the 4 bed passive house monitored bedroom facing west. Therefore, it is reasonable to suggest that the room orientation contributed to the differences in indoor temperatures observed between these rooms, during the day time, in the winter monitoring period.

3) External conditions (temperature)

In relation to indoor temperature differences, outdoor temperature was considered as a possible causal factor. However, as shown on the previous figure 4.4 none of the five passive houses seem to have indoor bedroom temperatures strongly correlating to outdoor temperature. Nevertheless, passive house PH3 seem to have lower temperatures (18^{o}C) in the bedroom, mostly at night time, and higher temperature (over 24^{o}C) during the day. Again, it seems unlikely that changes in indoor temperature are caused by outdoor temperatures, as no clear correlation was observed in figure 4.4. Another possible and acceptable explanation for this could be associated to occupancy levels in the bedroom during the day (e.g. children playing in the bedroom). Although, during the interviews occupants were asked when the main bedroom was used and why, and the answer was that it was used mainly during the night (for sleeping, relaxing, etc.), figure 4.5 shows that there was occupancy in the monitored bedroom (passive house PH3) also during the day. This is indicated by the high CO_2 levels (over 800 ppm) during the day time. Figure 4.5 shows some correlation between bedroom occupancy during the day and higher indoor temperatures in the monitored bedroom of passive house PH3.

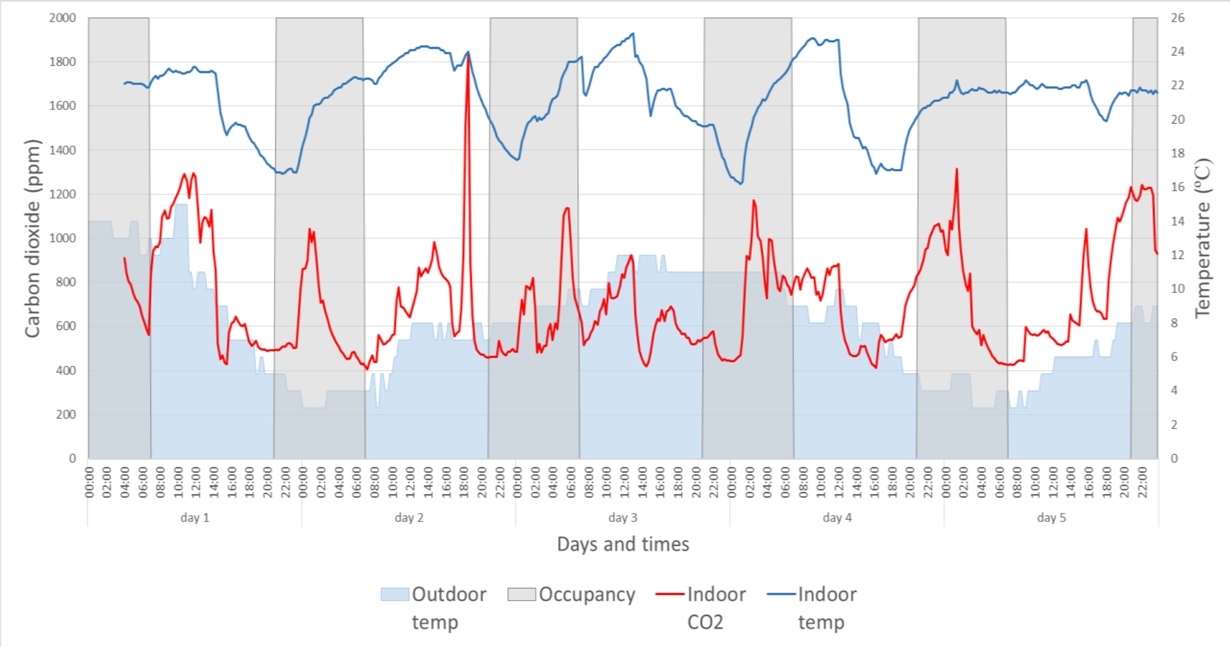

Figure 4.5 Indoor temperature and carbon dioxide in the monitored bedroom of the passive house PH3 during the winter season, during five days of monitoring. (The grey columns indicate the typical period of bedroom occupancy as indicated by the occupants – from 21:00 to 07:00)

4) Occupants' practices (occupancy levels, heating, ventilating by opening windows and using the MVHR)

The fourth analytical variable used to explain the differences in indoor temperature in passive houses is occupants' practices. This is closely related to occupancy levels, as previously discussed, as people (and their practices) can produce or reduce heat, which in turn can cause indoor temperature changes. In the monitored bedroom, such practices were associated with the use of radiators (or other heating sources), the use of electrical appliances and ventilation (e.g. opening the windows or boosting the MVHR system).

During the winter, all the five passive house householders admitted to having turned the radiators on a few times, for a brief period during the day (e.g. 20 min), to warm up the house. However, this variable seems weakly correlated with differences in bedroom temperature between passive houses. For instance, the monitored bedroom of passive house PH2 had overall the highest indoor temperature (as shown on figure 4.4). However, during the interviews PH2 occupants claimed to have turned the radiators on only twice during the winter, and for a short period of time (20 min). On the other hand, occupants of the other passive houses (PH3, PH4 and PH5) claimed to have turned on the radiators throughout the house on a daily basis during the winter, for a brief period of time (20 min) to warm up the house. Nevertheless, the monitored bedroom of PH3, PH4 and PH5 had much lower temperatures when compared with PH2. No other heating sources was used during the winter in any of the studied passive houses.

Another practice which could have influenced the indoor temperature in the monitored bedroom is ventilation (through opening windows). Since the external temperature was lower than the indoor temperature (figure 4.4), opening the window would reduce indoor temperatures, through outdoor/indoor air exchange.

During the winter season ventilation practices in the monitored bedroom were not performed in the same way by all five passive house householders. PH1, PH2 and PH4 households claimed to have left the bedroom window closed for most of the time. On the other hand, occupants of passive house PH3 claimed to have opened the bedroom window for 10 minutes every day and all night during the winter, whilst PH5 occupants claimed to have opened the bedroom window all day and night on the latch (by 5 cm) during the same season. Temperatures in the monitored bedroom of passive houses PH3 and PH5 were statistically significantly lower ($P<0.05$) when compared with the other three passive houses.

Ventilation practices performed in the monitored bedroom of passive houses PH3 and PH5 seem to offer a strong explanation for the low temperatures (under 18 ^{o}C) observed in the bedroom of those houses during the monitoring period. For instance, the bedroom of PH3 had the highest temperature variation compared with the other passive houses. High temperatures (over 24^{o}C) were observed during the day whilst low temperatures (under 18^{o}C) were observed mostly during the night. This seems to have been caused by occupants ventilating the bedroom all night, whilst only ventilating it for 10 minutes during the day.

Ventilation practices could also offer some explanation for the reasons why the monitored bedroom of the 3 bed passive houses had overall higher temperatures when compared with the bedroom of the 4 bed passive houses, during the winter season. Occupants of the 3 bed passive houses PH1 and PH2 claimed to have kept the bedroom windows closed for most of the time during the day and night. Therefore, there was less indoor air (warm) to outdoor air (cool) exchange in the bedroom of those houses compared to the bedroom of the 4 bed passive houses PH3 and PH5, for example.

It is interesting to note that the information contained in the passive house users' manual advised occupants not to leave the windows and doors open for long periods of time in the winter, and to keep the curtains open to collect as much heat from the sun (solar gains) as possible. The occupants of the five passive houses indicated to have kept the curtains in all room open during the day in the winter. However, only the occupants in passive houses PH1, PH2 and PH4 indicated to have kept the windows closed for most of the time in the winter. Contrary to the users' manual advice, occupants of passive houses PH3 and PH5 indicated to have left the bedroom window open all night in the winter, which likely contributed to the low temperatures (under 18^{o}C) observed in the monitored bedroom.

Statistically significant differences ($p<0.05$) were found between the monitored bedrooms of passive houses, living rooms and kitchens during the same season, as shown in table 4.2. When comparing temperatures in the monitored bedroom, during the same season, among all five passive houses, it was observed that there were statistically significant differences between all bedrooms, except between PH1 and PH3 during the winter season. Similarly, living room temperatures were statistically significantly different between most passive houses, with one exception (PH3 and PH5 in the winter). In the kitchen, all houses also presented statistically significant differences in median temperature, with two exceptions (PH1 and PH5, and PH2 and PH5 during the spring season).

These data show that in most cases, even identical houses presented statistically significant differences in room temperature during all the three seasons. For instance, when looking at the winter temperatures in the kitchen in figure 4.3, temperature differences can be observed among all five houses. The identical PH1 and PH2 houses show a median temperature of 22.4°C and 23.4°C respectively, whilst the identical PH3, PH4 and PH5 houses show a median temperature of 22.7°C, 21.1°C and 23.6°C respectively. The difference in temperature between passive house kitchens were statistically significantly ($p<0.05$) (refer to table 4.2). Possible explanations related to the differences observed in identical passive houses are explored in Chapter 6.

Season	**Rooms**		
	Bedroom	**Living room**	**Kitchen**
Winter	SSD between all rooms, except between PH1 & PH3	SSD between all rooms, except between PH3 & PH5	SSD between all rooms
Spring	SSD between all rooms	SSD between all rooms	SSD between all rooms, except between PH1 & PH5, PH2 & PH5
Summer	SSD between all rooms	SSD between all rooms	SSD between all rooms

Table 4.2 Statistically significant difference (SSD) in temperature between the monitored rooms in different passive houses. (P<0.05)

Comparisons of indoor temperature were also made between the monitored bedroom, living room and kitchen in the same passive house, during the same season. Figures 4.6, 4.7 and 4.8 show comparisons between the temperatures in these rooms during the winter, spring and summer seasons respectively.

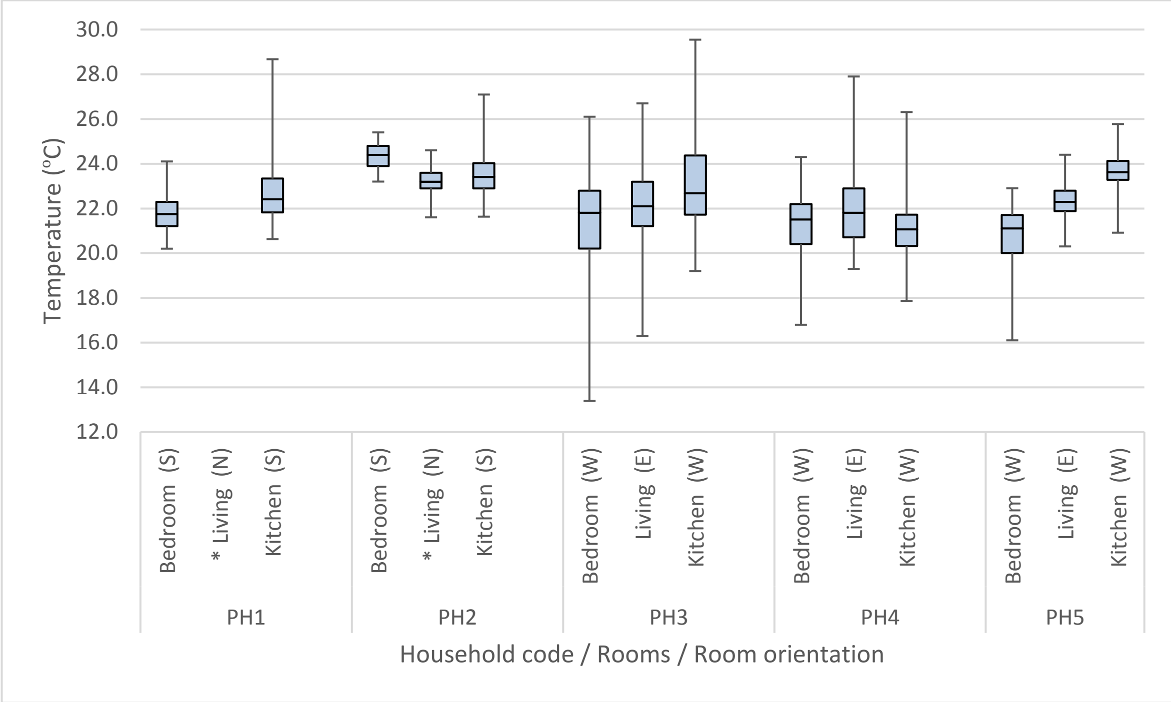

Figure 4.6 Boxplots showing temperatures in the monitored bedroom, living room and kitchen in passive houses (PH) during the winter season. (The letter in brackets refers to the room orientation. The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

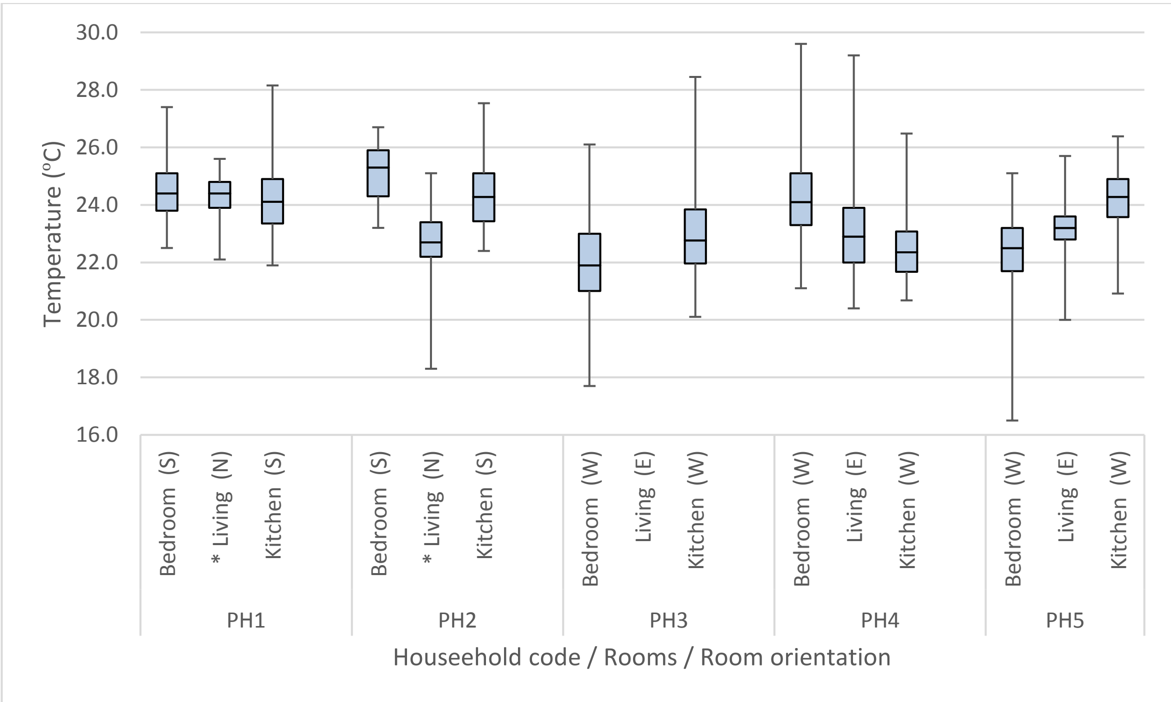

Figure 4.7 Boxplots showing temperatures in the monitored bedroom, living room and kitchen in passive houses (PH) during the spring season. (The letter in brackets refers to the room orientation. The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

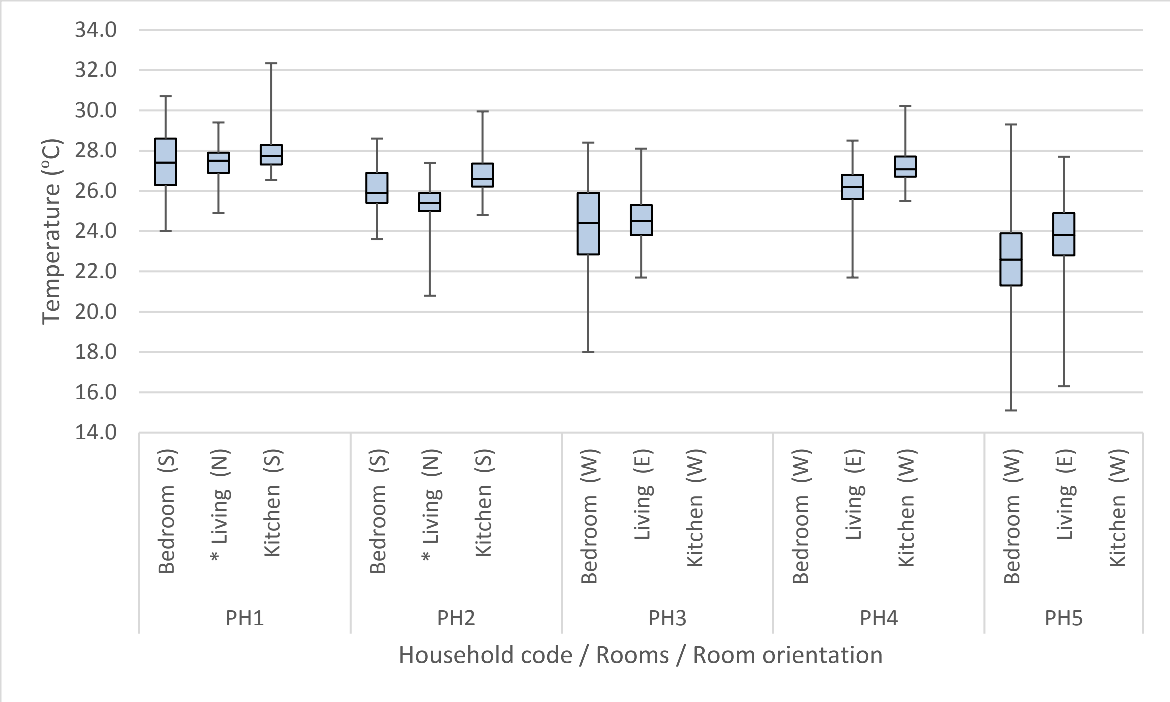

Figure 4.8 Boxplots showing temperatures in the monitored bedroom, living room and kitchen in passive houses (PH) during the summer season. (The letter in brackets refers to the room orientation. The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

Passive house code	**Season**		
	Winter	**Spring**	**Summer**
PH1	SSD between all rooms	SSD between all rooms except between Bed & LR	SSD between all rooms except between Bed & LR
PH2	SSD between all rooms	SSD between all rooms	SSD between all rooms
PH3	SSD between all rooms	SSD between all rooms	SSD between all rooms
PH4	SSD between all rooms	SSD between all rooms	SSD between all rooms
PH5	SSD between all rooms	SSD between all rooms	SSD between all rooms
Key: Bed = bedroom; LR = living room; Kit= kitchen			

Table 4.3 Statistically significant difference (SSD) in temperature between the monitored bedroom, living room and kitchen in the same passive house (PH). (P<0.05)

As shown in table 4.3, analysis revealed that in most cases, there were statistically significant differences in temperature between the three monitored rooms, in the same passive house. When these three rooms were compared, it was observed that, with a few exceptions, temperatures in kitchens were somewhat higher than in other rooms, especially during the summer season (figure 4.8). For instance, the lowest temperature observed in a passive house kitchen was 17.9°C, found in PH4 during the winter monitoring (figure 4.6). Additionally, the available data from the kitchen summer monitoring also show that passive houses PH1, PH2 and PH4 had maximum temperatures peaking beyond 30°C (figure 4.8). In contrast, passive house monitored bedrooms and living rooms had winter temperatures as low as 13.4°C (PH3) and 16.3°C (PH3) respectively (figure 4.6).

Figure 4.9 shows the temperature in the monitored bedroom, living room and kitchen in passive house PH2[22] during five days of monitoring. The figure also shows the CO_2 levels observed in the monitored bedroom and living room during the same period. Carbon dioxide levels were introduced in this figure, as they offer useful information regarding occupancy in the monitored rooms. For example, in a domestic environment, when CO_2 levels rise well beyond levels normally found outdoors (around 400 ppm), it is reasonable to suggest that the room is occupied.

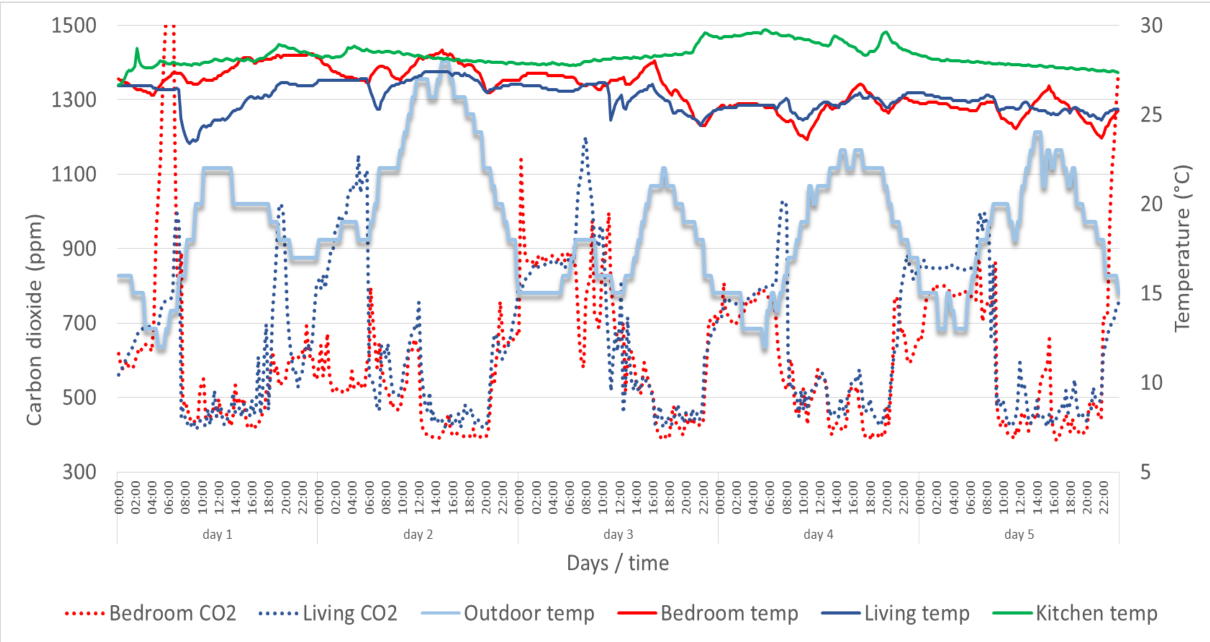

Figure 4.9 Indoor temperatures and carbon dioxide in the monitored bedroom, living room and kitchen of passive house PH2 during the summer season

Using the monitoring data collected from the bedroom, living room and kitchen in passive house PH2 and the data from interviews and diaries obtained from PH2 occupants, the following explanations were considered for the significant difference in temperatures between the three rooms:

1) PH design & construction (glazing area, solar shading, MVHR)

As previously discussed, the area of the glazing on the building envelope can influence the indoor temperature. During the summer season, buildings with large windows usually have higher indoor temperatures compared with building with smaller windows. Table 4.4 shows the glazing areas and the solar orientation of each monitored room in the studied passive houses. As the data suggest,

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[22] Passive house PH2 was chosen for this part of the analysis as it showed very high temperature in the kitchen during the summer season and because PH2 had a complete data set from the three monitored rooms.

glazing area offers a weak correlation to the high temperature in the kitchen of passive house PH2 since the kitchen had the smallest area of window glazing (2.35m^2) compared with the other two rooms, living room (4.11m^2) and bedroom (2.85m^2). Nevertheless, the kitchen had significantly higher temperatures when compared with the other two rooms. Therefore, this variable was rejected as an explanatory variable for the difference in temperatures in different rooms in the same passive house.

Another design characteristic considered was the existence of external solar shading (e.g. overhang, 'brise soleil' canopy, shutters) and/or internal solar shading (e.g. curtains). As previously explained, none of the studied passive houses had external shading features in any of the building elevations. Regarding internal shading, the three monitored rooms in the passive house PH2 had curtains on the window, albeit these were left open during the day and closed during the night in all rooms. Therefore, there was no window shading provided in any particular room during the day to reduce solar gains through the room glazing area. This meant that during the summer, south facing rooms (e.g. kitchen and bedroom) were constantly absorbing the sun's heat energy, resulting in higher indoor temperatures. However, since this design characteristic does not fully explain why the kitchen had higher summer temperatures than those found in the bedroom, it was considered weak as an explanatory variable.

Regarding the MVHR, it is not possible to know whether the high temperatures in the kitchen were the result of the underperformance of the system in that particular room. However, shortcomings related to the performance of the MVHR system in the kitchen only were not considered a strong explanatory variable for the significant differences in temperature found in the same passive house. It was assumed that because MVHR is a whole house ventilation system, inefficiencies in one room (kitchen) would affect the balance of the whole system, including the ventilation and extraction rates in other rooms.

2) Property characteristics (orientation)

In relation to orientation, the kitchen of passive house PH2 had a south facing window which can partially explain why the temperature in this room was higher than in the living room (north facing), since south facing glazing areas benefit more from solar gains than north facing ones. Although the living room window was bigger than the kitchen window (by 1.7 m^2), north facing elevations are the ones which least benefit from solar gains.

Nevertheless, room orientation was considered weak in explaining why the temperature in the kitchen was significantly higher than the temperature observed in the other two rooms during the summer. This is because the kitchen and the monitored bedroom were both south facing, which implies that if they had the same glazing area, they would equally benefit from solar gains. However, the kitchen had a smaller glazing area when compared to the bedroom. This suggests that the kitchen would benefit less from solar gains than the monitored bedroom. However, since the kitchen presented higher temperatures than the monitored bedroom, room orientation was also rejected when trying to explain the differences in indoor temperatures between rooms.

Room	**3 bed passive houses (PH1 & PH2)**	**4 bed passive houses (PH3, PH4 & PH5)**
Bedroom	2.85 m^2 (South)	2.85 m^2 (West)
Living room	4.11 m^2 (North)	4.77 m^2 (East)
Kitchen	2.35 m^2 (South)	2.35 m^2 (West)

Table 4.4 Glazing areas and solar orientation of the monitored rooms in the studied passive houses

3) External conditions (temperature)

Figure 4.9 shows a relationship between external temperature and indoor temperature in the monitored bedroom and living room of passive house PH2. On some days (e.g. days 2, 3 and 4) indoor temperature in those two rooms peaked following peaks in external temperature. On the other hand, no relationship was established between external temperature and indoor temperature in the kitchen. This suggest that other variables have contributed to the differences between kitchen temperatures and bedroom and living room temperatures, for example, occupants' practices.

4) Occupants' practices (cooking - using electrical appliances, heating, ventilating, occupancy)

Table 4.5 shows the frequency of practices performed by passive house PH2 occupants, in the three monitored rooms, during the summer monitoring period.

	Practices	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**
Kitchen	Cooking (using appliances)	3 times 06:50 16.35 18.20	2 times 12:00 17.30	1 time 17.00	2 times 10.00 17.00	2 times 08.30 17.15
	Using kettle	3 times	-	6 times	4 times	4 times
	Ventilating (opening window)	when cooking	when cooking	@08.30 and when cooking	when cooking	when cooking
Living	Ventilating (opening window)	Most of the day	All day	All day	All day	-
Bedroom	Ventilating (opening window)	Most of the day All night	All day All night	All day	All day	All day
Number of people in the house during the day		3	2	2	3	2
MVHR setting number		2	2	2	2	2
MVHR ventilation boosted?		no	no	no	no	no
Activities not performed in any rooms during the five days of monitoring		Ironing clothes, drying laundry, heating the room (using radiator or other heating appliance), using humidifier, using fan.				

Table 4.5 Frequency of practices performed in the passive house PH2 during the monitoring period, during the summer season.

As expected, cooking practices with the use of electric appliances (e.g. hob, oven, microwave oven, and kettle) were performed many times in the kitchen during the monitoring period. Although there is no strong evidence from the data shown on figure 4.9 and table 4.5 that cooking practices performed at a certain point in time have raised the temperature in the kitchen at that particular time or immediately after it, it is suggested that a combination of many electrical appliances being used in the kitchen, during the day, has contributed to the higher temperatures in that room.

Another variable considered as a possible cause of high temperature in passive house kitchens was occupancy levels, as occupants also produce heat. Nevertheless, it is difficult to say when the kitchen was occupied in the studied passive houses. Apart from the occasions where the occupants claimed to have used the kitchen (data obtained from interview and diaries), there is no other data source (e.g. monitoring of CO_2 levels) which confirms when the kitchen was occupied. Nevertheless, the CO_2 monitoring data obtained from the bedroom and living room are helpful in offering insights regarding possible relationships between occupancy levels and indoor temperature.

Figure 4.9 does not show strong evidence to suggest that high temperature peaks observed in the bedroom and in the living room of passive house PH2 were associated with higher CO_2 levels (above 400 ppm). Therefore, occupancy levels were not considered a strong variable to explain the high temperature in PH2 kitchen.

The other explanatory variable considered was ventilation practices. Table 4.5 shows that ventilation practices were performed more often in the bedroom and living room of passive house PH2 when compared to the kitchen. During the monitoring period, occupants claimed to have opened the window all day or for most of the day in the living room (day 1 to day 4) and in the bedroom all day or for most of the day (day 1 to day 5), and all night (day 1 and day 2). On the other hand, occupants claimed to have opened the kitchen window at certain times when they felt too hot or when they were cooking. As previously explained, figure 4.9 shows that on some days (e.g. days 2, 3 and 4) there was some correlation between external temperatures and bedroom and living room temperatures: bedroom and living room temperatures increased following the rise in outdoor temperatures. No relationship between outdoor and indoor temperature was observed in the kitchen of passive house PH2. Therefore this variable was considered weak to explain high temperatures in the kitchen.

Regarding high temperatures in the bedroom and living room in passive house PH2, the data from occupants' interviews and diaries shown on table 4.5, analysed in conjunction with the indoor temperature and external weather data suggest that the relationship observed between the outdoor temperatures and the living room and bedroom temperatures might be caused by ventilation practices. Table 4.5 shows that occupants in the passive house PH2 opened the windows for long periods (all day and most of the day) during the summer. It is suggested that by opening the windows during hot summer days (e.g. figure 4.9 shows outdoor temperatures peaking beyond 25ºC) in passive houses contributed to an increase in indoor temperature as indoor cooler air was replaced by warmer outdoor air through ventilation. However, there is no strong evidence suggesting that higher kitchen temperatures was caused by increases in outdoor temperatures combined with ventilation practices.

Other practices such as heating the room using radiators (or other heating appliances) were rejected as an explanatory variable for the high temperatures in the kitchen as occupants claimed not to have used such appliances in any room during the summer season.

b) Control houses

Temperatures in the monitored bedroom and living room of control houses were higher during the summer season when compared to winter and spring. Winter temperatures were lower than spring temperatures with one exception (the living room of CH1 had higher winter temperatures when compared with spring).

When comparing the median temperature in similar rooms (e.g. between two bedrooms), during the same season, the data show that there were significant differences among similar rooms. All monitored rooms in the control houses showed statistically significant differences, with one exception: no statistically significant difference was found between the median temperature in the monitored bedroom of control house CH1 and CH4 during the winter season (table 4.4).

Season	Rooms	
	Bedroom	**Living room**
Winter	SSD between all rooms, except between CH1 & CH4	SSD between all rooms
Spring	SSD between all rooms	SSD between all rooms
Summer	SSD between all rooms	SSD between all rooms

Table 4.6 Statistically significant difference (SSD) in temperature between the monitored rooms in different control houses. (P<0.05)

c) Comparing passive houses and control houses

When comparing passive houses and corresponding control houses, figures 4.1 and 4.2 show that overall, passive houses had higher indoor temperatures when compared with control houses. Table 4.7 shows that those differences were statistically significant in most cases.

Especially high temperatures were observed in the monitored bedroom of the two 3 bed passive houses (PH1 and PH2) during the summer, where they reached 30.7°C and 28.6°C (PH1 and PH2 respectively) with a median of 27.4°C and 25.9°C (PH1 and PH2 respectively).

Winter temperatures were also generally higher in passive houses when compared with control houses. For example in the monitored bedroom, passive houses had median temperature ranging from 21.1°C to 24.4°C whilst control houses ranged from 19.1°C to 20.1°C (with the exception of CH2 which showed a median temperature of 23.7°C).

Season	**Rooms**	
	Bedroom	**Living room**
Winter	SSD between all rooms	SSD between all rooms
Spring	SSD between all rooms, except between PH4 & CH2	SSD between all rooms
Summer	SSD between all rooms	SSD between all rooms

Table 4.7 Statistically significant difference (SSD) in temperature between the monitored rooms in passive houses and control houses. ($P<0.05$)

4.2.2. Relative humidity

Figures 4.10, 4.11 and 4.12 display boxplots showing the seasonal variation in relative humidity in the monitored rooms in passive houses and control houses. Figures 4.10 shows the data gathered in the bedroom of case and control houses, figure 4.11 shows the data gathered in the living room of case and control houses, whilst figure 4.12 shows the data gathered in the kitchen of the case houses only[23].

[23] Data obtained from the kitchen were only collected from passive houses due to constraints related to the research case study. Please refer to the methodology chapter for further details.

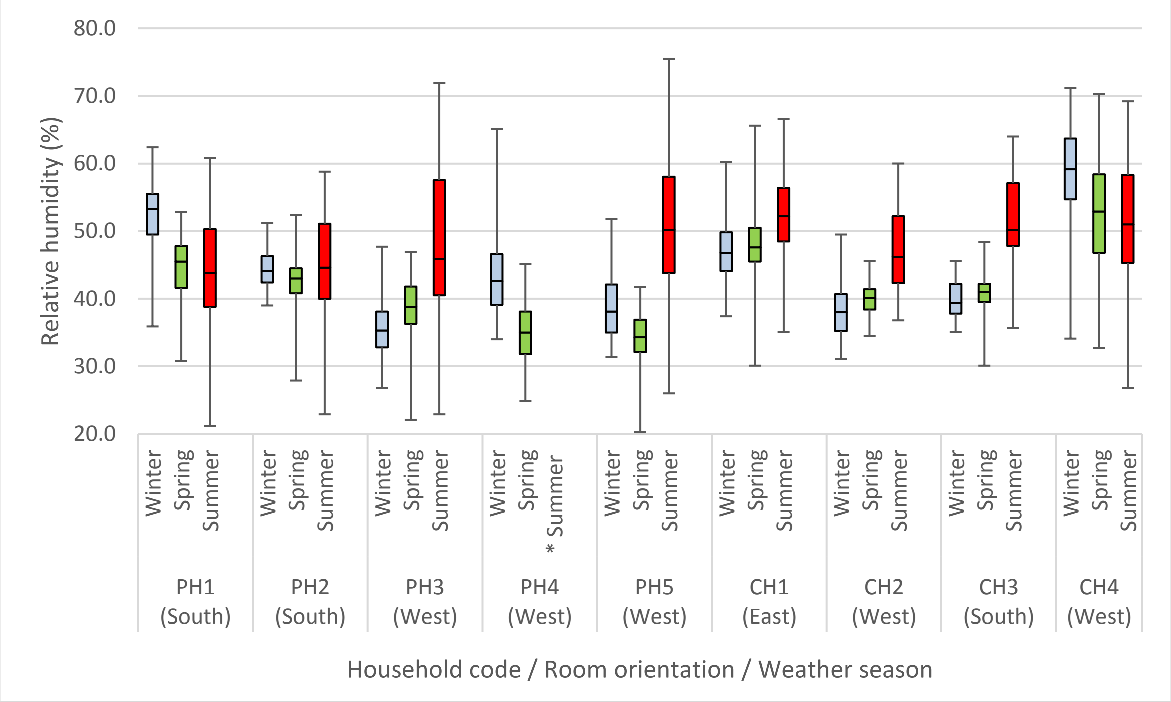


Figure 4.10 Boxplots showing seasonal variation of relative humidity in the monitored bedroom of passive houses (PH) and control houses (CH). (The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

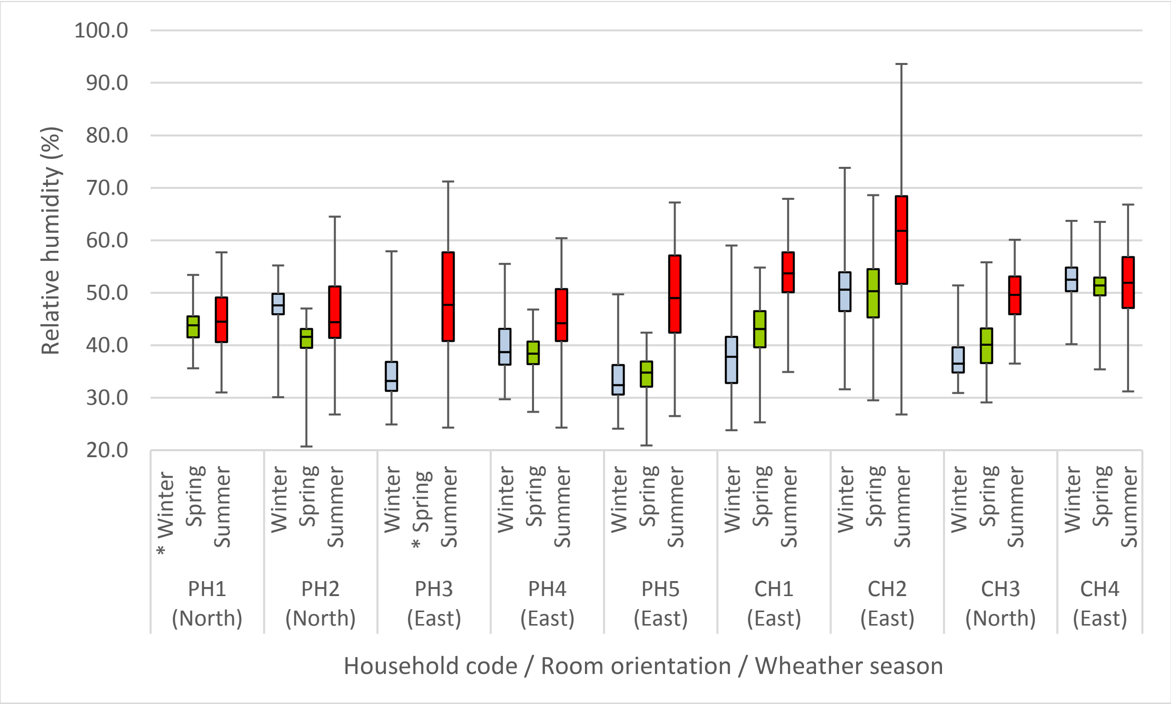


Figure 4.11 Boxplots showing seasonal variation of relative humidity in the living room of passive houses (PH) and control houses (CH). (The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

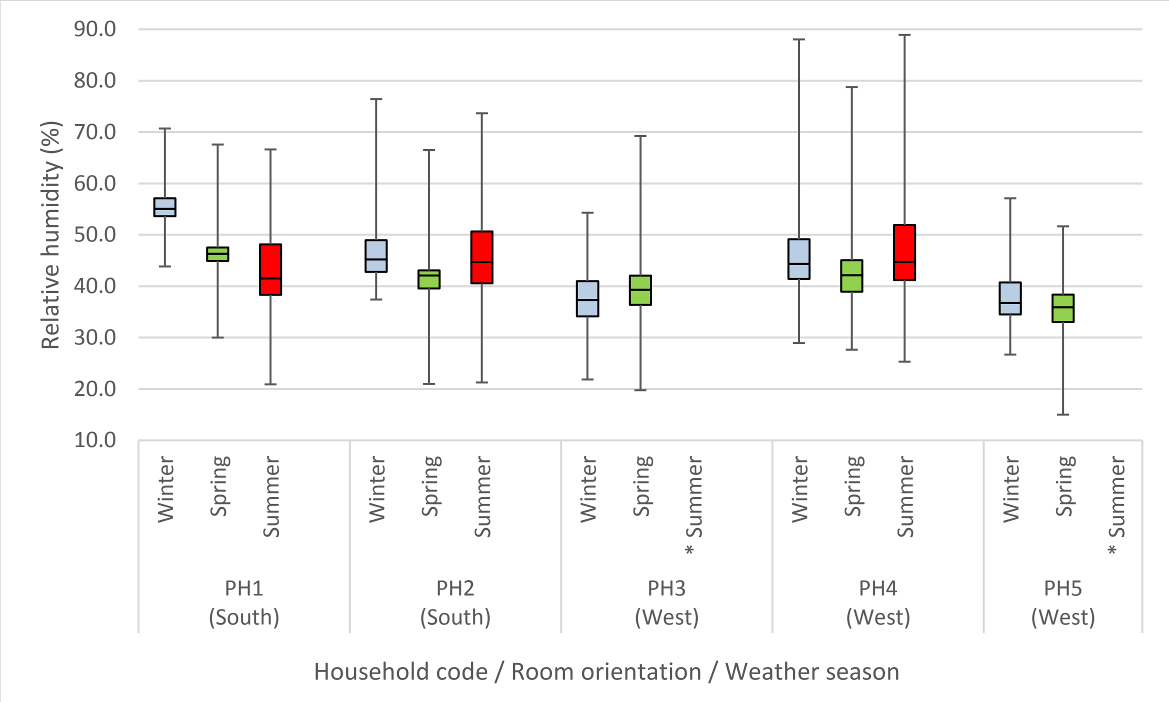


Figure 4.12 Boxplots showing seasonal variation of relative humidity in the kitchen of passive houses (PH). (The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

a) Passive houses

When comparing the RH of a particular room, during the same season, across different passive houses, similarities were observed as well as significant differences. In terms of similarities, all five passive houses presented RH levels between 40% and 60% for most of the time, during the summer, in the monitored bedroom and living room, with one exception (PH4) as there were no data available (figures 4.10 and 4.11). However, during the winter and spring seasons, much lower RH levels were observed in the monitored bedroom and living room of the 4 bed passive houses, when compared with the 3 bed passive houses.

Figure 4.13 shows relative humidity levels in the bedroom of the five studied passive houses, during the first five monitoring days, during the winter.

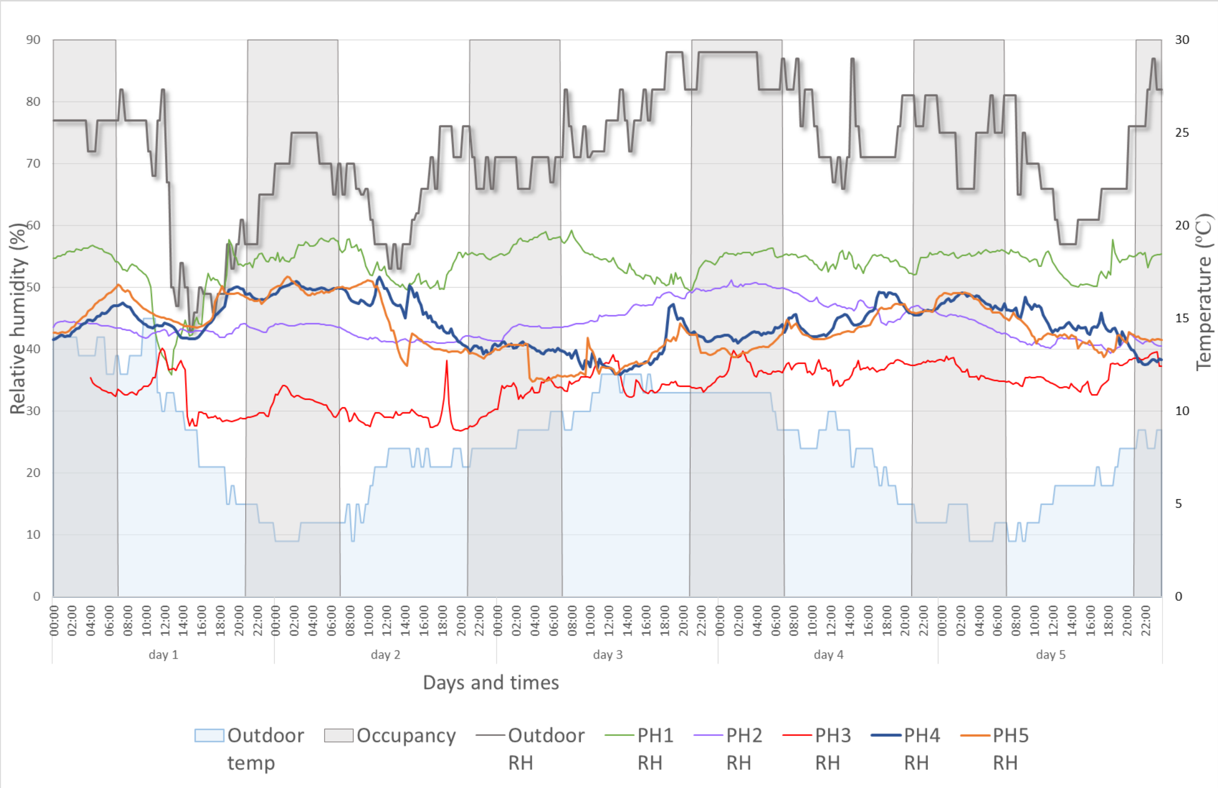


Figure 4.13 Relative humidity in the monitored bedroom of the passive houses during the winter season, during the first five days of monitoring. (The grey columns indicate the typical period of bedroom occupancy as indicated by the occupants – from 21:00 to 07:00)

It is interesting to note that for the first five days of winter monitoring, the 4 bed passive house PH3 had low RH levels (under 40%) for most of the time, while the other 4 bed passive houses PH4 and PH5 had low RH levels mostly on day 2 and day 3 only. On the other hand, low RH levels were not observed in the bedroom of the 3 bed passive houses PH1 and PH2, during the same period.

Before testing the explanatory variables to elucidate why the monitored bedroom of the 4 bed passive houses had low RH levels during the winter season, two general explanations for low indoor RH levels have been considered.

First, low indoor RH could be the result of a low amount of water vapour in the air. Second, since RH is inversely related to temperature (Bencloski, 1982), low RH could be the result of an increase in indoor temperature. This is because RH refers to the ratio (expressed in percentage) of the amount of moisture actually in the air to the maximum amount that the air can hold at a given temperature. Because air at higher temperatures can hold more water vapour than the same amount of air at lower temperatures, relative humidity will decrease when temperature increases, since warmer air is capable of holding more water (Rafidi, 2017). However, this relationship is only true if no more water vapour is introduced to the air.

Aiming to find out whether such a relationship was true in the monitored bedroom of the 4 bed passive houses PH3, PH4 and PH5, figure 4.14 shows the indoor temperature and RH levels in the monitored bedroom of those three passive houses during the first five days of winter monitoring. The 4 bed passive houses PH3, PH4 and PH5 were selected for further analysis as the monitored bedroom in those three houses presented lower RH levels when compared with the 3 bed passive houses PH1 and PH2.

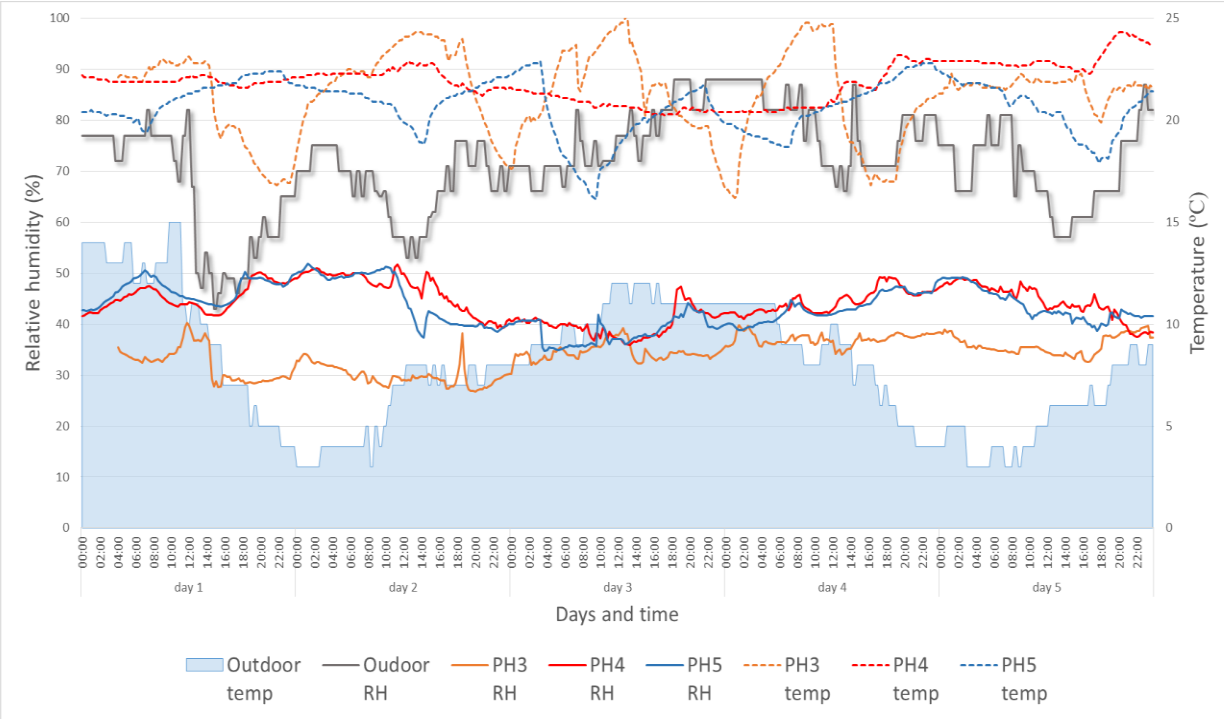


Figure 4.14 Relative humidity and temperature in the monitored bedroom of the passive houses PH3, PH4 and PH5 during the winter season

The data shown on figure 4.14 do not support the inverse relationship between indoor RH and temperature, as previously described. In many cases, as the bedroom temperature decreased the RH also decreased, and as the bedroom temperature increased the RH levels also increased. A reasonable explanation for this trend is that it is possible that additional water vapour was introduced into the air while indoor temperature increased. Conversely, it is reasonable to assume that some water vapour was removed from the indoor air as the temperature decreased.

The findings from the monitored data (figure 4.10) show that the bedroom of the 4 bed passive houses PH3, PH4 and PH5 had low RH levels (especially in passive houses PH3 and PH5, which presented low RH for more than 50% of the time) when compared with the monitored bedroom of the 3 bed passive houses.

The following variables from the analytical framework were considered relevant when trying to explain the causes of low RH levels found in the bedroom of the 4 bed passive houses during the winter:

1. **Passive house design & construction (MVHR)**

It is reasonable to question the performance of the MVHR in different passive houses. However, as explained earlier the only data available to the researcher regarding the performance of the ventilation system in the studied passive houses suggest that, at the time of commission (a few months before the winter monitoring), the MVHR ventilation/extraction rates in all rooms were within the 10% margin (as required by the Passivhaus standard). However it is not possible to know whether the MVHR performance (in terms of ventilation/extraction rates) during the five monitoring days were still similar to those reported during the commissioning stage.

Nonetheless, even if the MVHR system was not providing ventilation/extraction rates as intended, the assumption would be that there would be more stagnated indoor air (or less indoor/outdoor air exchange) in the house, and possibly higher RH levels in the rooms. Therefore, the MVHR performance was rejected as a strong explanatory variable for the low RH levels in the monitored bedroom of the 4 bed passive houses.

2. **Property characteristics (size, orientation)**

Explanatory variables related to property characteristics (e.g. size and orientation) were not considered relevant when analysing RH levels in passive houses, since no evidence from the literature was found to support that they can influence RH levels. Nevertheless, some comparisons were made between the 3 bed passive houses and the 4 bed passive houses. In terms of size, the monitored bedroom of the 3 bed passive houses had an area of 15 m^2 (volume of 36 m^3) whilst the monitored bedroom of the 4 bed passive houses had an area of 13 m^2 (volume of 31.2 m^3). Although the areas and volumes differ, the differences were not considered substantial to correlate with significant differences in indoor RH levels.

3. **External conditions (temperature, RH, season)**

Regarding season, this appeared to have influenced RH levels in passive houses as low RH was observed for longer periods of time during the winter and spring than those observed during the summer season. Nevertheless, this variable was less relevant when analysing RH levels in the bedrooms during the same season (winter).

The other two variables, temperature and RH, were also considered when trying to explain the low RH levels in the bedroom of the 4 bed passive houses. However, data from figure 4.14 do not show any strong correlation between outdoor temperature/RH and indoor RH. Additionally, because outdoor temperature/RH levels were similar for all five passive houses, these variables were also considered weak and therefore rejected.

4. **Occupants' practices (ventilating, occupancy levels)**

The practices considered in this part of the analysis are those which could have contributed to changes in the amount of water vapour present in the air in the monitored bedrooms. These include ventilation (by window opening) and bedroom occupancy (since occupants produce water vapour through their metabolism). Ventilation is an important variable since opening the bedroom window would have contributed to extracting water vapour from the indoor air. Clothes drying was not considered in the analysis as the occupants of all passive houses claimed not to have dried clothes in the monitored rooms during the monitoring period.

Bedroom occupancy was considered a weak explanatory variable since the data from occupants' interviews show that occupancy was similar in the monitored bedrooms. There were two adults sleeping in the monitored bedroom during the night (occupancy hours typically from 21:00 pm to 07:00 am).

On the other hand, the qualitative data from interviews and diary show that ventilation practices in the monitored bedroom during the winter season were not performed similarly between the passive houses. As mentioned earlier in section 4.2.1, the households of passive houses PH1, PH2 and PH4 claimed to have left the bedroom window closed for most of the time. Conversely, the occupants of passive houses PH3 claimed to have opened the bedroom window for 10 min every day whilst the occupants of passive houses PH5 claimed to have opened the bedroom window all day and night on the latch (by 5 cm).

Ventilation practices performed in the monitored bedroom of passive houses PH3 and PH5 seem to offer a strong explanation for the low RH levels observed there. This is because opening the window during the winter would have contributed to additional outdoor/indoor air exchange. As outdoor temperatures were lower than indoor temperatures, warmer indoor air was being replaced by cooler and drier outdoor air, lowering indoor RH levels. Therefore, it is reasonable to argue that the ventilation practices performed in the monitored bedroom of the 4 bed passive houses PH3 and PH5 have contributed to the low temperatures and low RH levels observed there.

However, it is important to point out that this variable does not offer an explanation for the low temperature and low RH levels also found in the monitored bedroom of passive house PH4, since PH4 occupants claimed to have kept the monitored bedroom window closed during the day and night for most of the time during the winter season.

Regarding RH levels observed in passive house kitchens, only the 3 bed passive houses presented RH levels between 40% and 60% for most of the time, during all three seasons. Low RH levels (below 40%) were observed in the kitchen of the 4 bed passive houses PH3 and PH5 for most of the time during the winter and spring monitoring.

Figure 4.15 shows the RH levels observed in the kitchen of the five studied passive houses during the first five days of winter monitoring. Similarly to the trend found in the monitored bedroom, the kitchen of the 4 bed passive house PH3 showed low RH levels (under 40%) for longer periods when compared to other passive houses. The other two 4 bed passive houses PH4 and PH5 also had low RH in the kitchen, albeit for shorter periods of time.

The low RH levels found in the 4 bed passive house rooms seem to be seasonal, as they were observed for longer periods during the winter and spring, when outdoor temperatures were lower, and much less frequent during the summer season. However, seasonality does not explain the reason why some 4 bed passive houses had low RH levels during the colder seasons (winter and spring), when compared to the 3 bed passive houses.

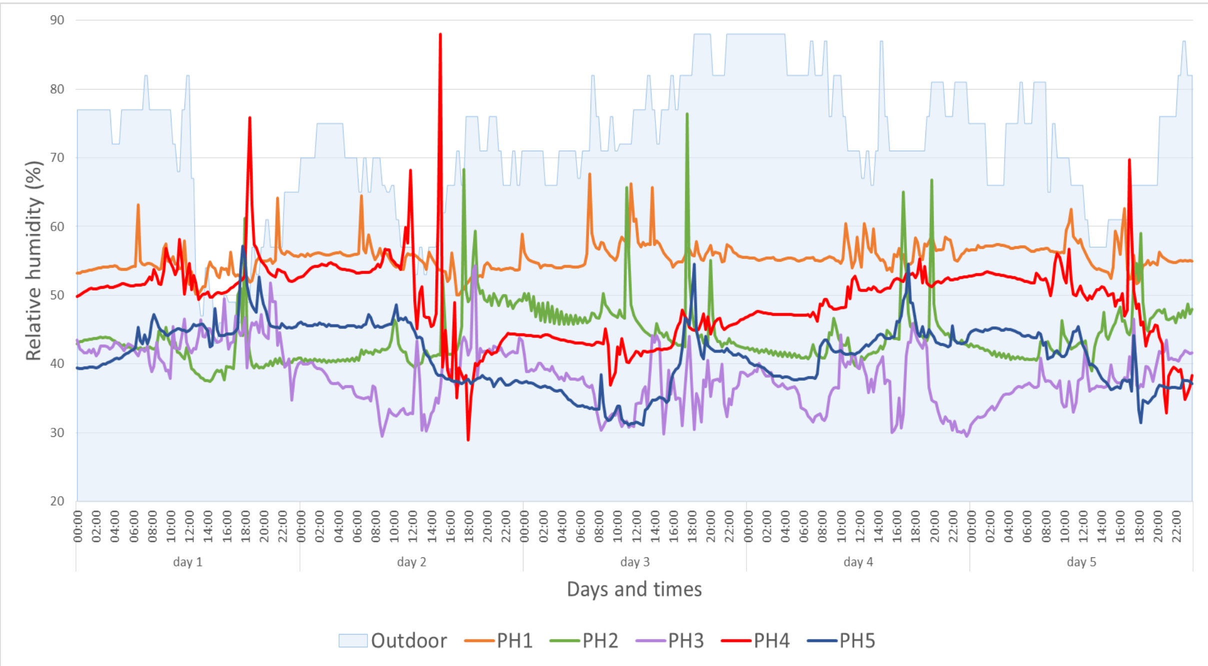


Figure 4.15 Relative humidity in the kitchen of the passive houses during the winter season, during five days of monitoring

In trying to explain the differences between passive houses, Figure 4.16 shows RH levels and indoor temperature in the kitchen of passive house PH1 and PH3 during the first five winter monitoring days. These houses were selected for this comparison as they show respectively the highest and the lowest RH levels in the kitchen, observed during the winter monitoring period. In addition, table 4.8 shows PH1 and PH3 occupants' practices performed in the kitchen during the same period.

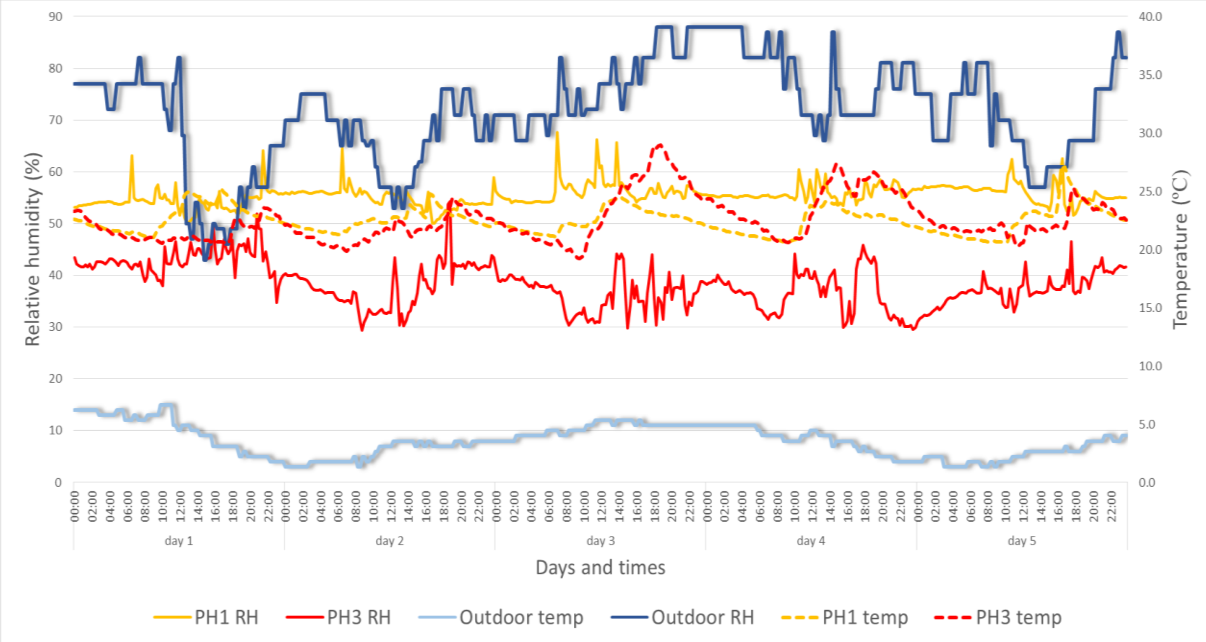


Figure 4.16 Relative humidity and temperature in the kitchen of the passive houses PH1 and PH3 during the winter season, during five days of monitoring

Practices	House	Day 1	Day 2	Day 3	Day 4	Day 5
Cooking (using appliances)	PH1	07.00 17.00	06.45 21.00	06.45 21.00	07.00 22.00	08.30 22.30
	PH3	12.00 17.00	17.00	12.00 17.30	11.30 14.00	11.45 17.30
Using kettle	PH1	2 times	2 times	2 times	2 times	2 times
	PH3	11 times	13 times	15 times	14 times	15 times
Ironing (with steam)	PH1	19.00	11.00 18.00	17.00	11.00 14.30	-
	PH3	-	-	-	-	-
Washing dishes (using dish washer)	PH1	Once or twice	Once or twice	Once or twice	Once or twice	Once or twice
	PH3	-	-	-	-	-
Ventilating (opening the window)	PH1	09.00 14.00 18.45	07.00 09.00 16.30 19.00	07.00 20.30	06.30 21.00	08.30 22.30
	PH3	Hourly (from 07.00 to 22.00)	Hourly (from 07.00 to 22.00)	Hourly (from 07.00 to 22.00)	Hourly (from 7.00 to 22.00)	Hourly (from 07.00 to 22.00)
MVHR setting number	PH1	2	2	2	2	2
	PH3	2	2	2	2	2
MVHR ventilation boosted?	PH1	no	no	no	no	no
	PH3	no	no	no	no	no
Number of people in the house during the day	PH1	1	2	1	4	4
	PH3	6	5	6	6	5
Activities not performed in the kitchen during the 5 days of monitoring	None of these two householders dried laundry, used humidifiers, used fans, or watered (or kept) indoor plants during the five days of monitoring.					

Table 4.8 Frequency of practices performed in the kitchen of passive houses PH1 and PH3 during the five days of monitoring

By using the explanatory variables from the analytical framework, the following possible explanations were considered in order to explain the differences in relative humidity levels found in passive houses:

1. **Passive house design & construction (MVHR)**

It is reasonable to question the performance of the MVHR and its correlation with the differences in RH levels found in the passive houses. As argued earlier, if the MVHR was underperforming in one of the passive house kitchens, the assumption would be that that room would have more stagnant air (or less indoor/outdoor air exchange) and possibly higher RH levels. Therefore, if the MVHR was underperforming in one of those two kitchens, it would be assumed that the underperforming MVHR extractor would be the one located in PH1 kitchen since it had significantly higher RH levels when compared with PH3 kitchen. Nevertheless, because it is not possible to know whether the extraction rates in PH1 kitchen at the time of monitoring were similar to those obtained at the time of commissioning, this variable could not be used when trying to explain the differences in RH levels observed between the kitchens of passive houses PH1 and PH3.

2. **Property characteristics (size, orientation)**

As explained earlier, variables related to property characteristics were not considered relevant when analysing differences in RH levels in different rooms.

3. **Occupants' practices (cooking, washing dishes, doing the laundry, using the kettle, ventilating, occupancy levels)**

The practices considered in this part of the analysis are those which generate or dilute water vapour (e.g. cooking, washing dishes, doing the laundry, using the kettle and ventilating), therefore influencing RH levels.

Some of these practices were performed with similar frequency in both households. For example cooking was performed twice a day most days. Unfortunately, there are no data available regarding the duration of cooking in each passive house, as occupants did not indicate the time duration of this practice. However, because the frequency was very similar, it is reasonable to suggest that this particular practice alone, was not the cause of the significant RH level differences in the kitchen of these two passive houses.

On the other hand, the frequency of other water vapour generating practices was very different from these two households. For example, occupants of passive house PH1 claimed to have ironed clothes in the kitchen (using the steam function) and washed dishes (using the dishwasher) once or twice a day during the five monitoring days. In comparison, the occupants of passive house PH3 indicated that they did not iron or use a dishwasher appliance in the kitchen during the same period.

Although on some occasions, figure 4.16 shows peaks in RH levels which coincide with the time occupants claimed to have cooked or ironed clothes in the kitchen (e.g. PH1 cooking on day 1 at 12.00 and 17.00), the data do not show evidence which suggests which of those specific practices caused the differences observed between the two passive houses.

In addition to water vapour generating practices, ventilation practices in the kitchen (e.g. opening the window) was taken into account during this part of the analysis, as outdoor/indoor air exchange could have also contributed to the RH differences observed. This is because indoor water vapour (high levels of humidity) can be purged faster via ventilation through the window as colder and dryer outdoor air mixes with indoor air.

Although table 4.8 shows that occupants of both passive houses opened the window in the kitchen many times a day, the data indicate that occupants of passive house PH3 ventilated the kitchen more frequently than in PH1. PH3 occupants opened the window briefly every hour from 07.00 to 22.00, whilst PH1 occupants opened the window briefly from twice a day to four times a day. The word 'briefly' here refers to a time duration of around 10 minutes, as both households opened the kitchen window to ventilate the kitchen whilst they smoked.

When integrating these different practices performed by occupants of passive house PH1 and PH3 some explanations for the low RH in PH3 kitchen (under 40%) are presented. The findings suggest that overall, PH1 occupants were possibly not only generating more water vapour in the kitchen (through more frequent water vapour generating practices such as dishwashing and ironing) but they were also opening the windows in the kitchen less frequently. Conversely, the frequent window opening and less frequent water vapour generating practices performed in the kitchen of passive house PH3, seemed to explain why this house presented low RH for most of the time in the kitchen, during the five days of winter monitoring.

Although figure 4.16 shows higher outdoor RH levels, the absolute humidity (the actual amount of water vapour) in the outdoor air was much lower during the winter season (as temperatures were lower and therefore they held less water particles). The frequent practice of window opening in the kitchen of passive house PH3, resulted in a more frequent exchange of the cooler and dryer outdoor with indoor air, and therefore, lower indoor RH levels.

Another explanatory variable considered for the differences in RH in passive house kitchens was occupancy levels. Nevertheless, as previous explained, it is difficult to say when the kitchen was occupied in the studied passive houses. Apart from the occasions where the occupants claimed to have used the kitchen (data obtained from interview and diaries), there is no other data source (e.g. monitoring of CO_2 levels) which confirms when the kitchen was occupied. Nevertheless, the CO_2

monitoring data obtained from the bedroom are helpful in offering insights regarding possible relationships between occupancy levels and indoor RH.

Figure 4.17 does not show strong evidence to suggest that high RH peaks observed in the bedroom of passive house PH1 and PH3 were associated with higher CO_2 levels (above 600 ppm) or associated with the periods in which occupants claimed to be in the bedroom (typically from 21:00 pm to 07:00 am). Therefore, occupancy levels were not considered a strong variable to explain the significant differences in RH levels between the kitchen of passive houses PH1 and PH3.

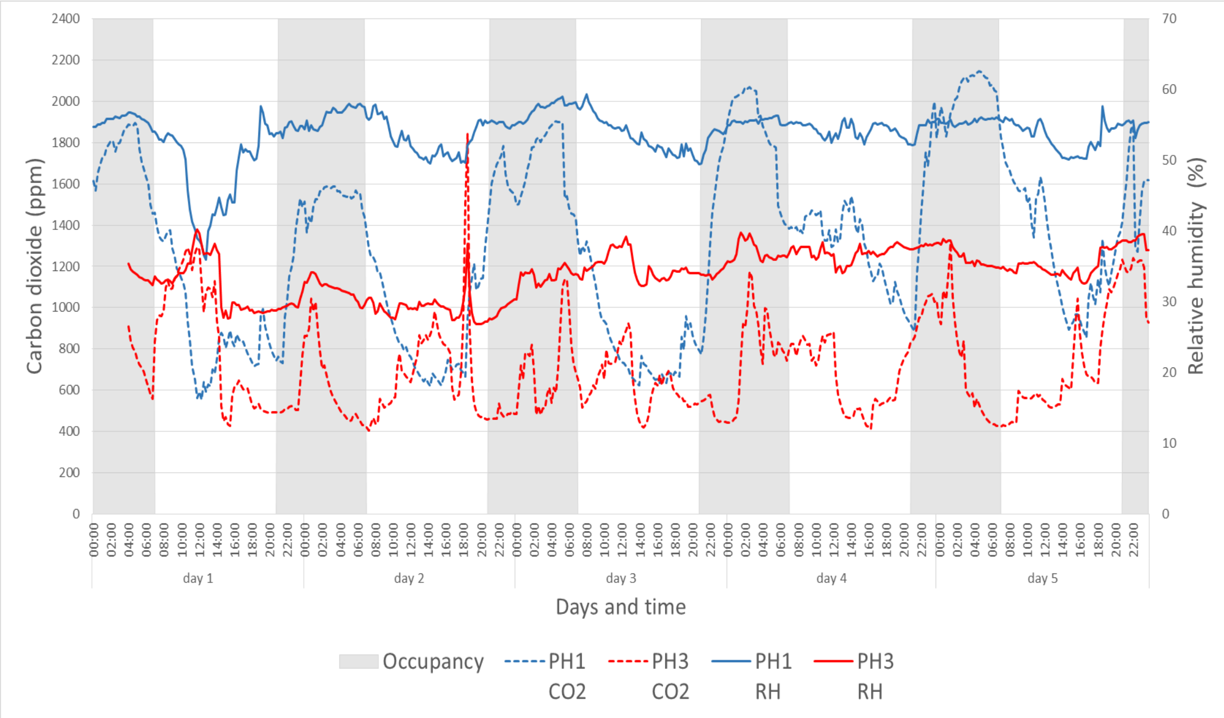


Figure 4.17 Relative humidity carbon dioxide levels in the monitored bedroom of passive houses PH1 and PH3 during the winter season, during five days of monitoring. The grey columns represent the typical period of occupancy as indicated by the occupants – from 21:00 to 07:00

Statistically significant differences were encountered not only between passive house kitchens but also between bedrooms and between living rooms, during the same season as shown in table 4.9. Passive house rooms appeared to present more similarities in RH levels during the summer season when compared with the RH levels observed during the winter and spring monitoring.

Season	Rooms		
	Bedroom	**Living room**	**Kitchen**
Winter	SSD between all rooms	SSD between all rooms, except between PH3 & PH5	SSD between all rooms, except between PH3 & PH5
Spring	SSD between all rooms	SSD between all rooms	SSD between all rooms, except between PH2 & PH4
Summer	SSD between all rooms, except between PH1 & PH2	SSD between all rooms, except between PH1 & PH2, PH1 & PH4, PH1 & PH5	SSD between all rooms, except between PH2 & PH4

Table 4.9 Statistically significant difference (SSD) in relative humidity between the monitored rooms in different passive houses. (P<0.05)

Comparisons of RH were also made between the monitored bedroom, living room and kitchen in the same passive house, during the same season. Figures 4.18, 4.19 and 4.20 show comparisons between RH levels in these rooms during the winter, spring and summer seasons respectively.

When making such comparisons, it was noted that RH levels between the monitored rooms in the same passive house were significantly different (P<0.05) in many cases, and in particular during the winter season (table 4.10).

During the winter and spring seasons, where most differences in RH occurred, the highest levels of RH were mostly found in the kitchen. However this was not the case in all passive houses as some presented higher RH levels either in the monitored bedroom or the living room (e.g. PH2 had higher RH levels in the living room during the winter season compared with those found in the kitchen and in the monitored bedroom).

As mentioned earlier, it is reasonable to suggest that more frequent practices which produce water vapour (e.g. laundering, cooking, washing dishes) explain the significantly higher RH levels observed in many passive house kitchens when compared to the bedroom and living room.

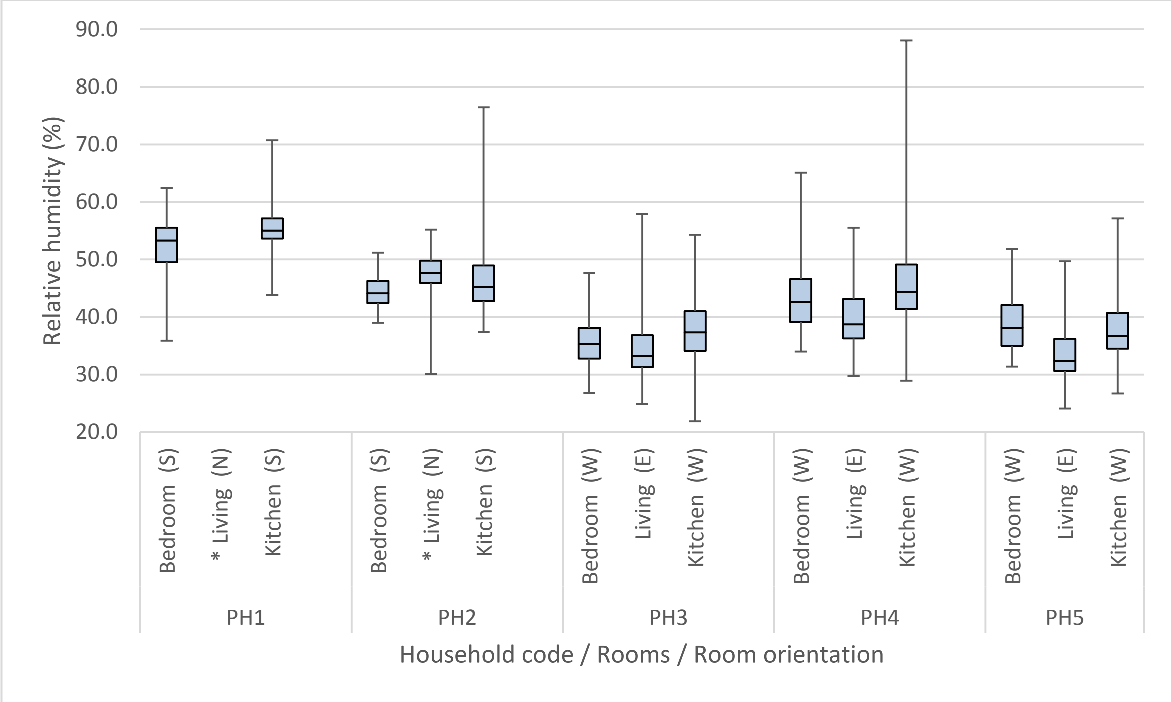


Figure 4.18 Boxplots showing relative humidity in the monitored bedroom, living room and kitchen in passive houses (PH) during the winter season. (The letter in brackets refers to the room orientation. The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

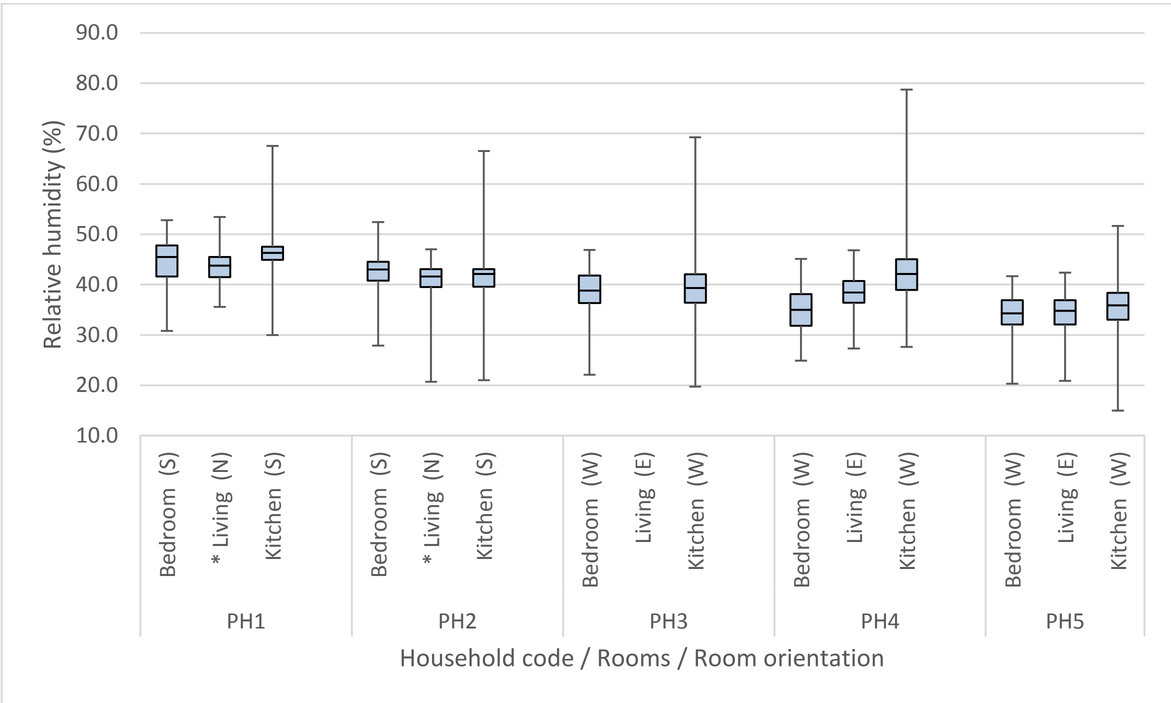


Figure 4.19 Boxplots showing relative humidity in the monitored bedroom, living room and kitchen in passive houses (PH) during the spring season. (The letter in brackets refers to the room orientation. The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

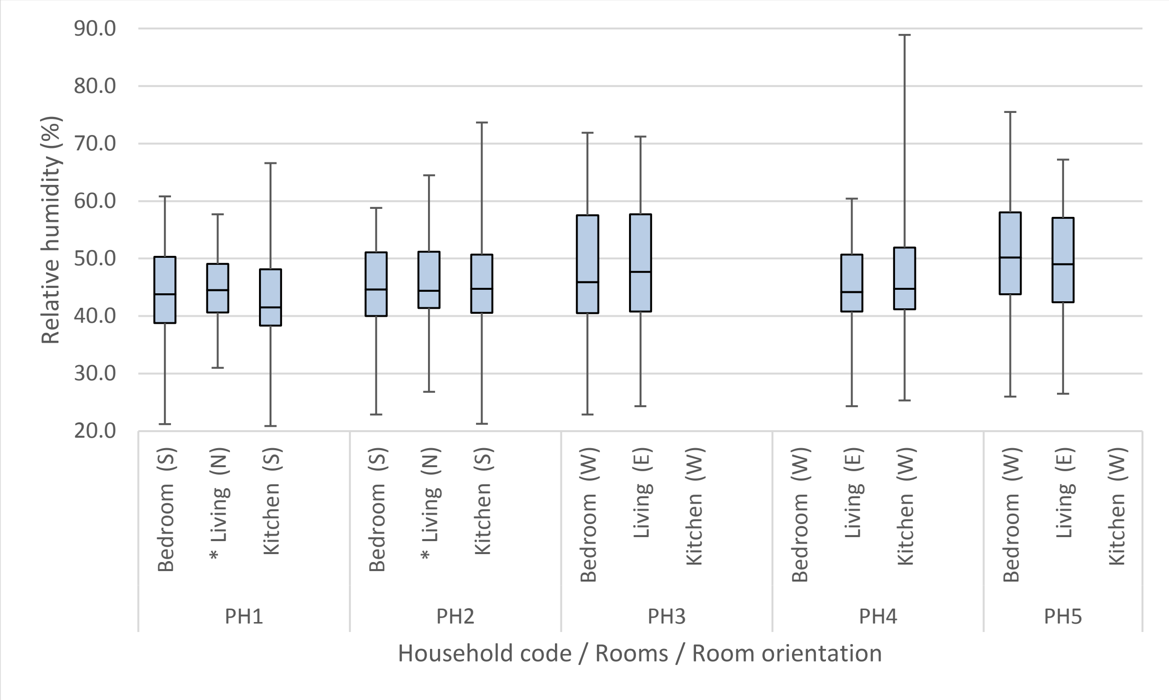


Figure 4.20 Boxplots showing relative humidity in the monitored bedroom, living room and kitchen in passive houses (PH) during the summer season. (The letter in brackets refers to the room orientation. The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

Passive house code	**Season**		
	Winter	**Spring**	**Summer**
PH1	SSD between all rooms	SSD between all rooms	SSD between all rooms
PH2	SSD between all rooms	SSD between all rooms except between LR & Kit	No SSD between Bed & LR No SSD between Bed & Kit No SSD between LR & Kit
PH3	SSD between all rooms	SSD between all rooms	SSD between all rooms except between Bed & LR
PH4	SSD between all rooms	SSD between all rooms	SSD between all rooms
PH5	SSD between all rooms	SSD between all rooms	SSD between all rooms
Key: Bed = bedroom; LR = living room; Kit= kitchen			

Table 4.10 Statistically significant difference (SSD) in relative humidity between the monitored bedroom, living room and kitchen in the same passive house (PH). (P<0.05)

b) Control houses

Generally, the highest RH levels observed in control houses were during the summer season. Nevertheless, summer RH levels were kept between 40% and 60% for most of the time in the monitored rooms of all four control houses, with one exception (the living room of CH2, where RH over 60% was observed for most of the time).

Low RH levels (under 40%) were observed during the winter season in three control houses (CH1, CH2 and CH3) for most of the time, either in the monitored bedroom or living room.

When comparing RH levels between similar rooms during the same season, the data show that the differences found were statistically significant in most cases (table 4.11). The only two exceptions were between the living room of control house CH1 and CH3 during the winter, and the monitored bedroom of control houses CH3 and CH4 during the summer season.

Season	Rooms	
	Bedroom	**Living room**
Winter	SSD between all rooms	SSD between all rooms, except between CH1 & CH3
Spring	SSD between all rooms	SSD between all rooms
Summer	SSD between all rooms, except between CH3 & CH4	SSD between all rooms

Table 4.11 Statistically significant difference (SSD) in relative humidity between the monitored rooms in different control houses. (P<0.05)

c) Comparing passive houses and control houses

Summer RH levels were generally higher in control houses when compared with passive houses. For instance, control houses presented median RH between 46.2% and 52.2% in the monitored bedroom, whilst passive houses presented a median RH between 43.8% and 50.2%. Nevertheless, all passive houses and control houses presented summer RH levels between 40% and 60% for most of the time (with the exception of CH2 monitored bedroom).

Regarding RH levels during the winter and spring seasons, passive houses had generally lower RH levels when compared with the control houses. This was especially evident with the 4 bed passive houses which presented low RH levels (under 40%) for most of the time during the winter and spring seasons in most cases (figures 4.10 and 4.11). The findings from the earlier analysis have suggested that the low RH levels in passive houses are the result of occupants' ventilation practices during the colder seasons.

The differences in RH levels between passive house and control houses were found to be statistically significant in most cases (table 4.12).

Season	Rooms	
	Bedroom	Living room
Winter	SSD between all rooms	SSD between all rooms
Spring	SSD between all rooms	SSD between all rooms
Summer	SSD between all rooms, except between PH3 & CH2	SSD between all rooms

Table 4.12 Statistically significant difference (SSD) in relative humidity between the monitored rooms in passive houses and control houses. (P<0.05)

4.3. Comparing indoor air quality and its seasonal variations in the bedroom and in the living room of passive houses and conventional houses

Indoor air quality data (CO_2 and VOCs) were collected from passive houses and control houses. CO_2 was monitored in the main bedroom and living room whilst VOCs were monitored in the main bedroom only. Following a similar structure to the first part of the chapter, indoor air quality findings will be presented by comparisons being made between the five passive houses, comparisons between the two groups of identical passive houses, comparisons between different rooms in the same passive house as well as comparisons between passive houses and control houses. The findings from the comparisons made between passive houses will be further analysed through the analytical framework, aiming to explain the causes of the possible differences observed.

CO_2 data are presented by boxplot graphs. The bottom and the top of the boxes represent the 25th and 75th percentiles and the line near the middle of the box represents the median. The end of the whiskers indicates the minimum and maximum CO_2. VOCs data are presented by a table showing the top 10 most abundant compounds found in the monitored bedroom of each passive house and control house and their concentrations (with the exceptions mentioned in the methodology chapter).

4.3.1. Carbon dioxide

Figure 4.21 shows carbon dioxide levels in the monitored bedroom of the five passive houses (PH) and four control houses (CH). Since control house CH4 shows very high levels of CO_2, making it difficult to visualise the CO_2 levels found in the other houses, figure 4.22 displays boxplots showing the seasonal variation of CO_2 in the monitored bedroom of the five passive houses (PH) and three control houses (CH1, CH2 and CH3). Control house CH4 was excluded from figure 4.22 so the data from the other houses could be better compared. Additionally, figure 4.23 displays boxplots showing the seasonal variation of carbon dioxide in the monitored living room of the studied passive houses (PH) and control houses (CH).

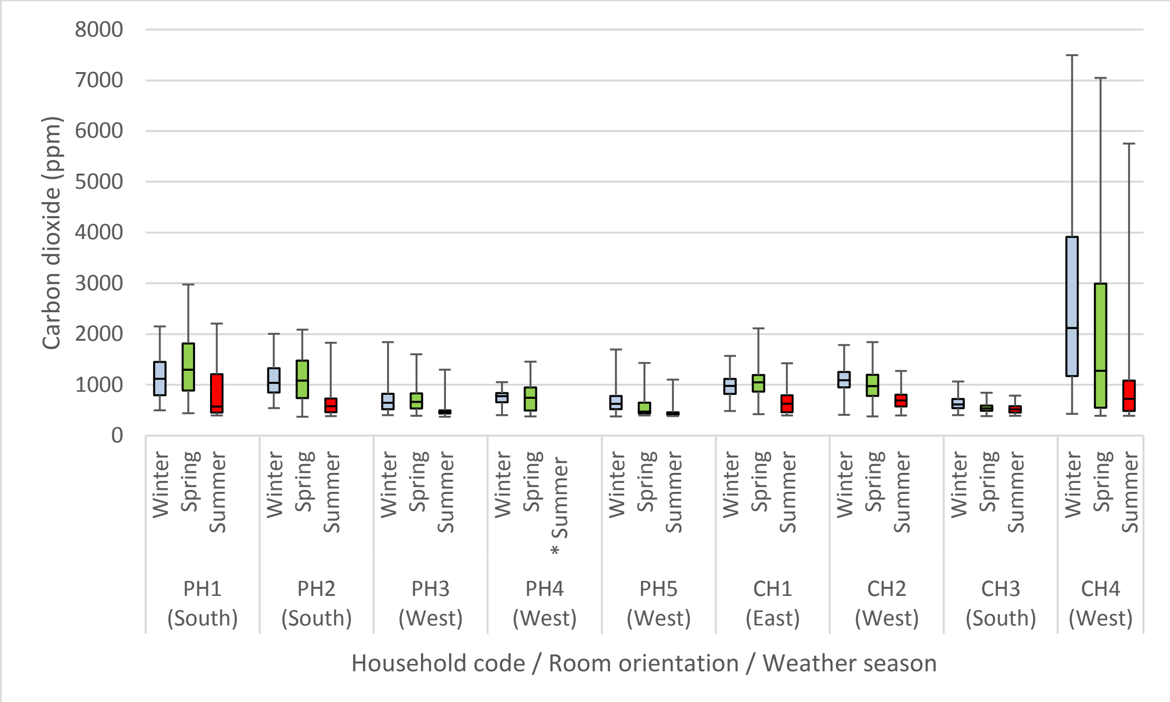


Figure 4.21 Boxplots showing seasonal variation of carbon dioxide in the monitored bedroom of passive houses (PH) and control houses (CH). (The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

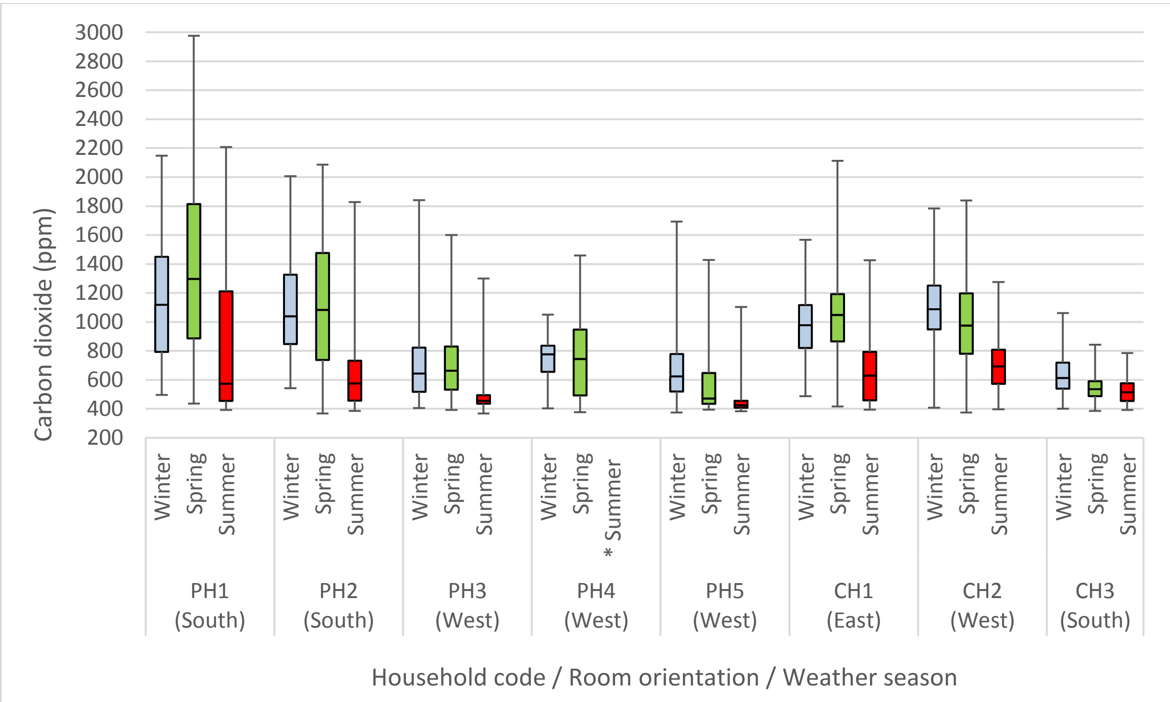


Figure 4.22 Boxplots showing seasonal variation of carbon dioxide in the monitored bedroom of passive houses (PH) and three control houses (C1, CH2 and CH3), excluding control house CH4. (The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

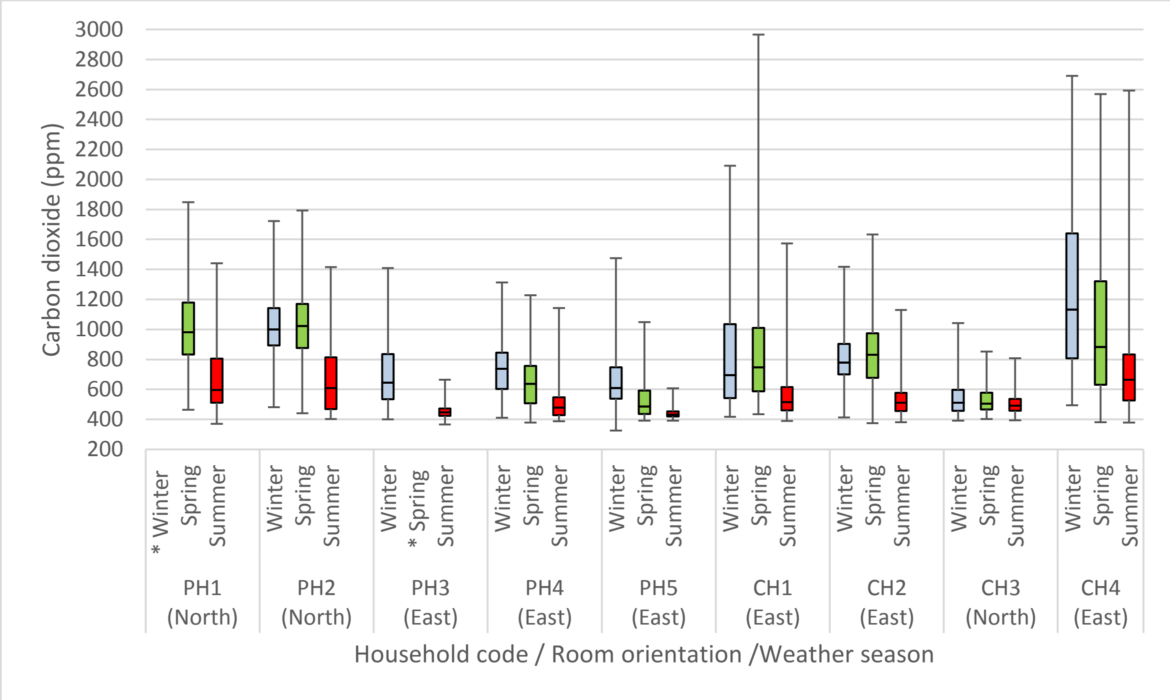


Figure 4.23 Boxplots showing seasonal variation of carbon dioxide in the living room of passive houses (PH) and control houses (CH). (The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

a) Passive houses

The 3 bed passive houses (PH1 and PH2) had overall higher CO_2 levels during the spring compared with the winter (with the exception of the living room of the 3 bed passive house PH1, where winter data was missing, thus there is no data available for comparison), whereas the 4 bed passive houses (PH3, PH4 and PH5) show a different trend. Overall, the 4 bed passive houses had CO_2 levels higher in the winter compared with the spring season, with one exception (the bedroom of PH3 passive house).

Nevertheless, the most significant differences observed were between summer CO_2 levels compared with winter and spring CO_2 levels. Generally, CO_2 levels were found to be significantly lower during the summer when compared with winter and spring seasons, in the monitored bedroom and living room of all five passive houses (figures 4.21 and 4.23).

Aiming to understand the reason for the variation in CO_2 levels between summer and the other two seasons, the following explanatory variables from the analytical framework were considered relevant:

1. External conditions (atmospheric seasonality of CO_2)

Although, it was not possible to obtain outdoor CO_2 data for the studied and control dwellings, it is generally acceptable that atmospheric CO_2 concentrations in the Northern hemisphere are currently around 405 ppm (Earth System Research Laboratory, 2017).

It is important to mention that the seasonal variation of CO_2 observed in the monitored rooms of passive houses, is not an exclusively indoor phenomenon, but also a trend which occurs outdoors. Atmospheric CO_2 in the Northern hemisphere is known to decrease in May as plants begin to photosynthesize in the spring and summer, and to rise in October when plants start to save energy by decreasing photosynthesis during the winter season (Bacastow et al., 1985). The current difference between spring/summer and winter atmospheric CO_2 levels in the Northern hemisphere is generally less than 10 ppm (Earth System Research Laboratory, 2017).

However, the atmospheric seasonality of CO_2 levels cannot explain the seasonal variations found in indoor CO_2 observed in the passive houses. Although indoor and outdoor CO_2 levels seem to follow similar patters: they rise in the winter and fall during spring and summer seasons, the increase in CO_2 levels found in some passive houses were much higher than those found outdoors (e.g. around 2000 ppm observed in the bedroom of PH1 and PH2 during the winter).

2. Occupants' practices (occupancy levels, ventilating, keeping indoor plants)

Regarding occupancy levels, data from occupants' interviews show that occupancy in the monitored bedroom was very similar during the three monitoring seasons. Occupants claimed to have spent an average of 10 hours in the monitored bedroom (mostly from 21:00 pm to 07:00 am). Therefore, this variable seem to offer a weak explanation for the seasonal variations in indoor CO_2.

On the other hand, occupants' ventilation practices offer a stronger explanation in relation to the differences in seasonal indoor CO_2 found in passive house rooms. Data from occupants' interviews and diaries show that generally ventilation practices were intensified (e.g. windows were opened more often) in the bedroom and living room during the summer when compared with the winter and spring seasons. The more frequent summer ventilation can explain the lower CO_2 levels observed in the monitored rooms as greater outdoor to indoor air exchange can help to dilute the indoor concentration of CO_2 and other pollutants.

Another variable considered relevant was the presence of indoor plants, since some plants can reduce or increase the concentrations of CO_2 to a certain extent during the day or during the night respectively (Cetin & Sevik, 2015). However, none of the passive house occupants kept indoor plants for the duration of the three monitoring periods.

In addition, data in figures 4.21, 4.22 and 4.23 show that all houses had CO_2 levels over 800 ppm at some point in the monitored bedroom and living room. However, higher CO_2 levels were found in the 3 bed passive houses (both bedroom and living room), compared with CO_2 levels found in the 4 bed passive houses. CO_2 levels in PH1 and PH2 houses were the highest among all passive houses, especially during the winter and spring seasons: over 800 ppm most of the time in both monitored rooms, reaching near 3000 ppm in the spring (PH1 monitored bedroom) and around 2000 ppm in the winter (PH1 and PH2 monitored bedrooms).

Although generally, CO_2 levels were lower in the living room of passive houses when compared with the monitored bedroom, the 3 bed passive houses PH1 and PH2 also presented CO_2 levels in the living room over 800 ppm for most of the time during the winter and spring seasons.

In trying to explain why the 3 bed passive houses had much higher CO_2 levels when compared with the 4 bed passive houses, monitored CO_2 data obtained from the bedroom of the five studied passive houses during the winter, were compared (figure 4.24) and further analysed.

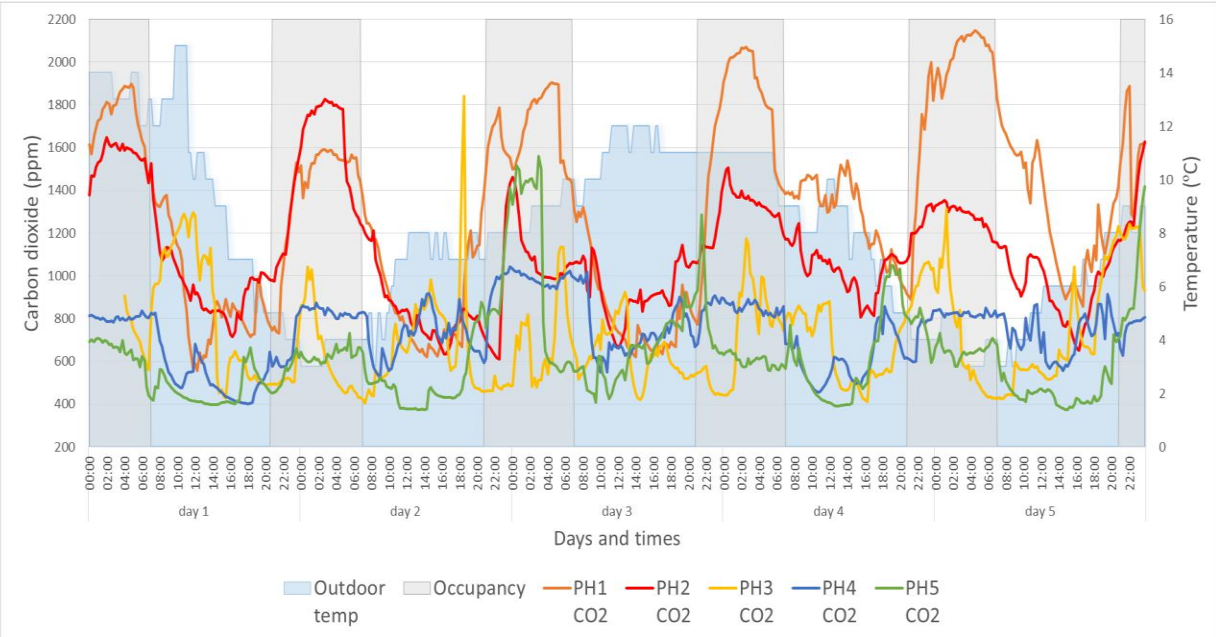


Figure 4.24 Carbon dioxide in the monitored bedroom of the passive houses during the winter season, during five days of monitoring. The grey columns indicate the typical period of bedroom occupancy as indicated by the occupants – from 21:00 to 07:00

The following variables were considered when analysing the reason the 3 bed passive houses had higher CO_2 levels when compared with the 4 bed passive houses:

1. Property characteristics (size)

The monitored bedroom of the 3 bed passive houses had indeed a different area and volume (area: 15 m^2, volume: 36 m^3) when compared with the monitored bedroom of the 4 bed passive houses (area: 13 m^2, volume: 31.2 m^3). Under similar room occupancy (two adults), it would be expected that the room with the biggest volume and higher air exchange rate would have the lowest CO_2 concentrations (Batog & Badura, 2013). However that was not the case. The monitored bedroom of the 3 bed passive houses had an additional 4.8 m^3 in volume as well as an additional 2m^3/h air exchange rate. These figures show that although the monitored bedroom of the 3 bed passive houses had 15% bigger volume and 8% higher air exchange rate, they presented significantly higher CO_2 concentrations (around 50%) when compared with the monitored bedroom of the 4 bed passive houses. Consequently, room size was considered a weak explanatory variable for the significant differences in CO_2 levels between the monitored bedroom of the 3 bed and 4 bed passive houses.

2. Occupants' practices (occupancy levels, ventilation)

Regarding occupancy, the highest CO_2 levels in the bedroom of passive houses PH1 and PH2 were observed during the night time, when occupants (two adults) were sleeping in the bedroom. However, the number of occupants in the bedroom during the night and the occupancy patterns (e.g. the monitored bedroom was mainly used to sleep during the night) was also similar in the 4 bed passive houses. Therefore, this variable was considered weak to explain the observed differences in CO_2 levels between the two groups of passive houses.

Lower ventilation rates in passive houses PH1 and PH2, caused either by occupants opening the window less frequently, or by occupants changing the settings on the MVHR system were also considered. Regarding changes in the MVHR settings, data from occupants' interviews and diaries as well as visual inspection of the MVHR control (carried out during the interview with the occupants) show that the MVHR settings were kept on number two (normal occupancy) for the entire winter monitoring period in all five passive houses. Additionally, all passive house occupants claimed to have never boosted the ventilation during the winter season. Since the settings of the MVHR system in all five passive houses were not changed at all during the winter monitoring period, this was also considered as a weak explanatory variable.

Regarding lower ventilation rates caused by occupants opening the window less frequently, the data from occupants' interviews and diaries show that occupants in the 3 bed passive houses PH1 and PH2 rarely opened the bedroom window during the winter season. However, the data also show that in the 4 bed passive house PH4, opening the window was also very infrequent in the monitored bedroom. Nevertheless, CO_2 levels were much lower in the bedroom of the PH4 when compared with PH1 and PH2 bedrooms. Therefore, ventilation practices performed by occupants were not considered a strong explanatory variable for the significantly higher CO_2 levels observed in the 3 bed passive houses.

Furthermore, passive house occupants were generally instructed to keep the windows closed during the winter season to improve thermal performance. This is a standard advice for passive house occupants – that the ventilation rates provided by the MVHR are sufficient to provide fresh air and comfortable temperatures (International Passive House Association, 2010). Nevertheless, this was not the case in the 3 bed passive houses, as under normal occupancy (2 adults sleeping in the bedroom), CO_2 levels in the bedroom were still high (peaking beyond 2000 ppm) during the winter.

All the previously discussed variables were not considered sufficiently strong to explain the high CO_2 levels in the monitored bedroom of 3 bed passive houses when compared with the 4 bed passive houses. Therefore, the hypothesis offered by the researcher is that after commissioning, the MVHR system used in the 3 bed passive houses (which was a different model than the one used in the 4 bed passive houses), was not working as efficiently, resulting in an unbalanced system or decreased ventilation rates in the 3 bed passive houses.

Table 4.13 shows that the differences in CO_2 levels observed in passive house rooms were statistically significant in most cases. No statistically significant difference was observed between some rooms in the same group of passive houses. For example, between the monitored bedroom of the 3 bed passive houses or between the monitored bedroom of the 4 bed passive houses.

Season	**Rooms**	
	Bedroom	**Living room**
Winter	SSD between all rooms, except between PH1 & PH2, PH3 & PH5	SSD between all rooms
Spring	SSD between all rooms, except between PH3 & PH4	SSD between all rooms, except between PH1 & PH2
Summer	SSD between all rooms	SSD between all rooms

Table 4.13 Statistically significant difference (SSD) in carbon dioxide between the monitored rooms in different passive houses

Comparisons of CO_2 were also made between the monitored bedroom and living room in the same passive house, during the same season. Figures 4.25, 4.26 and 4.27 show comparisons between CO_2 levels between these two rooms during the winter, spring and summer seasons respectively.

Unfortunately, due to some missing datasets, it was not possible to make comparisons between CO_2 levels from the monitored bedroom and the monitored living room in all five passive houses. Nevertheless, the data obtained and the analysis performed was considered sufficient to produce some insights into the possible differences and similarities regarding indoor air quality in different rooms in the same passive house.

In the 3 bed passive houses, CO_2 levels were higher in the monitored bedroom compared with the living room, during the winter and spring seasons in PH2, and during the spring season in PH1. During the summer season however, the living room presented higher CO_2 levels when compared with the monitored bedroom. These differences were statistically significant in most cases (table 4.14).

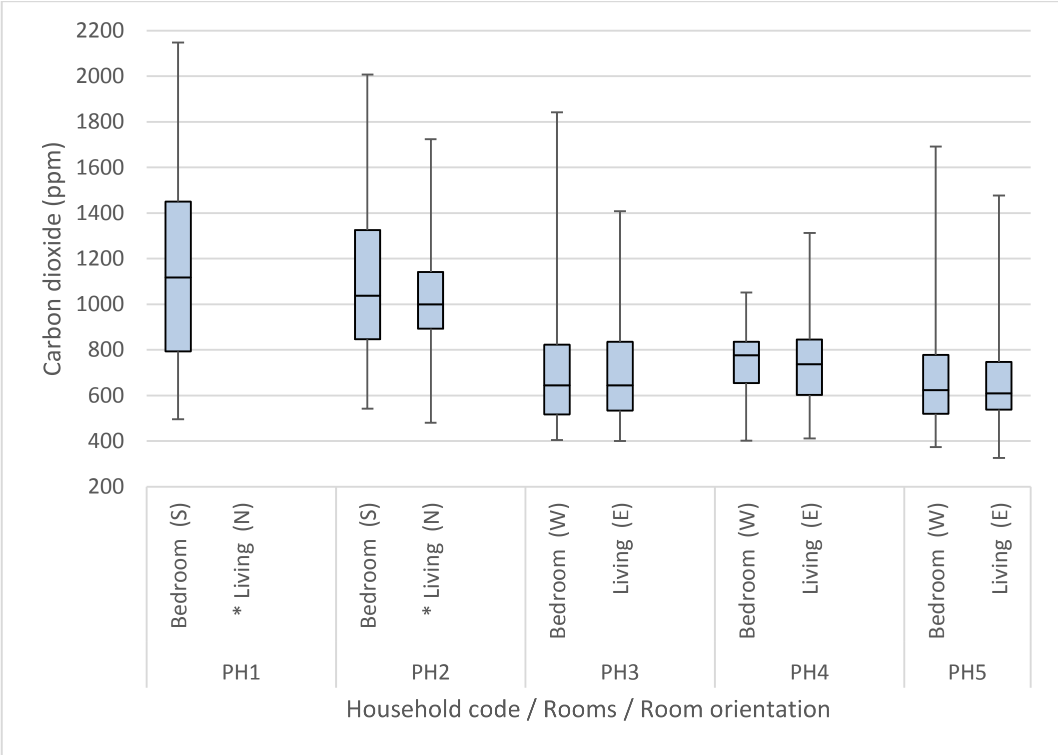


Figure 4.25 Boxplots showing carbon dioxide in the monitored bedroom and living room in passive houses (PH) during the winter season. (The letter in brackets refers to the room orientation. The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

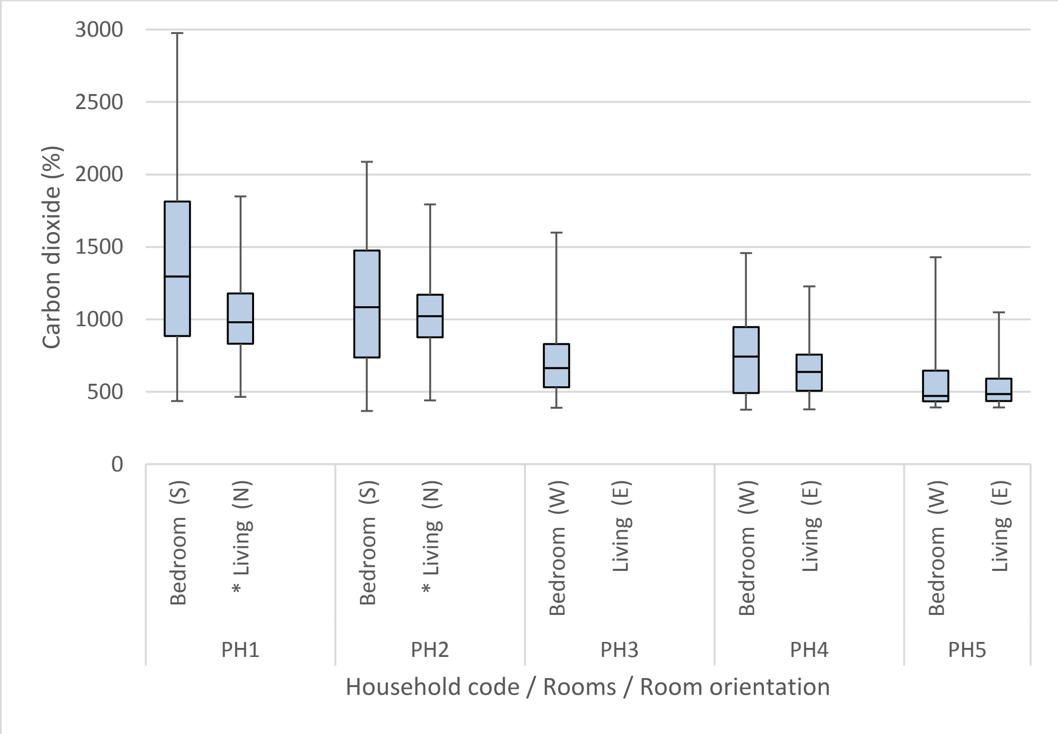


Figure 4.26 Boxplots showing carbon dioxide in the monitored bedroom and living room in passive houses (PH) during the spring season. (The letter in brackets refers to the room orientation. The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

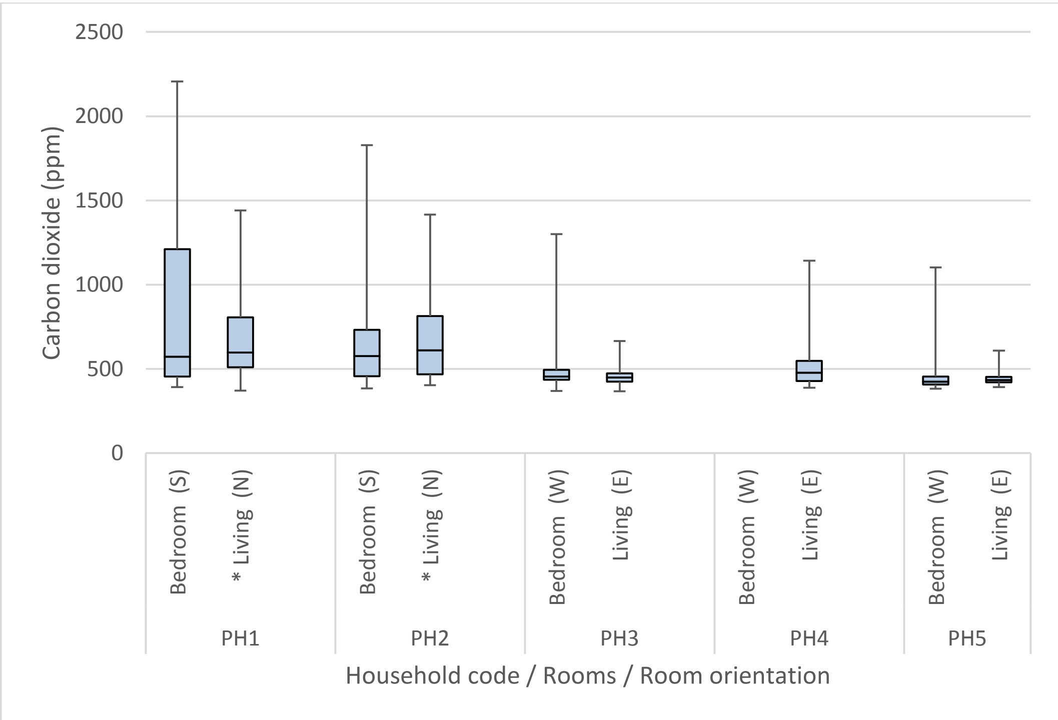


Figure 4.27 Boxplots showing carbon dioxide in the monitored bedroom and living room in passive houses (PH) during the summer season. (The letter in brackets refers to the room orientation. The asterisk on the horizontal axis of the graph indicates some missing data. Refer to the Methodology chapter for further details)

Passive house code	Season		
	Winter	Spring	Summer
PH1	Missing data	SSD between all rooms	SSD between all rooms
PH2	SSD between all rooms	SSD between all rooms	No SSD between Bed & LR
PH3	SSD between all rooms	Missing data	SSD between all rooms
PH4	SSD between all rooms	SSD between all rooms	Missing data
PH5	No SSD between Bed & LR	No SSD between Bed & LR	SSD between all rooms
	Key: Bed = bedroom; LR = living room; Kit= kitchen		

Table 4.14 Statistically significant difference (SSD) in carbon dioxide between the monitored bedroom and living room in the same passive house (PH). (P<0.05)

Aiming to explain the reason for such significant differences between the monitored bedroom and the living room in the 3 bed passive houses, CO_2 levels (monitored during the spring) in those two rooms in passive house PH1 and PH2 were compared (figure 4.28), and analysed in conjunction with data from occupants' interviews and diaries (table 4.15).

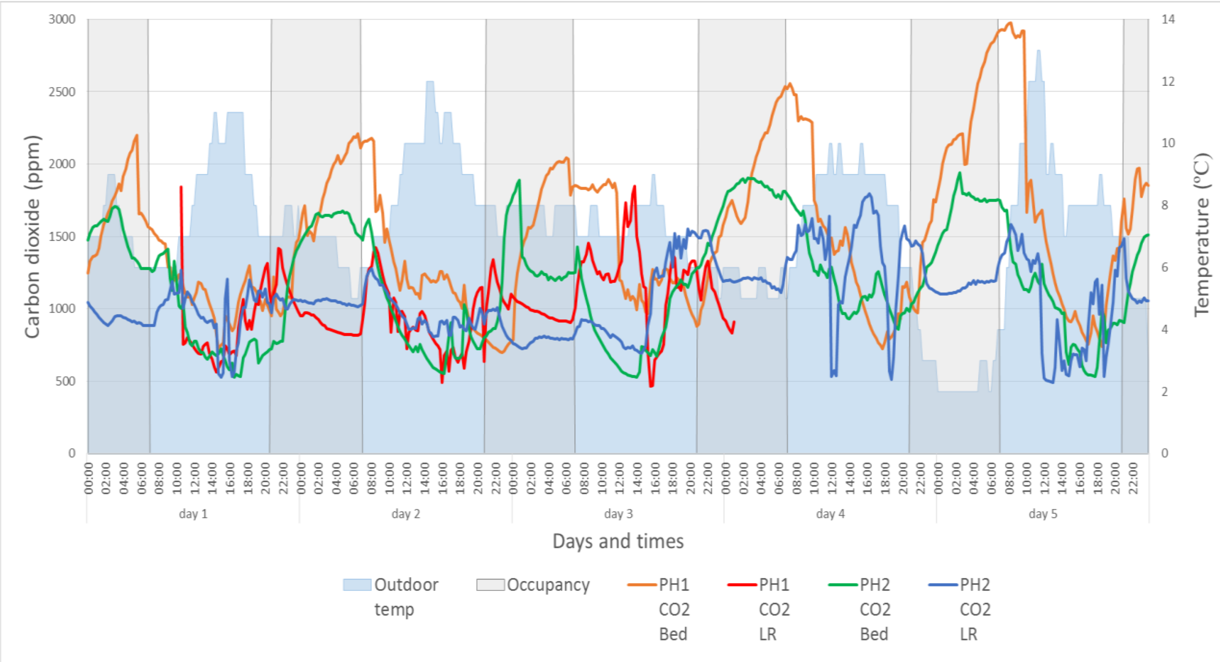


Figure 4.28 Carbon dioxide in the monitored bedroom of the passive houses PH1 and PH2 in the spring season, during five days of monitoring. The grey columns indicate the typical period of bedroom occupancy as indicated by the occupants – from 21:00 to 07:00

Practices	House	Room	Day 1	Day 2	Day 3	Day 4	Day 5
Ventilating (opening the window)	PH1	Bedroom	14.30	-	-	-	-
		Living	15.00	14.00	16.30	18.00	17.15
	PH2	Bedroom	-	-	-	-	-
		Living	-	-	-	18.00	-
MVHR setting number	PH1	N/A	2	2	2	2	2
	PH2	N/A	2	2	2	2	2
MVHR ventilation boosted?	PH1	N/A	no	no	no	no	no
	PH2	N/A	no	no	no	no	no
Number of people in the house during the day	PH1	N/A	3	4	4	0	0
	PH2	N/A	Not known	Not known	Not known	Not known	Not known
Practices not performed in these rooms during the five days of monitoring	Keeping indoor plants, keeping pets						

Table 4.15 Frequency of practices performed in the monitored bedroom and living room of passive houses PH1 and PH2 in the spring, during five days of monitoring

In terms of CO_2 levels in different rooms in the same passive house, the following variables were considered relevant:

1. **Passive house design & construction (MVHR)**

Both the monitored bedroom and the living room of the studied passive houses had a ceiling mounted inlet which constantly supplied air to these habitable rooms. Other rooms, such as bathroom and kitchen were provided with ceiling mounted outlet which extracted air. These inlets and outlets were designed and commissioned so they supplied and extracted respectively, a certain volume of air (m^3/h). This was calculated talking into account the room volume and occupancy. As previously mentioned, the MVHR systems were commissioned before handover, and the units were balanced within the 10% margin. Therefore, the initial assumption was that the air inlets/outlets in each room were providing/extracting ventilation rates as designed. Nevertheless, due to very high CO_2 levels found in the 3 bed passive houses, the following hypothesis was formulated: that after commissioning, the MVHR unit in the 3 bed passive houses was not working as efficiently (e.g. unbalanced or/and supplying low ventilation rates or/and extracting insufficient air).

If this hypothesis were true, it is possible that the inefficiency in the MVHR system contributed to the significant differences in CO_2 levels observed between the monitored bedroom and living room in the 3 bed passive house. However, since this is only a hypothesis, it does not offer a strong explanation for the differences observed.

2. Occupants' practices (occupancy levels, ventilation)

Regarding ventilation practices via window opening, the occupants in passive house PH1 seemed to have opened the living room window more frequently than the bedroom window, during the spring (table 4.15). The timings which PH1 occupants indicated to have opened the living room window, indeed correspond to the drop in CO_2 levels observed on figure 4.28. At first, it could be suggested that ventilation practices (through opening windows) are a strong variable which explains the significant differences in CO_2 between the monitored bedroom and the living room in the 3 bed passive houses. However, even during the periods when the window was kept closed in both rooms (e.g. night time), CO_2 levels in the bedroom were still much higher when compared with the living room. In addition to this, a different trend was observed in passive house PH2. PH2 occupants claimed to have rarely opened the monitored bedroom and the living room window during the five days of spring monitoring. Nevertheless, the CO_2 levels observed in the bedroom were significantly higher than those observed in the living room. Consequently, occupants' practices (though window opening) was rejected as an explanatory variable for the higher CO_2 levels observed in the bedroom.

Occupants' ventilation practices (via MVHR interactions) were also considered. Occupants could have increased the ventilation rates in their rooms by boosting the ventilation (for a period of 15 min) or increased or decreased the ventilation permanently by changing the MVHR setting to number 1, 2 or 3. Number 1 would decrease ventilation rates whilst number 3 would increase them to the maximum. Data from table 4.15 show that during the five days of spring monitoring, occupants of both passive houses PH1 and PH2 claimed not to have boosted the ventilation, nor did they change the ventilation setting, keeping it on number 2 for the entire monitoring period. Nevertheless, even if the occupants had boosted or increased/decreased the ventilation rates permanently by changing the setting number, the same change in ventilation would have occurred simultaneously in both rooms (bedroom and living room). Because MVHR is a whole house ventilation system, it does not offer the option of increasing/decreasing ventilation rates in one room only. Therefore, occupants' ventilation practices (via MVHR interaction) was also rejected as an explanation for the higher CO_2 levels found in the bedroom of the 3 bed passive houses.

The last relevant variable to be considered in relation to indoor CO_2 is occupancy levels. Figure 4.24 compares the different CO_2 levels observed in both the monitored bedroom and the living room of passive houses PH1 and PH2 as well as the period of bedroom occupancy as claimed by the occupants. Evidence from the data shows that during the night and part of the morning CO_2 levels in the bedroom were generally much higher than those observed in the living room. Although occupants have claimed that two adults occupied the monitored bedroom from 21:00 to 07:00 (period of occupancy), the CO_2 data show that on some days (e.g. day 3 and 4) CO_2 levels were beyond 1000 ppm until around 10:00 am. This suggest that either the bedroom occupancy was longer than was claimed or CO_2 levels dropped at a much lower rate, which infers poorer exchange rate than designed for.

Living room CO_2 levels were generally lower than those found in the monitored bedroom. High CO_2 peaks (e.g. beyond 1500 ppm) were generally observed between 07:00 to 21:00, the period when occupants claimed to use the living room. Dissimilar to the monitored bedroom which was occupied by two adults for at least ten hours every night, the living room was occupied more sporadically. Data from occupants' interviews indicated that between the hours of 07:00 and 21:00, the families in passive house PH1 and PH2 used the living room intermittently, as some family members went out (e.g. to work, school) or used other rooms (e.g. kitchen).

Therefore, occupancy levels were considered a stronger variable to explain the higher CO_2 levels in the monitored bedroom when compared to the CO_2 levels observed in the living room of the of the 3 bed passive houses.

b) Control houses

In general, lower CO_2 levels were observed during the summer season in both the monitored bedroom and living room in the control houses, when compared with the spring and winter seasons (figures 4.21, 4.22 and 4.23). Summer CO_2 levels in the monitored bedroom and living room were under 800 ppm for most of the time in all monitored rooms.

The 4 bed control houses (CH1 and CH2) showed higher CO_2 levels, especially during the spring and winter seasons, when compared with the 3 bed control house (CH3). For instance, control houses CH1 and CH2 had CO_2 levels over 800 ppm for most of the time in the monitored bedroom, during the spring and winter seasons, whist the 3 bed control house CH3 had CO_2 levels under 800 ppm in the monitored bedroom for most of the time, during both seasons (spring and winter).

However, the 3 bed control house CH4 showed statistically significantly higher CO_2 levels in the monitored bedroom and living room, when compared with the other 3 bed control house CH3 and the two 4 bed control houses CH1 and CH2 (figures 4.21 and 4.23).

Although all four control houses used in this study were chosen following the selection criteria previously described in the *Methodology Chapter*, control house CH4 presented CO_2 levels much higher than those observed in the other three control houses. For instance, the monitored bedroom of control house CH4 presented significantly higher CO_2 levels: over 1000 ppm for more than 75% of the time during the winter, peaking beyond 7000 ppm. Therefore, it would be appropriate to assume that control house CH4 was an outlier among the other control houses.

A hypothesis for such high CO_2 levels in the monitored rooms in the control house CH4 when compared with the other three control houses is drawn from Hashemi & Khatami's (2015), where it was demonstrated that houses with no background ventilation, such as trickle ventilation, had much higher CO_2 levels when compared with houses with functional and open background ventilation. Since CH4 was the only house among the control houses group which had no trickle ventilation or other form of background ventilation, it is reasonable to assume that this could have contributed to the high CO_2 levels observed there, especially during the colder season, when window opening activities are less frequent (Herkel et al., 2005).

Nevertheless, although control house CH4 could be considered an outlier among the other control houses (which were provided with background ventilation), there could be many other houses in the UK lacking background ventilation.

Although, the UK Building Regulation Approved Document Part F (Ventilation) has specific mandatory requirements for the provision of background ventilation in new domestic buildings, the earliest version of this document was only introduced in 1995, after the Building Act 1984 came into force. Statistics show that 61% of the dwellings in England were built after 1945 (particularly between 1965 and 1984) and that only 7% of the dwellings in England were built since 1995 (ONS, 2009). Although, no information could be found showing what percentage of dwellings in the UK may lack background ventilation, it is possible that many of these dwellings, pre-dating 1995, were not provided with any type of deliberate background ventilation, and as a consequence, they may show the same high levels of CO_2, as observed in control house CH4.

Due to the ethical duty of the researcher of ensuring that research participants were not harmed or left in a position where their health was compromised, after the first monitoring period (winter season), CH4 house occupants were informed by the researcher that their house (main bedroom and living room) presented very high levels of CO_2, which could potentially be harmful to their health.

The researcher has acknowledged that this information may have changed the practices and behaviours of the occupants of control house CH4, which may have impacted the monitoring data obtained from the other two monitoring periods.

In addition, when comparing the CO_2 levels observed in similar rooms during the same season, statistically significant differences were observed between all rooms with only two exceptions (table 4.16). Control houses CH1 and CH2 showed no statistically significant differences in CO_2 levels between the monitored bedrooms and between the living rooms during the spring season.

Season	Rooms	
	Bedroom	Living room
Winter	SSD between all rooms	SSD between all rooms
Spring	SSD between all rooms, except between CH1 & CH2	SSD between all rooms, except between CH1 & CH2
Summer	SSD between all rooms	SSD between all rooms

Table 4.16 Statistically significant difference (SSD) in carbon dioxide between the monitored rooms in different control houses. (P<0.05)

c) Comparing Passive Houses and Control Houses

In terms of CO_2 levels, 3 bed and 4 bed passive houses presented different trends when compared with their corresponding control houses. In general, the 4 bed passive houses (PH3, PH4 and PH5) had considerably lower CO_2 levels in both the monitored bedroom and living room, during all three seasons, when compared with their corresponding control houses (CH1 and CH2). On the other hand, the 3 bed passive houses (PH1 and PH2), as shown on figures 4.21, 4.22 and 4.23, had considerably higher CO_2 levels in both the monitored bedroom and living room during all three seasons when compared with the 3 bed control house CH3. Nonetheless, the 3 bed passive houses had much lower CO_2 levels when compared with the control house CH4, which as explained earlier, was considered an outlier.

Differences in CO_2 between the monitored rooms in passive houses and their corresponding control houses were statistically significant among all houses, during all three seasons, except between the living rooms of passive house PH4 and control house CH1 during the winter season (table 4.17).

Earlier analysis have suggested that MVHR inefficiencies in the 3 bed passive houses could be the cause of the significantly higher CO_2 levels observed there.

Season	Rooms	
	Bedroom	Living room
Winter	SSD between all rooms	SSD between all rooms, except between PH4 & CH1
Spring	SSD between all rooms	SSD between all rooms
Summer	SSD between all rooms	SSD between all rooms

Table 4.17 Statistically significant difference (SSD) in carbon dioxide between the monitored rooms in passive houses and control houses

4.3.2. Volatile organic compounds

Table 4.18 displays a list of the 10 most abundant volatile organic compounds (and their corresponding concentrations) found in the five passive houses and in the four corresponding control houses. The table also includes the most abundant VOCs found outdoors, at the passive house site and at the control houses site.

VOCs (μgm^{-3})	PH1	PH2	PH3	PH4	PH5	Out PH	CH1	CH2	CH3	CH4	Out CH
Alpha-Pinene	81.54	44.70	13.86	14.46	14.70	-	-	14.69	-	10.26	-
3-Carene	60.21	27.40	-	-	-	-	-	-	-	-	-
Limonene	51.46	30.87	14.80	19.69	-	-	78.44	24.81	8.96	78.60	-
Decane	22.67	-	-	-	-	-	-	-	-	-	-
Undecane	34.37	-	-	-	-	-	-	-	-	-	-
Tetradecane	-	23.16	-	-	-	-	-	-	-	-	-
Pentadecane	41.82	29.02	-	18.62	18.75	-	-	-	-	-	-
Heptadecane	-	-	-	-	25.78	-	-	-	-	-	-
Tetracosane	-	66.62	-	-	-	-	-	-	-	-	-
Naphthalene	-	15.61	14.48	-	15.74	4.44	-	15.44	12.62	13.61	6.17
Docosane	-	-	62.43	-	-	-	-	-	-	-	-
Acetic Acid	-	-	-	-	-	-	3.21	-	2.86	-	-
1,4-Dichlorobenzene	-	-	-	-	-	-	-	-	-	135.33	-
m/p-Xylene	-	-	-	-	-	2.47	-	-	-	-	-

Table 4.18 Volatile organic compounds (VOCs) and their concentrations found in the monitored bedroom of passive houses and control houses and those found outdoors in case and control houses sites

a) Passive houses

A total of 11 VOCs species were found in the monitored bedroom of the five studied passive houses. With one exception, none of the VOCs found in the monitored bedrooms were detected outdoors. The only exception (Naphthalene) was detected outdoors in a much lower concentration than those found indoors.

The most common VOCs found in the monitored bedroom of passive houses were alpha-pinene, found in all five passive houses, followed by limonene and pentadecane, which were found in four passive houses (PH1, PH2, PH3 and PH4) and (PH1, PH2, PH4 and PH5) respectively. Naphthalene was found in three passive houses (PH2, PH3 and PH5).

Limonene and alpha-pinene are classified as naturally occurring terpenes, as they are contained in citrus fruits. Due to its pleasant odour, limonene is usually used as a flavour and fragrant additive in food, as well as in cleaning, household and personal care products (Sarigiannis et al., 2011). Similarly, alpha-pinene is contained in cleaning and household products, paints and varnish removers. Alpha-pinene is also emitted by wooden-based products (Brooks and Davis, 1992).

Concentrations of alpha-pinene and limonene found in the 3 bed passive houses (PH1 and PH2) were much higher than those found in the 4 bed passive houses (PH3, PH4 and PH5). Passive house PH1 had more than five times the alpha-pinene concentration found in the other 4 bed passive houses, whilst PH2 had nearly three times the concentration found in passive houses PH3, PH4 and PH5. Additionally, the 3 bed passive house PH1 had the highest limonene concentration (51.46 μgm^{-3}) amongst all four passive houses, followed by the 3 bed passive house PH2 (30.87 μgm^{-3}). The 4 bedroom passive houses PH3 and PH4 had lower limonene concentration of 14.80 μgm^{-3} and 19.69 μgm^{-3} respectively.

Naphthalene, found in passive houses PH2, PH3 and PH5 is the most volatile polycyclic aromatic hydrocarbon (PAH), which has a characteristic odour of mothballs (WHO, 2000). Indoor sources also originate from consumer products such as hair sprays, solvents, lubricants and rubber materials, whilst naphthalene insect repellents (or mothballs), used to protect textiles stored in closets, is one of the main indoor sources (WHO, 2000). Passive houses PH2, PH3 and PH5 had very similar concentrations of naphthalene with 15.61 μgm^{-3}, 14.48 μgm^{-3} and 15.74 μgm^{-3} respectively.

3-Carene, a VOC classified as a monoterpene, was only found in the 3 bed passive houses PH1 and PH2 with concentrations of 60.21 μgm^{-3} and 27.40 μgm^{-3} respectively. Common indoor sources of 3-carene are wooden-based materials (Brooks & Davis, 1992).

Other VOCs, such as docosane, decane, undecane, tetradecane and tetracosane were detected in a single passive house. Building materials (e.g. pressed wood products, gypsum board, insulating materials, plastic piping) are the possible source of some of these VOC species (Maroni et al., 1995). Furthermore, decane, detected in the monitored bedroom of passive house PH1 (with a concentration of 22.67 μgm^{-3}) can also be emitted indoors by cigarette smoking (NCI, 2002; Rodgman & Perfetti, 2013).

Based on the VOC species and their concentrations observed in the monitored bedroom of the studied passive houses, combined with information found in the literature about possible sources of VOCs, the following variables were considered to explain the differences observed in the monitored rooms:

1. **External conditions (VOCs)**

As shown earlier, with one exception (Naphthalene) which was detected outdoors in a much lower concentration than those found indoors, none of the VOCs found in the monitored bedrooms were detected outdoors. Therefore, it would be reasonable to assume that the VOCs detected in the passive houses were emitted by indoor sources. Consequently, outdoor conditions were rejected as an explanatory variable for the concentration of VOC species observed indoors.

2. **Occupants' practices (smoking, ventilation)**

Decane was only detected in the monitored bedroom of passive house PH1. As explained earlier, this VOC species can be emitted by tobacco smoking. Data from occupants' interviews and diaries show that two adults in passive house PH1 smoked in the monitored bedroom a few times during the night on a daily basis. Therefore, smoking practices were considered a strong explanatory variable for the presence of this VOC species in the monitored bedroom of passive house PH1.

Additionally, ventilation practices were also considered as an explanatory variable for the difference in VOC concentrations observed in the monitored bedrooms since indoor/outdoor air exchange can help to purge indoor air pollutants.

As shown earlier, some VOC species were found in significantly higher concentrations in the monitored bedroom of the 3 bed passive houses when compared with the monitored bedroom of the 4 bed passive houses (e.g. alpha-pinene, limonene). Although the source of these VOCs is attributed to cleaning and personal hygiene products, it is possible that poorer ventilation rates in the 3 bed passive houses were also the cause for the higher VOC concentrations. This hypothesis is supported by previous data which showed that CO_2 levels in the 3 bed passive houses were generally significantly higher than those observed in the 4 bed passive houses. It was suggested that the MVHR system in the 3 bed passive houses was not providing ventilation rates as intended. Therefore, it is possible that poorer ventilation rates in the 3 bed passive houses also contributed to the higher concentration of some VOC species when compared with the 4 bed passive houses.

3. **Other explanatory variables (choice of furniture, choice of cleaning and personal hygiene products, building materials)**

Since the indoor presence and corresponding concentrations of many of the detected VOCs are usually attributed to the use of cleaning and personal hygiene products as well as wood-based materials, the VOC concentrations found in different houses could be the result of occupants' choices of cleaning and personal care products, the frequency with which those products were used, as well as occupants' choice of furniture.

b) Control houses

A total of five VOCs species were found in the monitored bedroom of the four control houses. With the exception of naphthalene, none of the VOCs detected in the monitored bedrooms was found outdoors.

Similarly to passive houses, alpha-pinene, limonene and naphthalene were the most common VOCs detected in the monitored bedroom of control houses. The difference between the highest and the lowest concentration of limonene found in the monitored bedroom of different control houses varied by a factor of eight. Higher limonene concentration was found in control houses CH1 (78.44 μgm^{-3}) and CH4 (78.60 μgm^{-3}) than those found in CH2 and CH3, (24.81 μgm^{-3} and 8.96 μgm^{-3}) respectively.

On the other hand, very similar concentrations of alpha-pinene and naphthalene were detected in the monitored bedroom of different control houses. Alpha-pinene concentrations varied from 10.26 μgm^{-3} to 14.69 μgm^{-3}, whilst naphthalene concentrations varied from 12.62 to 15.44 μgm^{-3}.

The most abundant VOC detected in the control houses was 1, 4 dichlorobenzene, which was only detected in the monitored bedroom of control house CH4 (in a concentration of 135.33 μgm^{-3}). The common indoor source of 1, 4 dichlorobenzene is consumer products such as deodorant, air fresheners, mould and mildew control products (Hess-Kosa, 2012).

c) Comparing passive houses and control houses

The three most common VOC species detected in the monitored bedroom of passive houses and control houses were alpha-pinene, limonene and naphthalene. Compared with the control houses, passive houses had higher concentrations of alpha-pinene, similar concentrations of naphthalene and both, higher and lower concentrations of limonene in the monitored bedrooms. The data also suggest that for some VOC species (e.g. alpha-pinene), the 3 bed passive houses PH1 and PH2 had much higher concentrations (81.54 μgm^{-3} and 44.70 μgm^{-3} respectively) when compared with the corresponding 3 bed control house CH4 (10.26 μgm^{-3}), whilst the 4 bed passive houses PH3, PH4 and PH5 showed similar concentrations (around 14 μgm^{-3}) when compared with the corresponding 4 bed control house CH2 (14.69 μgm^{-3}).

Drawing from the previous analysis it is possible that the higher concentration of some VOC species found in the 3 bed passive house when compared with the corresponding 3 bed control house were caused by occupants' choices of cleaning/personal products. Nevertheless, following the hypothesis established earlier, poorer ventilation rates in the 3 bed passive houses could have also contributed to the differences observed.

Some VOC species were only detected in passive houses and not found in the corresponding control houses. These include 3-carene, decane, undecane, tetradecane, pentadecane, heptadecane, tetracosane and docosane. As previously mentioned, some of these VOCs are commonly emitted by building materials.

It has been accepted that new buildings can emit higher VOC concentrations when compared with established buildings as new building materials have a higher rate of VOC emission (Brown, 2002). Therefore, it is not surprising that these VOCs were detected as the top 10 most abundant in the recently built[24] passive houses, and not in the more established control houses.

4.4. Conclusion

The aim of this chapter is to investigate the indoor climate and the indoor air quality of passive houses reliant on the use of a MVHR system, during different seasons, and to compare these indoor parameters with those found in conventional, less airtight houses. The methodological approach used in this part of the research has a threefold purpose. First, it attempts to investigate the indoor environment of UK passive houses, by re-directing the focus from the well-researched passive house thermal performance/energy efficiency viewpoint, to the health viewpoint, which has been rarely addressed. Second, it aims to enhance the current state of knowledge of the indoor environment of passive houses by investigating multiple rooms in the same house, through different seasons. An analytical framework was used in an attempt to explain the reasons for the observed differences in IC and IAQ between passive houses. Third, this methodological approach provides supplementary data to be used when working with the other research objectives. For example, Chapter 5 employs some of the data discussed here, aiming to understand how these results can affect the health of passive house occupants.

Five passive houses and four conventional control houses were investigated. The passive houses presented two dwelling types (3 and 4 bed houses) with identical construction, layout, building volume and solar orientation, whereas the conventional control houses were selected to match as closely as possible the passive house dwellings (in terms of size and number of occupants).

Although this thesis chapter does not explicitly discuss the health of passive house occupants in relation to the indoor environment parameters monitored here, it does contribute towards it. The current chapter compares and contrasts the different health related indoor parameters found in passive and control houses. By using an analytical framework, it also provides explanations for some

[24] The building process of the monitored passive houses was completed less than 6 months prior to the VOCs monitoring.

of the significant differences observed in passive houses. These data and related findings will be a central part of the discussions in the next chapter, which aims to evaluate whether passive houses provide a healthy indoor environment to their occupants.

The chapter revealed the following main findings:

First, temperature and relative humidity levels in the monitored bedroom of the 3 bed passive houses were overall higher than those observed in the 4 bed passive houses during all three seasons. During the winter, low temperatures and low RH levels were observed in the monitored bedroom of the 4 bed passive houses for longer periods than those observed in the 3 bed passive houses, particularly during the night.

By using the analytical framework for further analysis, it was suggested that the room orientation and occupants' ventilation practices were strong explanatory variables for the difference in temperature between the 3 bed passive houses and the 4 bed passive houses during the winter. Contrary to the advice contained in the users' manual, occupants of passive houses PH3 and PH5 claimed to have left the bedroom window open all night during the winter season, which likely contributed to the low temperatures observed there. Nevertheless, ventilation practices did not offer a strong explanation to the low bedroom temperatures in the 4 bed passive house PH4. Low bedroom temperature in passive house PH4 was considered an outlying result for which no explanation was found. The other explanatory variables: MVHR performance, energy performance, property size, glazing area and external conditions were not considered strong variables to provide explanations to why the 4 bed passive houses had significantly lower bedroom temperatures in the winter and therefore they were rejected.

Regarding the low RH levels observed in the monitored bedroom of the 4 bed passive houses during the winter, the data analysis through the analytical framework revealed that ventilation practices offered a strong explanation. Occupants opening window during the winter would have contributed to additional outdoor/indoor air exchange where warmer indoor air was being replaced by cooler and dryer outdoor air, lowering indoor temperatures. Nonetheless, this variable does not offer an explanation for the low RH levels observed in the monitored bedroom of passive house PH4. Low bedroom RH in passive house PH4 was considered an outlying result for which no explanation was found. The other variables: MVHR performance, property size and orientation, external conditions and occupancy were not considered robust in explaining the low RH levels in the 4 bed passive houses.

Second, the data findings also show that temperatures in the kitchen were significantly higher ($p<0.05$) when compared with the monitored bedroom and living room. Very high temperatures (peaking over 30°C) were observed in some passive houses kitchens during the summer monitoring.

Through the analytical framework analysis, it was suggested that a combination of many electrical appliances being used in the kitchen during the day has contributed to the higher temperatures in passive house kitchens. The other variables: glazing area, solar shading, MVHR performance, orientation, occupancy and external conditions were considered weak when explaining high kitchen temperatures.

Third, the 3 bed passive houses had significantly higher CO_2 levels ($p<0.05$) when compared with the 4 bed passive houses. This was especially problematic during the winter and spring seasons, as CO_2 levels in the monitored bedroom of the 3 bed passive houses PH1 and PH2 peaked beyond 2000 ppm. When using the analytical framework for the analysis of possible explanations, all the relevant explanatory variables were considered weak in explaining high CO_2 levels in the two 3 bed passive houses. Those considered variables are property size, occupancy levels and occupants practices (ventilation). The hypothesis offered by the researcher is that after commissioning, the MVHR system used in the 3 bed passive houses (which was a different model that the one used in the 4 bed passive houses) was not working as efficiently as it was designed for, resulting in an unbalanced system or in decreased ventilation rates in the 3 bed passive houses. Malfunctions and shortcomings related to the performance of MVHR systems were described as common on other studies (e.g. Balvers et al., 2012; Lowe & Johnston, 1997).

Additionally, the data findings also show that CO_2 levels were significantly lower ($p<0.05$) in the monitored bedrooms and living rooms during the summer when compared with the winter and spring seasons. The analysis though the analytical framework revealed that occupants' ventilation practices offer a strong explanation for the differences observed. This is based on evidence suggesting that since windows were being opened more often during the summer, there was additional indoor to outdoor air exchange which contributed to lower the indoor CO_2 levels. The other variables analysed: atmospheric CO_2 seasonality, occupancy levels and keeping indoor plants were considered weak in explaining the seasonal differences in indoor CO_2 observed in passive houses.

Seasonal variation of indoor CO_2 was also observed by Derbez et al. (2014) in a study where CO_2 and other indoor air quality parameters (e.g. $PM_{2.5}$) were monitored. The authors similarly reported that the concentrations of these indoor air quality parameters were lower in the summer than in the winter. Other authors (Wallace et al., 2002) have also suggested that such seasonal variations could be related to an increase in air exchange during the summer, possibly caused by house occupants opening the window more frequently.

Fourth, the findings from this study revealed that the identical 3 bed passive houses PH1 and PH2 and the identical 4 bed passive houses PH3, PH4 and PH5 presented very different indoor climate and indoor air quality. The difference in temperature, RH and CO_2 levels were generally statistically significant between identical passive houses. The VOCs monitoring data supported this claim by showing that in some cases, identical houses had dissimilar levels of specific VOCs. These results are supported by an earlier study (Maier et al., 2009) where 22 identical houses were monitored aiming to investigate their energy consumption. The authors observed that although identical, these houses presented dissimilar energy consumption as well as differences in their indoor environment (e.g. the difference of mean concentration of CO_2 between some identical houses with the same number of occupants was nearly twofold). The hypothesis for such significant differences was that occupants in different passive houses performed different practices (e.g. ventilating, cooking, cleaning, smoking) or used different cleaning products (containing more or less VOCs), which in turn affected the quality of their indoor environment.

By applying the analytical framework, the findings from this thesis chapter also suggest that many of the differences found in VOC species and their concentrations between passive houses are caused by different practices performed by occupants (e.g. smoking, ventilating by opening windows) as well as different choices of cleaning and personal hygiene products and furniture. External conditions were found to be a weak variable to explain differences in indoor VOC species and their levels.

The findings also suggest that it would be very difficult to make generalisations between the very airtight passive houses and less airtight conventional houses regarding the quality of their indoor environment. This is because passive houses performed either better or worse depending on the indoor parameter analysed. Generally, passive houses had higher indoor temperatures when compared with control houses. Especially high temperatures were observed in the 3 passive houses PH1 and PH2 during the summer (e.g. peaking over 28°C). On the other hand, regarding CO_2 concentrations, the 4 bed passive houses presented lower levels when compared with the control houses. Nonetheless, the opposite trend was observed with the 3 bed passive houses, which generally had CO_2 levels much higher than those observed in the corresponding control houses (e.g. peaking beyond 2000 ppm during winter and spring seasons). Interestingly, some of the concentrations of VOCs species found in the monitored bedroom of the 3 bed passive houses were much higher than those found in the 4 bed passive houses. This finding supports the hypothesis from other studies (Chatzidiakou et al., 2015; Seppänen, 1999) which suggest that CO_2 concentrations are a significant predictor of indoor air pollutants. The authors of those studies propose that high CO_2 concentrations are related to low ventilation rates and therefore linked with the inability of indoor pollutants to be purged through ventilation.

This thesis chapter has investigated the indoor climate and indoor air quality of passive houses from a health perspective, comparing the findings from passive houses with the findings from conventional houses. It has shown that some of the significant differences observed between passive houses were caused by occupants' practices (e.g. ventilation, smoking, practices which involves the use of electrical appliances in the kitchen) and possible inefficiencies with the MVHR ventilation system.

Nevertheless, since this thesis has a health perspective, a few questions are still to be answered. First, what do the findings from the indoor environment of passive houses tell us about any possible health outcomes for the house occupants? Second, how do these compare with any possible health outcomes for the occupants of conventional houses?

The next thesis chapter aims to answer these questions. It does that by analysing whether the indoor parameters (and their concentrations) observed in the passive houses could be associated with any known adverse health outcome. This is attempted through a review of the epidemiological, toxicological and other health related published literature on the possible health effects of exposure to the levels of temperature, relative humidity, CO_2 and VOCs found in passive houses.

4.5. Strengths, limitations and recommendations

This study has for the first time, as far as the researcher knows, investigated different internal rooms in the passive house, during different seasons, aiming to provide a richer understanding of the indoor climate and indoor air quality of these houses. This investigation of the indoor environment of passive houses was undertaken from a health viewpoint, and not from the well-researched energy efficiency viewpoint.

There were a few limitations in this study which include the small amount of missing data due to house occupants unplugging the monitors. Additionally, some indoor environment monitoring data (from different passive houses and control houses) were not collected concurrently for the entire two weeks of the same seasonal period. This is due to householders cancelling the booked appointment (when the monitors were to be set up) and rescheduling them due to personal circumstances. Finally, the control houses were not located within close proximity to the passive houses. As previously discussed, this was due to difficulties in recruiting participants within that area (e.g. no response from any of the 100 leaflets given to local householders). Nevertheless, another location was identified, which matched as closely as possible the surroundings of the passive house site.

Taking these strengths and limitations into account, it would be interesting to have other studies also investigating the indoor environment of passive houses from a health viewpoint, using control houses in a very close proximity to the studied passive houses. Such studies could be able to address the stability of the findings outlined here.

Chapter 5 – The health of passive house occupants

5.1. Introduction

The passive house, an internationally acknowledged building standard for very energy-efficient buildings, prescribes the design and construction of a well-insulated and airtight building envelope, combined with the use of a MVHR system for ventilation and heat recovery. Passive house advocates claim that this building standard not only produces highly energy-efficient houses, but it also creates healthy buildings (International Passive House Association, 2010). The following are some quotes from the International Passive House Association:

> *"The ventilation system constantly provides good quality indoor air; it automatically extracts moisture and clearly improves living comfort. There are no draughts, no cold corners in the houses, and fresh air is constantly available"* (International Passive House Association, 2010, p.8).
>
> *"A passive house ventilation system constantly provides for excellent air quality – and also saves energy through heat recovery"* (International Passive House Association, 2010, p.29).

Due to a large body of research (e.g. Feist & Schnieders, 2009; Feist et al., 2005; Ridley et al., 2013), there is little doubt that passive house standards do produce highly energy-efficient homes. On the other hand, there is insufficient research which explores and challenges the claims that passive house standards do provide a healthy environment with good indoor air quality, improving living comfort and health. Furthermore, there have been concerns that energy efficient homes, such as the passive houses, may fail to provide a healthy environment and actually harm the health of their occupants (Bone et al., 2010; Yu & Kim, 2012). For that reason, there is a clear need for a research study to investigate the indoor environment of passive houses and determine if there are health effects or health concerns related to them.

Accordingly, the aim of this chapter is to analyse whether passive houses provide a healthy indoor environment for their occupants. Additionally, if the research findings suggest that passive houses might provide a potentially unhealthy indoor environment, the researcher aims to explore the possible causes of problem.

Consequently, this chapter has three objectives. First, through a review of the literature on epidemiological, toxicological and other interventional and observational health related research, it aims to bring to light any health effects related to the indoor climate and indoor air quality parameters found in the passive houses, and to reveal safe threshold levels of exposure. Second, by comparing the findings from the health related literature review and the findings from the indoor climate and indoor air quality of passive houses, the aim is to analyse the health status of the indoor environment of passive houses. This is done by the analysis of data showing the proportion of time the monitored indoor parameters were outside recommended thresholds together with the analysis of occupants' exposure to those potential hazards. By making those analysis, the chapter ultimately attempts to reveal whether passive houses provide a healthy environment to their occupants.

The cause of possible health risks in passive houses is investigated by drawing on the explanatory variables from the analytical framework discussed in the previous chapter. In Chapter 4, explanations for differences in IC and IAQ within passive houses were provided based on testing a set of explanatory variables. Based on this understanding, conclusions are presented at the end of this chapter for possible health risks in passive houses drawn from those variables which were considered to strongly explain a particular phenomenon (e.g. high indoor temperatures).

Additionally, the researcher also aims to find out how the results related to the health status of the indoor environment of passive houses compared with the results from conventional houses.

5.2. Health outcomes associated with the indoor climate and indoor air quality parameters monitored in passive homes – a brief review of the literature

In the previous chapter the researcher has investigated the indoor climate and indoor air quality parameters found in passive houses, and compared those with the same parameters found in conventional houses. Indoor climate parameters included temperature and relative humidity, whilst indoor air quality parameters included carbon dioxide and VOCs. Accordingly, through the literature review undertaken here the researcher aims to find out what levels of indoor temperature, relative humidity, carbon dioxide and certain VOCs could represent a health risk for passive house occupants. After analysing the possible health risks passive house occupants might be exposed to, the explanatory variables identified in the previous chapter will be evaluated to provide explanations for possible health outcomes in passive houses.

5.2.1. Temperature

Temperature related studies were included in this review if they were conducted in the UK or in countries considered to have a similar climate. The aim of this review is to bring to light possible health risks associated with cold and hot indoor temperatures and to provide an evidence-based, indoor temperature threshold which minimises adverse health effects associated with both low and high indoor temperatures.

Although ambient temperature related studies have been mainly undertaken by disciplines such as climatology, epidemiological research investigating temperature have received more attention over the past few years (Basu, 2009). Concerns related to extreme temperature and ill health began to receive special interest from epidemiological researchers due to possible health effects of climate change in the wake of the Western Europe heat wave in 2003 (Kosatsky, 2005; McMichael et al., 2006). Additionally, scientists have predicted that temperatures across Europe will continue to rise over the next decades whilst doubling the frequency of periods of extreme temperatures (WHO et al., 2003). Such extreme temperatures have been associated with natural (non-accidental) mortality and hospital admissions (Basu and Samet, 2002; McMichael et al., 2006; Schwartz et al., 2004) due to a range of morbidity such as heat stroke, respiratory and cardiovascular disease (Semenza et al., 1999; Urban et al., 2014).

In the UK, the increase in mortality and morbidity rates associated with extremes of temperatures have been linked with both cold and hot temperatures. Mortality in the UK is however, substantially higher during colder months (usually winter), when compared with other seasons (PHE, 2014). DCLG (2012) suggest that in the UK, around 2,000 deaths occur per year due to heat, compared with around 25,000 due to cold. The numerous cold and damp homes have been held responsible for the high number of temperature related deaths during colder seasons (Healy, 2002). Nonetheless, high temperatures in the UK have also been associated with an increased risk of mortality (Armstrong et al., 2010) and hospital admissions (Kovats et al., 2004). Furthermore, climate change projections for the UK suggest that heat related mortality and morbidity could rise by around 257% by 2050 from the current annual baseline (Hajat et al., 2014).

Current UK building regulations do not enforce indoor temperature thresholds for health. However, it has been suggested by building designers (CIBSE, 2005) that the maximum temperature threshold for thermal comfort in dwellings is 28°C in the living room and 26°C in the bedroom, where overheating occurs when these temperatures are exceeded more than 1% of the time. Nevertheless, there are two primary concerns with such guidelines. First, these guidelines are generally based on concepts of thermal comfort (e.g. the lowest and highest temperatures at which occupants experience discomfort) and not entirely based on health criteria (NHBC, 2012). Second, they are not fully representative of the wider population who occupy domestic settings and who may have a range of vulnerabilities that make them more prone to low or high temperature related illness (Anderson et al., 2013). As argued by Kunst et al. (1993, p.331), "exposure of the human body to unfavourable ambient air temperatures is not just uncomfortable but creates a direct threat to human survival". Additionally, epidemiological research studies have revealed that heat related mortality and morbidity may begin at comparatively lower temperatures (Hajat et al., 2002) than those thresholds recommended by building designers.

The World Health Organization (WHO) has produced a few reports containing indoor temperature threshold recommendations for homes. Through a review on the literature on ambient temperatures and health, the World Health Organization (WHO, 1984) recommended indoor temperatures for sedentary individuals, between 18°C and 24°C. However, this report has been criticised for not giving references for the evidence on the temperature range they recommended and for providing insufficient data at the time, on the impact of the indoor climate on high risk groups (e.g. elderly, children) (Ormandy & Ezratty, 2012). Later reports (WHO, 1987; WHO, 1990) adopted the same range of indoor temperature thresholds, albeit they made the recommendation that some high risk groups such as the very old (reference made to people over 65 years old) and the very young, should have a minimum indoor temperature of 20°C.

Recommendations for minimum temperatures in homes in the UK have been given by Public Health England (2014), where it is advised that the daytime temperature threshold should be 18°C for healthy people (and up to 64 years old) and slightly higher than 18°C for people over 65 years old or with pre-existing medical conditions. For overnight ambient temperature, the recommendation is to maintain 18°C threshold for those over 65 years old or with pre-existing medical conditions and that this threshold may be less important for healthy people (up to 64 years old) if they have sufficient bedding. These recommendations are based on an epidemiological literature review on the health impacts of cold indoor temperature.

Epidemiological studies on temperature exposure can be observational or experimental. With observational studies, the researcher analyses what has already occurred, whilst with experimental studies, the researcher intervenes and analyses the results.

Generally, most epidemiological studies are observational, relying on data that are usually collected from a large population (Rudge & Gilchrist, 2007). Since measuring the daily temperature of the indoor environment is impractical and expensive (Basu & Samet, 2002), many studies tend to make use of outdoor temperature data obtained from weather stations, as these are easily available. The external temperature data obtained at city and country level (usually daily mean, maximum and minimum temperatures) are associated with the number of hospital admissions for a range of diseases and natural (non-accidental) mortality. This epidemiological study design, known as time-series study, has been widely used to examine the short term effects of ambient temperature on mortality and morbidity (Gasparrini et al., 2014; Kovats et al., 2004). Ye et al. (2012, p.20) explain that in time-series analysis, mortality and morbidity "counts or rates were usually used as the outcome measures, whereas temperature measurements at corresponding intervals were employed as exposure indicators".

However, as Basu (2009) argues, measuring ambient outdoor temperature exposure at city and country level scale is likely to misclassify the indoor temperature exposure in houses, since indoor temperatures in dwellings greatly depend on the building characteristics (Oreszczyn et al., 2006). Furthermore, a review undertaken by Anderson et al. (2013) on indoor heat thresholds showed the difficulties in using outdoor indices to establish indoor heat threshold and to predict the possible health effects of indoor heat. Anderson and colleagues argue that there are several variables that may significantly impact on the validity of an index, such as indoor heat gains, solar gain, density of occupants and adaptive behaviour.

Another important point taken into account when reviewing epidemiological studies and analysing their findings is that there are groups of people who are more vulnerable to low and high indoor temperatures. These include the elderly (especially those living on their own), young children, individuals with pre-existing medical conditions, people living in overcrowded accommodation, and the socio-economically deprived (Parsons, 2003; Vardoulakisa et al., 2015). Some of these more vulnerable groups were included in the studies which are part of the literature review for this thesis chapter, and therefore the effect of low and high indoor temperature on these individuals will be further discussed in the second part of this chapter (section 5.3).

Although there is abundant literature on the associations of outdoor ambient temperature and human health, few epidemiological studies have measured indoor temperature and made associations with health outcomes. The literature search reviewed a small number of studies on the health risks of low indoor temperature thresholds in non-industrial settings. These studies were analysed as part of this literature review. However, only three comprehensive studies on the health risks of high indoor temperature thresholds in the UK or countries with similar climate were found within the literature. Anderson et al. (2013) have advised that there is a great need for more research in this area.

Following the inclusion criteria set out in the methodology chapter, seven papers were identified through the literature search on low indoor temperature thresholds and associated health risks. These studies used cross sectional analysis. Health outcomes included blood pressure (BP), respiratory symptoms, core and skin temperature and physical performance. The studies include two large population based, randomised trial studies (with no clear indication of pre-existing medical conditions), four very small, laboratory-based studies with healthy subjects exposed to various temperatures, and one study of 140 patients admitted to a hospital with exacerbation of chronic obstructive pulmonary disease (COPD).

Within the adult population, there was some epidemiological evidence suggesting that BP rises when indoor temperatures falls to 18ºC or below (Inoue et al., 1992; Saeki et al., 2013; Shiue & Shiue, 2014). For example, a large country-wide, population-based cross sectional study (Shiue & Shiue, 2014) using a cohort of 113,710 adults (aged 16 to 95 years), established that occupants of houses heated at below 18ºC have a higher risk of high BP, doubling the risk when indoor temperatures reach below 16ºC.

Other studies (Collins et al., 1985; Lindemann et al., 2014; Neild et al., 1994; Shiue, 2015) which targeted older populations when examining possible health risks of low indoor temperatures, found that indoor temperatures at 18ºC and below were associated with a number of health effects. For instance, using a cross-sectional design study with a large number of older adult participants (7,997 adults aged 50+ years), Shiue (2015) found that older participants living in homes heated at below 18ºC showed higher BP readings, worse handgrip, lower vitamin D levels, higher insulin-like growth factor levels, higher haemoglobin levels, lower white blood cell counts and worse lung conditions than those participants living in homes heated at 18ºC or higher. It is unclear, however, if the population investigated was healthy or had pre-existing medical conditions.

Another smaller study (Collins et al., 1985) found that older participants (aged 63-70 years) had a decrease in heart rate when exposed to 12ºC or below. However, no significant heart rate changes were observed when participants were exposed to 15ºC. The authors suggested that 15ºC would be the minimum level at which the elderly should live in their homes.

The association between indoor temperature and physical performance on older women was also explored by a laboratory based study (Lindemann et al., 2014). Eighty eight community dwelling women (70+ years) were exposed to 25ºC and 15ºC room temperatures. Muscle power of lower limbs and sit-to-stand performance velocity were assessed. The authors reported that in general physical performance was lower at 15ºC compared with 25ºC. The decrease in the level of physical performance ranged from 2% to 10%. Handgrip strength was unaffected at 15ºC. The study confirmed the hypothesis that physical performance in older women is reduced in a cold environment.

In addition another small study, investigating whether cold temperature could induce haematological changes on the elderly, found that older men and women (aged 66-71 years) presented an increase in cholesterol concentration when they were exposed to 2 hours at 18±0.5ºC (Neild et al., 1994).

Regarding possible adverse health effects on people with chronic illness, the evidence base was very limited. One study (Osman et al., 2008) investigated whether the health status of patients with COPD was associated with the number of hours when homes reached recommended standards of indoor temperature (21ºC for the living room and 18ºC for the bedrooms). A hundred and forty patients admitted to Aberdeen Royal infirmary with exacerbation of COPD between 2003 and 2004 participated in the study. After measuring for lung function, forced expiratory volume (FEV) and forced vital capacity (FVC), the authors concluded that patients with fewer days at 21^{o}C for at least 9 hours had significantly worse respiratory symptoms scores, with smokers showing more health effects of less warmth than non-smokers. The authors also suggested that a better health was associated with indoor temperatures at and above 21^{o}C for elderly patients, patients with pre-existing medical conditions and tobacco smoking patients.

Based on this epidemiological literature and other published systematic reviews (e.g. Jevons et al., 2016), there was some evidence to suggest that indoor temperature below 18^{o}C may be associated with adverse health effects for the general adult population (16 to 64 years) as well as to the older population (65+ years). Correspondingly, others have suggested that higher temperatures (21^{o}C) may be preferable for the more vulnerable populations: the elderly, individuals with pre-existing conditions and smokers (Osman et al., 2007).

The findings of this literature review on the health effects of low indoor temperatures on the general adult population have supported the guidance from Public Health England (2014), which recommends indoor temperatures of 18^{o}C or above to minimise possible adverse health effects.

Unfortunately, no consensus was found within the literature regarding the level of exposure (to temperatures under 18^{o}C) that leads to adverse health effects. Indeed, this was considered a topic which requires further research (Jevons et al., 2016).

Regarding indoor heat threshold for the health of house occupants, the literature review highlighted the need for more research to be undertaken as available data on high indoor temperature exposure and their effect on human health are sparse (Anderson et al., 2013). Only three studies, fitting the search criteria were found within the published literature. This was considered insufficient and especially important since the majority of heat related fatalities occur at home (Quinn et al., 2014). More evidence on indoor heat threshold is considered vital for certain parts of the UK (e.g. the southern part of England), which is predicted to have the largest risk of indoor overheating in the UK (DCLG, 2012a; DCLG, 2012b; DCLG, 2010). Therefore, establishing indoor heat thresholds for homes is vital due to concerns over overheating in highly insulated homes (NHBC, 2012a), such as passive houses.

Nevertheless, a few studies have provided information on high indoor temperature and some guidance on indoor heat threshold for health. The first study aimed to determine whether high indoor temperatures were associated with cardiovascular and respiratory conditions (Uejio et al., 2015). Using a case-control study, the authors investigated the indoor environment of people receiving emergency medical care from 10 paramedic teams operating throughout five boroughs in

New York City, US. Data sources included outdoor weather conditions, temperature and relative humidity inside buildings where patients received emergency care, patients' demographics and patients' care reports. The authors reported that indoor temperatures above 26^{o}C increased the proportion of respiratory distress calls, although not significantly. No associations were found between cardiovascular cases and indoor heat exposure threshold. Other studies have also reported that high temperatures can increase respiratory morbidity (Kovats et al., 2004; Michelozzi et al., 2009). For instance, Kovats et al. (2004) reported that in London, hospital admissions linked to respiratory diseases increased 5.4% per ^{o}C above a threshold of 23^{o}C. Although Kovats et al. (2004) research supports Uejio et al. (2015) findings that high temperature is associated with increased respiratory morbidity, the earlier study is based on outdoor ambient temperature, which may be inconsistently associated with indoor temperature (e.g. Tamerius et al., 2013). Because at any outdoor temperature there will be a range of indoor temperatures, depending on building characteristics for example, it is not possible to correlate outdoor and indoor temperatures and establish with any certainty an indoor heat-health threshold.

Metabolic effects of indoor temperature were examined by Daly (2014) in a study involving over 100,000 adult participants (16+ years). The study aimed to investigate whether indoor temperatures above a thermal neutral zone (~23^{o}C) were associated with reduced body mass index (BMI). The author showed that occupants living in temperatures above 23^{o}C had reduced BMI levels ($P<0.001$) compared with those living below 19^{o}C. Groups exposed to intermediate temperature ranges (19^{o}C-20.5^{o}C; 20.5^{o}C-21.5^{o}C and 21.5^{o}-23^{o}C) did not differ in their BMI levels from those living below 19^{o}C. The main findings of this study were that high indoor ambient temperature (above 23^{o}C) predicted lower BMI levels. The authors also suggest that energy balance emerges at high temperatures where appetite is suppressed, food intake is diminished and energy expenditure rises.

The effect of indoor heat exposure on blood pressure and physical performance in older women was examined by Stotz et al. (2014). Twenty six community-dwelling woman (70+ years) were exposed to hot (30^{o}C) and normal (20^{o}C) indoor temperatures. After 60 minutes exposure to 30^{o}C room temperature, blood pressure at rest was statistically significantly lower when compared with 20^{o}C room temperature, whilst core and calf skin temperature and heart rate were higher. Additionally, in the 30^{o}C condition, systolic and diastolic blood pressure (median difference 10 and 8 mmHg respectively) and the distance walked in 6 minutes (median difference 29.3 m) were lower than in the 20^{o}C condition. The results confirmed the authors' hypothesis that blood pressure is lower in a hot environment (30^{o}C) in older people.

Since there is very limited evidence on the adverse health effects of high indoor temperature exposures, it is not possible, at this time, to define a strong evidence-based indoor heat threshold for health risks. However, the limited number of studies found within the literature suggest that indoor temperatures over 23°C, 26°C and at 30°C can affect the health of home occupants, by reducing BMI levels, increasing respiratory conditions and lowering blood pressure (in older people) respectively. Nonetheless, although increase in respiratory conditions and low blood pressure are understood as conditions potentially adverse to the health of building occupants, reduction in BMI levels may not be necessarily detrimental to people's health, in general. For instance, reduction in BMI levels has been seen as a vital requirement to improve the body composition and the cardiometabolic health of obese and overweight individuals (Ford al., 2010). Reduction in BMI may be detrimental to the health of underweight individuals, however this is a less common phenomena when compared to the rise of obesity (Deitel, 2003). Therefore, based on the epidemiological literature findings related to the wider population, it is proposed that known adverse health outcomes may be associated with indoor temperatures above 26°C. Regarding exposure to high temperatures, no evidence was found within the literature to inform the level of exposure that leads to adverse health effects.

Finally, in establishing indoor temperature thresholds for the health of house occupants, the existing evidence suggests that adverse health effects may be minimised at indoor temperatures between 18°C and 26°C, for a general adult population and between 21°C and 26°C for a more vulnerable population (e.g. elderly, individuals with pre-existing conditions). Nevertheless, it is important to emphasise that these findings are based on evidence from a very limited number of studies and therefore should be used with caution. On the other hand, these findings are not too dissimilar from the WHO (1987) guidance for air temperature in homes, which recommends temperatures between 18°C and 24°C to protect the health of home occupants (Ormandy & Ezratty, 2012). However, because no evidence was found within the published literature to support that 24°C should be used as the maximum indoor temperature threshold to minimise adverse health effects on house occupants, the 26°C threshold will be used in the analysis.

5.2.2. Relative humidity

Relative humidity refers to the ratio of the amount of moisture present in the air. The level of indoor relative humidity is an important factor for the health of house occupants since very low or very high relative humidity levels can provide physical discomfort as well as be an indirect cause of ill health (Arundel et al., 1986).

Many studies have reported that very low indoor relative humidity can cause eye irritation, dehydration of the nasal mucous membrane and dehydration of the skin (Gavhed & Klasson, 2005; Sunwoo et al., 2006; Sunwoo et al., 2006a). Studies investigating the influence of low relative humidity on physiological conditions (Sunwoo et al., 2006a; Sunwoo et al., 2006b) suggested that indoor relative humidity greater than 10% is necessary in order to avoid dryness of the nasal mucous membrane, whilst relative humidity greater than 30% is necessary to avoid dryness of the eyes and skin.

Other authors have shown that high indoor relative humidity can have an indirect effect on health by providing an ideal environment for the proliferation of house dust mites, fungi, and other allergens and organisms, which could in turn be detrimental to human health (Andersen & Korsgaard, 1986; Arshad et al., 2001; Sporik et al., 1992). Health concerns related to house dust mite allergens includes rhinitis, asthma and atopic dermatitis, among other allergic conditions (Colloff, 2009). Special concern is demonstrated in relation to the harmful effect that house dust mite allergens have on the respiratory health of building occupants. For instance, Niven et al. (1999, p.756) describe house dust mite allergens as “one of the most important factors in the determination and expression of asthma worldwide”.

The link between house dust mites and humidity levels has been investigated extensively with many studies reporting a significant association between increased occurrence of mite population and increased indoor relative humidity (De Andrade et al., 1995; Hart, 1998; Murray & Zuk, 1979). Hart and Whitehead (1990) examined 30 houses in the UK and found that relative humidity was the most important factor influencing mite numbers, with mite population being mostly strongly correlated with humidity above 64% in the bedrooms. Some studies suggested that different homes within the same region can present differences in terms of mite concentrations due to indoor relative humidity alone. For example, Korsgaard (1983; 1983b) examined 50 apartments within the same region in Denmark and found that the seasonal variation in mite population was associated with indoor humidity only, with apartments with low indoor humidity presenting unnoticeable concentrations of house dust mite.

Research associating house dust mite exposure and asthma have been extensive within the literature, with some studies identifying early childhood exposure to house dust mite allergens as an important determinant of the subsequent development of asthma (Sporik et al., 1990). These findings have been supported by others (Brussee et al., 2005; Peat et al., 1996; Peat et al., 1993). Nevertheless, claims that exposure to environmental allergens causes childhood asthma have also been contested (Lau et al., 2000).

Research has also provided evidence that there is an association between degrees of exposure to domestic mite allergens and asthma severity. For instance, a study investigating the relationship between mite allergen exposure and the clinical severity of asthma within adult patients suffering already from the disease (Custovic et al., 1996) concluded that the clinical activity and severity of asthma among these patients are related to the exposure to the mite allergen, with levels of exposure being an important indicator of asthma activity. Tunnicliffe et al. (1999) also found a positive association between the degrees of mite allergen exposure in sensitised adults and asthma severity.

Due to strong evidence from the literature linking the exacerbation of asthma with the exposure to dust house mite allergens (Bush, 2008; Kim et al., 2013; Krämer et al., 2006; Milián & Díaz, 2004; Peat et al., 1996; Sears et al., 1989), it has been suggested that a reduction in relative humidity is necessary in order to control mite populations in homes (Fletcher et al., 1996), consequently minimising the adverse health effects related to them.

A few studies (Arlian et al., 1999; Arlian et al.,1982; Korsgaard, 1982; Murray & Zuk, 1979) provided evidence that the mite population was considerably reduced in winter when indoor relative humidity was below 40%-50%. For example, a study which collected mattress dust from two houses at monthly intervals for two and a half years (Murray & Zuk, 1979) found that live mites were only seen with indoor relative humidity over 50%. Korsgaard (1982) investigated house dust mite concentrations in 98 houses and found that indoor relative humidity below 45% presented less than 10 live mites per gram of house dust. In a study of mite population in 19 houses, Arlian et al. (1982) showed that indoor relative humidity at 40% presented less than 50 mites per gram of dust, a small number compared with a population between 400 and 1100 mites per gram of dust when indoor relative humidity was at 70%. Munir et al. (1995) examined levels of dust house mites in 130 homes (bedrooms and living rooms) of asthmatic children in three regions in Sweden. Evidence from this study shows that high mite allergen concentration (above 2μg/g) was present in all bedrooms and all living rooms with relative humidity levels over 45%. The finding from these studies support the recommendation given by Korsgaard (1998, p.38), where after an analysis of epidemiological data, the author concluded that "in order to prevent the build-up of dangerous levels of house dust mites in dwellings, the indoor air humidity must be kept below a level of 45% relative humidity at normal indoor air temperature".

Relative humidity has also been associated with fungi found in indoor environments, which is known to cause health problems such as asthma and rhinitis (Arundel et al., 1986). Fungi growth occurs when relative humidity reaches between 75% and 95% (Gravesen, 1979). As a consequence, fungal populations are usually found in kitchen and bathrooms areas due to frequent condensation caused by high RH levels (Arundel et al., 1986).

Indoor relative humidity has also been associated with the survival of airborne bacteria and viruses (Benbough, 1969; Harper, 1961; Hatch and Dimmick, 1966). Tang (2009) has shown that, generally, viruses with lipid envelopes (e.g. influenza virus, parainfluenza virus, infections caused by measles, rubella, and varicella zoster viruses) will tend to survive longer at lower (20-30%) RHs whilst non-lipid enveloped viruses (e.g. rhinoviruses and respiratory adenoviruses) tend to survive longer at higher

(70-90%) RHs. For example, Myatt et al. (2010) have investigated the airborne survival of aerosolized influenza virus in a residential setting and the ability of home humidifiers to control air moisture content, decreasing the survival of influenza viruses. The authors found that by increasing the indoor RH levels from approximately 30% to 40-60%, it decreased the influenza virus survival by between 17.5 and 31.6%, with the largest decrease rate related to the larger increase in moisture levels. On the other hand, Miller & Artenstein (1967) showed that adenoviruses exhibited a maximum stability at 80% RH level.

However, more complex relationships between viruses and indoor relative humidity levels were found by other authors. An experiment undertaken by Lowen et al. (2007) using guineas pigs as a model host, has shown that influenza virus transmission varied with different levels of indoor relative humidity. Transmission was highly efficient (occurred to three or four of four exposed guinea pigs) at low RH values of 20% or 35%. The high transmission rate was also observed with RH at 65%. On the other hand, only one of four animals contracted the virus with intermediate RH level at 50%, while no transmission of the virus was observed at a high RH of 80%. The authors suggested that influenza virus transmission could potentially be minimised by maintaining room temperatures above 20^{o}C and RH levels maintained either Intermediate (50%) or high (80%). The results from this study was supported by very similar findings elsewhere (Schaffer et al., 1976).

The effects of relative humidity on bacteria are more complex than with viruses (Cox, 1998), as experimental conditions have significant influence on the experiment outcomes (Tang, 2009). However some studies have investigated the effect of RH levels for the survival of some types of Gram-negative bacteria (e.g. Salmonella, Escherichia coli [E. coli], Shigella, Legionella and Pseudomonas). For example, Mcdade and Hall (1964) investigated the survival of various strains of Gram-negative bacteria by isolating them in a controlled environment with a series of constant relative humidities. The authors showed that the death of all investigated gram-negative bacteria (Escherichia coli, Salmonella derby, Pseudomonas aeruginosa and Proteus) was accelerated and progressive at intermediate and high RH levels: the organisms' death rate increased at 25^{o}C and 53% or 85% RH, whilst at 25^{o}C and 11% RH, the survival rate was considerably increased.

Nevertheless, other studies investigating similar types of bacteria, presented different findings. For instance, a study examining another species of Gram-negative bacteria (Pasteurella pestis) (Won & Ross, 1966) found that the bacteria were significantly diminished when exposed to high RH levels (between 65-87%). High humidity levels (40-60%) were found to increase the death rate of the Gram-negative bacteria E. coli (Hatch & Wolochow, 1969).

The literature search has provided evidence that indoor RH is indeed associated, directly and indirectly with adverse health outcomes. It has also shown that the survival of different organisms which affect the health of house occupants (e.g. house dust mites, viruses and bacteria) depend on RH levels in the indoor environment. However, the studies reviewed here also show that different agents which contribute to ill health may survive, proliferate or die at different RH levels. Therefore, finding the perfect RH threshold which minimises the survival of all agents and at the same time, provides sufficient indoor humidity to diminish possible health effects caused by low RH (e.g. eye irritation, dehydration of the nasal mucous and skin) may be an impossible task. Nonetheless, a study which has looked into most of these agents, recommended indoor RH in the range between 40% and 60% (Arundel et al., 1986). Although this threshold is unable to minimise all ill health agents, Arundel and colleagues explain that most health effects either increase in severity above 60% and/or below 40% RH. Regarding exposure to relative humidity levels outside the recommended threshold, no evidence was found within the literature review to inform the level of exposure that leads to adverse health effects.

5.2.3. Carbon dioxide

The primary source of indoor carbon dioxide is human expelled air. Secondary common indoor sources include gas cooking appliances, space heaters, wood-burning appliances and tobacco smoke (Hess-Kosa, 2012). Indoor carbon dioxide concentrations are dependent on the number of occupants, the duration of occupancy, the volume of the room and the ventilation rate (Seppänen & Fisk, 2004). Carbon dioxide is not considered a harmful gas, but an indicator of indoor air quality (Szczurek et al., 2014). This is due to evidence suggesting that CO_2 concentrations can be considered as a surrogate for other occupant generated pollutants and for ventilation rate per occupant (Scheff et al., 2000; Erdmann et al., 2002). Some authors have proposed that indoor environments with CO_2 concentrations which exceed those typically found indoors (between 500-1500 ppm), could be harmful to human health (Seppänen & Fisk, 2004), since other pollutants may be generated in similar proportions to occupant-generated CO_2 (Seppänen, 1999). The hypothesis that CO_2 concentrations may be related to the concentration of other indoor pollutants was confirmed by Chatzidiakou et al. (2015). The authors monitored some indoor air quality parameters (temperature, RH, CO_2, PM_{10}, $PM_{2.5}$, PM_1 and TVOCs) in 18 classrooms from six London schools. After controlling for the effect of occupancy levels, they found that indoor CO_2 concentrations were a significant predictor for indoor particulate matter (PM) levels. They proposed that high CO_2 concentrations were related to low ventilation rates and therefore also linked with the inability of particulate matter to be purged through ventilation.

Another study on indoor air quality has also reported on the association of CO_2 and other air pollutants (Ramalho et al., 2015). Ramalho and colleagues investigated the association between indoor CO_2 concentrations and concentrations of formaldehyde, acetaldehyde, acrolein, benzene, $PM_{2.5}$, and PM_{10} in 567 French dwellings and 310 French schools. They reported that CO_2 concentration was significantly correlated with average concentrations of formaldehyde and benzene in both dwellings and schools, whilst CO_2 concentration was significantly correlated with acetaldehyde, acrolein, $PM_{2.5}$ and PM_{10} in the dwellings. Nevertheless, there is some scepticism over the ability of indoor CO_2 concentrations to provide reliable information on the concentration of occupant-independent indoor pollution (Persily, 1997). For this reason, Ramalho et al. (2015) warned that CO_2 concentrations cannot be considered as a unique air quality indicator.

Due to the general acceptance of the use of indoor CO_2 concentration as an indicator of air quality and ventilation efficiency in buildings (Huie et al., 2008) and the evidence suggesting positive association between indoor CO_2 concentration and the concentration of other indoor pollutants (Kim et al., 2002; Ramalho et al., 2015), guidelines containing maximum levels of indoor CO_2 have been recommended for the preservation of the health of building occupants (Persily, 2015).

The most used guideline for indoor CO_2 was endorsed by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Standard 62-1989, which recommends concentrations below 1000 ppm (assuming an outdoor CO_2 concentration of 350 ppm[25] and a CO_2 generation rate per person of 0.31 L/min (equivalent to 0.005 L/second)). This is based on mass-balance calculations which correspond to the lowest minimum ventilation rate guideline of 8Ls^{-1} per person (Apte et al., 2000). Although the first version of ASHRAE Standard 62 states the organisation's goal of protecting 'occupants' health, safety and wellbeing', critics (Persily, 1997) argue that relying on the limit for indoor CO_2 concentrations of 1000 ppm alone may not comply with Standard 62. Persily (1997) points out that because Standard 62 contains limits for seven other contaminants (four and three of predominantly outdoor and indoor origin respectively), these contaminants must also be kept below specific levels if compliance with the Standard 62 and its goals are to be met.

More recently, through a review of intervention studies, the German Working Group on Indoor Guideline Values of the Federation of the Environmental Agency and the States' Health Authorities of Germany have made recommendations for maximum indoor CO_2 levels based on health and hygiene considerations. They have established that concentrations of indoor CO_2 below 1000 ppm are regarded as harmless, concentrations between 1000-2000 ppm as elevated and those above 2000 as unacceptable (GWG, 2008). Although the German review paper provides an evaluation of several studies reporting associations between indoor CO_2 and health effects, it offers limited evidence supporting the health based recommendation of specific indoor CO_2 thresholds. In particular, the

[25] Due to global warming, higher atmospheric CO_2 levels (around 400 ppm) have been recorded more recently (Refer to McGee, 2017).

review does not show enough evidence to support the claim that indoor CO_2 concentration below 1000 ppm is harmless to human health.

Other studies exploring the relationship between measured indoor CO_2 concentrations and health outcomes have suggested that adverse health outcomes may be associated with CO_2 levels much lower than the recommended maximum of 1000 ppm (Seppänen, 1999; Tsai et al., 2012).

The large majority of these studies are cross-sectional, which is a type of observational study where the relevant data (e.g. data on health of building occupants and CO_2 monitoring) is collected in multiple buildings and analysed with statistical models, aiming to determine associations between CO_2 concentrations and health effects. The weakness of cross-sectional study design was mentioned by Seppänen (1999) when the author explains that many factors, other than CO_2 concentrations for example, which vary among different buildings may influence health outcomes, confounding the association between CO_2 levels and health effect. Nevertheless, strong cross-sectional study designs control for potential confounding factors.

Within the literature, studies investigating associations between elevated indoor CO_2 concentrations and health outcomes are mostly exploring the Sick Building Syndrome[26] (SBS). Health outcome data are generally collected through the use of questionnaires completed by participants. The questionnaires usually gather data on SBS self-reported symptoms such as dry eyes, sore throat, cough and wheeze, among others (Apte et al., 2000; Erdmann et al., 2002). A thorough review of the literature undertaken by Seppänen (1999) which includes 21 studies of SBS symptoms, totalling 30,000 subjects and more than 400 buildings in North America, reported that 9 (50%) of the CO_2 assessments related to SBS found a significantly higher prevalence of symptoms with higher CO_2 concentrations. The other 50% of studies found non-significant associations, which were attributed to a possible temporal variation in indoor CO_2 concentrations (Tsai et al., 2012). The literature review (Seppänen, 1999) also reports that several studies suggested that the risk of SBS continued to decrease with CO_2 concentrations below 800 ppm (which corresponded to a steady ventilation rate of $11.6Ls^{-1}$ per person). A more recent study on SBS has reported similar findings. Tsai et al. (2012) conducted a study with 121 building occupants in an office in Taiwan. Based on a questionnaire with 17 SBS symptoms and continuous indoor temperature, RH and CO_2 measurements, the authors found that CO_2 levels greater than 800 ppm were associated with an increase in building occupants' SBS symptoms, especially eye irritations and upper tract respiratory symptoms (including sore or dry throat, stuffy or runny nose, cough and sneezing).

[26] Sick Building Syndrome "is used to describe a set of adverse health or discomfort symptoms that individuals experience when they spend time indoors, particularly in office buildings, and that lessen while away from the building" (Apte at al., 2000, p. 247).

Another study has shown that indoor CO_2 concentrations at 1000 ppm can have a direct adverse effect on human performance. For example, Satish et al. (2012) assessed decision making outcomes in 22 participants, exposed to a range of CO_2 concentrations (600, 1000 and 2500 ppm), in an office-like chamber. Six groups of four participants were exposed to each of the three conditions for 2.5 hours per condition. Before, after and during exposure, participants had to complete decision-making tests and questionnaires on perceived indoor air quality and health symptoms. The results show that the performance for six of nine decision-making measures decreased moderately and statistically significantly at 1000 ppm when compared to the baseline of 600 ppm, whilst seven of nine decreased substantially at 2500 ppm.

Overall, the published literature on the associations between indoor CO_2 concentrations and human health has pointed towards a threshold of indoor CO_2 of 800 ppm. This is based on the literature which makes associations between indoor CO_2 concentrations and many SBS symptoms, including eye irritation and upper tract respiratory symptoms. Several of these studies have reported an increase in SBS symptoms at indoor CO_2 concentrations over 800 ppm and a decrease in symptoms at indoor CO_2 concentrations below 800 ppm. Nevertheless, no evidence was found within the literature review to inform the level of exposure that leads to those adverse health effects.

Although many of the papers reviewed have suggested that high levels of indoor CO_2 are associated with adverse health outcomes, they also clarify that indoor CO_2 concentration itself is not the cause of adverse health effects (e.g. Kim et al., 2002). Instead, indoor CO_2 concentration is considered an approximate surrogate for the indoor concentrations of other pollutants, which may contribute to ill health.

5.2.4. Volatile organic compounds (VOCs)

Indoor volatile organic compounds found in homes and office environments are typically 2 to 100 times higher indoors than outdoors (Hess-Kosa, 2012). More than three hundred different compounds have been found in the indoor air (Berglund et al., 1986). VOCs are released into indoor air by occupants and their activities, from building materials and contents, or enter the building through outdoor air infiltration (Maroni et al., 1995). The most common VOC species found indoors and their sources are summarised in table 5.1.

Common VOCs found indoors	Sources
Aliphatic hydrocarbons (n-decane, branched alkanes), aromatic hydrocarbons (toluene, xylenes), halogenated hydrocarbons (methylene chloride), alcohols, ketones (acetone, methyl ethyl ketone), aldehydes (formaldehyde), esters (alkyl ethoxylate), ethers (glycol ethers), terpenes (limonene, alpha-pinene).	Consumer and commercial products
Aliphatic hydrocarbons (n-hexane, n-heptane), aromatic hydrocarbons (toluene), halogenated hydrocarbons (methylene chloride, propylene dichloride), alcohols, ketones (methyl ethyl ketone), esters (ethyl acetate), ethers (methyl ether, ethyle ether, butyl ether).	Paints and associated products
Aliphatic hydrocarbons (hexane, heptane), aromatic hydrocarbons, halogenated hydrocarbons, alcohols, amines, ketones (acetone, methyl ethyl ketone), esters (vinyl acetate), ethers.	Adhesives
Aromatic hydrocarbons (styrene, brominated aromatics), halogenated hydrocarbons (vinyl chloride), aldehydes (formaldehyde), ethers, esters.	Furnishings, wood-based boards and clothing
Aliphatic hydrocarbons (n-decane, n-dodecane), aromatic hydrocarbons (toluene, styrene, ethylbenzene), halogenated hydrocarbons (vinyl-chloride), aldehydes (formaldehyde), ketones (acetone, butanone), ethers, esters (urethane, ethylacetate).	Building material
Aliphatic hydrocarbons (propane, butane, isobutane), aldehydes (acetaldehyde, acrolein)	Combustion appliances
Halogenated hydrocarbons (1,1,1-trichloroethane, chloroform, trichloroethane).	Potable water

Table 5.1 Common VOCs found indoors and their sources. (Source: Maroni et al., 1995)

Exposure to some types of VOC can result in both acute and chronic health effects to humans (Brooks and Davis, 1992). Studies have linked exposure to VOC concentrations to a variety of adverse health effects. These include asthma (Arif and Shah, 2007; Norback et al., 1995; Wieslander et al., 1996), worsening in lung function (Cakmak et al., 2014), depressing the central nervous system (Maroni et al., 1995) and causing irritation of the eyes and respiratory tract (Mølhave, 1991). Exposure to high concentrations of some types of VOCs (e.g. benzene, chloroform, methylene, p-dichlorobenzene), have been associated with cancer in laboratory animals (Wallace, 1991).

This part of the literature review does not seek to evaluate each individual known VOC, since there are hundreds of different VOCs which have been identified in the indoor air. Therefore, attempting to establish possible health effects for each one of them would be an exhaustive task. Instead, this part of the literature review attempts to find out if exposure to the VOCs found in each of the passive houses and control houses have been associated with possible health effects, and if so at what concentrations. Consequently, the literature search only includes the top 10 most abundant VOCs found in each of the passive houses and control houses. Because the top 10 most abundant VOC species varied from house to house (as no two houses presented exactly the same 10 VOCs), the final combined list of VOCs found in passive houses and control houses comprises of a total of 13 VOCs: Alpha-pinene, 3-carene, limonene, decane, undecane, tetradecane, pentadecane, heptadecane, tetracosane, naphthalene, docosane, acetic acid and 1,4-dichlorobenzene.

a) Limonene and alpha-pinene

As previously mentioned, alpha-pinene and limonene are classified as terpenes which are commonly found indoors. Their regular occurrence in the indoor environment is due to the fact that they are used in many household products such as detergents, cleaning products, air fresheners, varnishes, paints and solvents (Sarigiannis et al., 2011b). Within the published literature, a few studies were identified which associated these terpenes with health outcomes. For instance, Norback et al. (1995) found a statistically significant association between bronchial hyper-responsiveness and indoor concentration of limonene. The study shows that the mean concentration of terpene (64% limonene, 15% δ-karen and 21% of α-pinene) in the bedroom and living room of dwelling occupants showing symptoms of nocturnal breathlessness and chest tightness were 96 μgm^{-3} (5-580 μgm^{-3} range) and 130 μgm^{-3} (7-1010 μgm^{-3} range) respectively. Absence of symptoms were found in bedrooms and living rooms with terpene mean concentration of 52 μgm^{-3} (5-350 μgm^{-3} range) and 60 μgm^{-3} (5-960 μgm^{-3} range) respectively. Although this study presents a strong association between terpene, especially limonene, and bronchial hyper-responsiveness, it is not possible to establish, from the obtainable data, any safe exposure threshold for terpene or limonene concentration.

Other studies and published literature reviews regarding individual terpenes were also found within the literature. Filipsson et al. (1993) attempted to provide an exposure threshold for limonene. Using clinical trials where eight participants were exposed to 10 mgm^{-3}, 225 mgm^{-3} and 450 mgm^{-3} of limonene for 2 hours during light physical exercise on an ergometer bicycle at a workload of 50 W, sensory irritation (discomfort in the eyes, nose and throat) was rated by the subjects before, during and after each exposure. Following this procedure, the subjects did not report any adverse symptoms and as a result, the authors identified a (NOAEL) (no observed adverse effect level) for acute exposure to limonene of 450 mgm^{-3} for sensory irritation. This is equivalent to 450,000 μgm^{-3}.

Nonetheless, a more recent published literature review (Kim et al., 2015) evaluating the health risks associated with the inhalation of limonene from air freshener exposure has found that a lower exposure to limonene concentration may result in adverse health effects. The authors found that acute exposure (30 min) to limonene concentration of 4,500 μgm^{-3} may cause sensory irritation.

Regarding the long-term effects of limonene exposure based on sensory irritation, the only study found within the literature which gives some guidance on health threshold exposure, is the Health Risk Assessment (HRA) of exposure undertaken by Trantallidi et al. (2015). Their findings are based on extrapolation from short-term data (from Filipsson et al. (1993)), due to the lack of long-term toxicological data. The authors' findings indicate a long-term (24 hours) critical exposure limit (CEL) of 9 mgm^{-3} for limonene (equivalent to 9,000 μgm^{-3}).

The short-term exposure limit for the terpene alpha-pinene based on sensory irritation (eye, nose and throat irritation) was established by Falk et al. (1990) in a study where eight volunteers were exposed to 10 mgm^{-3} , 225 mgm^{-3} and 450 mgm^{-3} of alpha-pinene for 2 hours during light physical exercise on a bicycle ergometer (at a workload of 50 W). Following the trials, Falk and colleagues identified an exposure limit value of 450 mgm^{-3} (equivalent to 450,000 μgm^{-3}) as the threshold for alpha-pinene short-term exposure based on sensory irritation effects. However, based on the findings of Falk et al. (1990) and further short-term data extrapolation based on findings from Alexeeff et al. (2002) and Nielsen et al. (2007), Trantallidi et al. (2015) established a much lower alpha-pinene short-term exposure limit of 45 mgm^{-3} (equivalent to 45,000 μgm^{-3}) based on sensory irritation effects.

Long-term alpha-pinene exposure on sensory irritation was identified by Trantallidi et al. (2015) using the same approach the authors used for limonene. Based on extrapolation from short-term exposure data, Trantallidi and colleagues identified a long-term (24 hours) exposure limit of 4.5 mgm^{-3} (equivalent to 4,500 μgm^{-3}) for sensory irritation effects.

Additional guidance regarding alpha-pinene exposure threshold was given by a literature review (Mersch-Sundermann, 2007), aiming to assess potential human health risks by alpha-pinene exposure via the indoor air. Through a thorough analysis of the literature on the exposure and toxicity data from animal, occupational, and test chamber studies which focused on the effects on the respiratory tract, the authors estimated a safe indoor air exposure level for alpha-pinene of about 4 mgm^{-3} (equivalent to 4,000 μgm^{-3}). The literature review however, does not specify the duration of exposure for the recommended threshold.

Other authors (e.g. Anderson et al., 2013; Kim et al., 2015) also argue that at high concentrations certain terpenes (e.g. limonene and alpha-pinene) can react with ozone in the air, generating other VOCs (e.g. formaldehyde and particulate matter) which may be harmful to health. The health significance of the reaction of terpene and ozone in the air has been thoroughly reviewed elsewhere (Rohr, 2013). However, because terpene oxidation is an extremely complex process (Rohr, 2013) and any possible health outcomes are also dependent on the indoor concentration of ozone and other gases (Wilkins et al., 2003), possible adverse health effects of terpene oxidation, will not be discussed in this thesis.

b) Naphthalene

According to the World Health Organisation (WHO, 2000, p. xix), "the principal health concern of exposure to naphthalene are respiratory tract lesions, including tumours in the upper respiratory tract". Naphthalene has also been identified as a blood toxicant which can destroy red blood cells and cause anaemia (USEPA, 2003).

At the point of the literature review search for this part of the thesis, no epidemiological or toxicological studies associating exposure to naphthalene concentrations and adverse health outcomes on human subjects were found within the published literature. Published studies found in the literature making such associations were mainly laboratory trials which used mice/rats as the subjects (e.g. USEPA, 2003). Studies such as this make the assumption that adverse health effects observed in mice are consistent with the health effects on human subjects.

Nevertheless, a literature review undertaken by Koistinen et al. (2008) found that the exposure limit for naphthalene has been set at 10 μgm^{-3}. This threshold is based on a study (NTP, 2000) where male and female rats were exposed to naphthalene vapour concentrations of 0, 53, 159 or 318 mgm^{-3} for 6 hours a day, 5 days a week for 105 weeks. Chronic inflammation was observed in almost all rats exposed to the lowest dose of 53 mgm^{-3}. Due to the absence of adequate published data associated to less severe nasal effects, 53 mgm^{-3} was adopted as the lowest observed adverse effect level (LOAEL). Following that, adjustments were made for continuous exposure (by dividing 53 by a factor of 6/24 and 5/7) and 10 μgm^{-3} was attained. Further adjustments were made for interspecies variability, intraspecies variability, and for the use of a LOAEL (lowest observed adverse effect level), arriving at the indoor air quality guidance (IAQG) adopted by WHO (2010) of 10 μgm^{-3} (annual average concentration).

c) Decane, undecane and 1.4 dichlorobenzene

Decane, undecane and 1.4 dichlorobenzene are classified as aliphatic hydrocarbons. Regarding human health, decane and undecane are considered to have substantial human toxicological impact since they have repeatedly been found in the presence of other proven carcinogenic hydrocarbons (e.g. those released by cigarette smoke and fuel combustion products) (NTP, 2002a; NTP, 2002b). Similarly, 1.4 dichlorobenzene is anticipated to be a human carcinogen based on evidence from studies in experimental animals (NTP, 2010).

Nevertheless, there are a very limited number of studies which provide information on indoor concentrations and associated health effects. No study giving an indication of a safe threshold for human exposure to these types of VOCs has been identified within the literature. The only comprehensive study found within the published literature investigated exposure to decane concentrations in the air and possible health effects (Kjærgaard et al., 1989). Although it does not give a safe threshold for human exposure, it provides some guidance on unhealthy indoor levels. In this study, 63 healthy subjects were exposed to either 0, 10, 35 or 100 µl/l (7.3, 26 and 73μgm^{-3}

respectively)[27] of pure n-decane in a chamber for 6 hours a day, for 1 day a week, for 4 weeks, in a controlled, double blind design study. Subjects exposed to all concentrations of decane presented decreased tear film stability (dry eye) and irritation of the mucous membrane of the eyes. Initial eye redness was also more pronounced among smokers than among non-smokers. This gives an indication that even the lowest concentration of decane (7.3 μgm^{-3}) was found to be associated with adverse health effects on humans.

d) Other VOCs

No comprehensive epidemiological or toxicological study was identified within the literature which provided information of possible health effects associated with exposure levels for the other seven VOCs found in the bedroom of the studied passive houses and control houses: 3-carene, tetradecane, pentadecane, heptadecane, tetracosane, docosane and acetic acid. For this reason, these seven VOCs were not considered in the next part of this thesis – which therefore remains a significant uncertainty in terms of health outcomes.

5.3. Health and the indoor environment of passive houses

In the first part of this chapter, the researcher aimed to find out at what levels the indoor climate and indoor air quality parameters found in the passive houses could represent a risk for human health. A summary of the literature review findings is presented in table 5.2. In this second part of chapter 5, the researcher attempts to analyse whether passive houses provide their occupants a healthy indoor environment. Additionally, it is also attempted to find out how the results related to the health status of the indoor environment of passive houses compare with the results from conventional houses. This involves a comparison of findings from the literature review with the findings from the indoor environment of passive houses and control houses.

[27] For conversion calculations, please refer to Appendix 12.

Indoor climate and indoor air quality parameters	Levels and possible health effects	Recommended levels to minimise known adverse health effects
Temperature	<18ºC – higher blood pressure (adult population 19-95 years), lower level of white blood cell (older population 50+ years), lower vitamin D levels (older population 50+ years), worsening in respiratory conditions (older population 50+ years), worsening hand grip (older population 50+ years) decrease of physical performance (women 70+ years); <21ºC – worsening in respiratory symptoms (elderly (age not specified) and individuals with pre-existing conditions); >23ºC – lowering BMI levels (adults, age not specified); >26ºC – worsening respiratory conditions (adults, age 16+); >30ºC – lowering blood pressure (older woman 70+) **Level of exposure was not specified**	**between 18ºC - 26ºC** (for general adult population) **between 21ºC to 26ºC** (for more vulnerable population: elderly, individuals with pre-existing conditions)
Relative humidity	<10% dryness of the nasal mucous membrane <30% dryness of the eyes and skin >45% - Increase in house dust mite population (associated to asthma); <40% - Increased chances of survival of influenza virus; between 20% - 35% , and at 65% - highly efficient transmission of influenza virus; >75% - growth of fungi population (associated to asthma) between 40% - 60% - Gram-negative bacteria (E-coli) significantly diminished; Between 65% - 87% - Gram-negative bacteria (Pauteurella pestis) significantly diminished **Level of exposure was not specified**	**between 40% - 60%**
CO_2	>800 ppm – Increase in SBS symptoms (eye irritation and upper tract respiratory symptoms, including sore or dry throat, stuffy or runny nose, cough and sneezing); At 1000 ppm – Significant decrease in decision-making performance; At 2500 ppm – Substantially significant decrease in decision-making performance **Level of exposure was not specified**	**below 800 ppm**
VOCs		
Limonene	Acute exposure (30 min) at 4,500 μgm^{-3} – sensory irritation Long-term exposure (24 hours) at 9,000 μgm^{-3} – sensory irritation	**below 4,500 μgm^{-3}**
Alpha-pinene	Acute exposure (30 min) at 45,000 μgm^{-3} – sensory irritation Long-term exposure (24 hours) at 4,500 μgm^{-3} – sensory irritation > 4,000 μgm^{-3} – effects on the respiratory tract (level of exposure not specified).	**below 4,000 μgm^{-3}**
Naphthalene	Long-term exposure (no specific definition) at >10 μgm^{-3} (annual concentration) – Chronic inflammation in the nasal olfactory epithelium	**below 10 μgm^{-3} (annual concentration)**
Decane	6 hours exposure at ≥7.3 μgm^{-3} – decreased tear film stability (dry eyes) and irritation of the mucous membrane of the eyes	**Not known**

Table 5.2 Indoor climate and indoor air quality parameter levels and known adverse health effects

5.3.1. Temperature

Table 5.3 shows a summary of the proportion of time that the temperature levels found in the monitored bedroom and in the living room of passive houses and control houses were outside the recommended threshold (between 18°C and 26°C).

Indoor parameter		3 bed houses				4 bed houses			
		Bedroom		Living room		Bedroom		Living room	
		Passive Houses	Control Houses	Passive Houses	Control Houses	Passive Houses	Control Houses	Passive Houses	Control Houses
Temp High (above 26°C)	Winter	PH1 0% PH2 0%	CH3 0% CH4 0%	PH1 - PH2 0%	CH3 0% CH4 0%	PH3 0.2% PH4 0% PH5 0%	CH1 0% CH2 11%	PH3 1% PH4 2% PH5 0%	CH1 0.5% CH2 0%
	Spring	PH1 6% PH2 7%	CH3 0% CH4 0%	PH1 0% PH2 0%	CH3 0% CH4 0%	PH3 0.1% PH4 12% PH5 0%	CH1 0% CH2 13%	PH3 - PH4 1% PH5 0%	CH1 0.2% CH2 0%
	Summer	PH1 0.5% PH2 5%	CH3 2% CH4 6%	PH1 99% PH2 22%	CH3 0% CH4 4%	PH3 24% PH4 - PH5 6%	CH1 1% CH2 32%	PH3 13% PH4 57% PH5 1%	CH1 0% CH2 4%
Temp Low (below 18°C)	Winter	PH1 0% PH2 0%	CH3 15% CH4 0.2%	PH1 0% PH2 0%	CH3 29% CH4 18%	PH3 9% PH4 1% PH5 5%	CH1 0% CH2 0%	PH3 1.2% PH4 0% PH5 0%	CH1 30% CH2 75%
	Spring	PH1 0% PH2 0%	CH3 13% CH4 13%	PH1 0% PH2 0%	CH3 11% CH4 18%	PH3 0.2% PH4 0% PH5 0.5%	CH1 0.5% CH2 0%	PH3 - PH4 7% PH5 0%	CH1 14% CH2 45%
	Summer	PH1 0% PH2 0%	CH3 0% CH4 0%	PH1 0% PH2 0%	CH3 0% CH4 0%	PH3 0.1% PH4 - PH5 3%	CH1 0% CH2 0%	PH3 3% PH4 0% PH5 2%	CH1 0% CH2 26%

Table 5.3 Proportion of time that the monitored indoor temperature levels were outside the recommended threshold which minimises known adverse health effects

The data show that high indoor temperatures (over 26°C) were observed mostly during the summer season, and for longer periods in passive houses when compared with the corresponding control houses. In addition, high indoor temperature in passive houses seemed to be more problematic in the living room, as this room had longer periods with temperature over 26°C when compared with the monitored bedroom (e.g. during the summer, the bedroom of PH1 had temperatures over 26°C for 0.5% of the time while the living room had similar temperatures for 99% of the time).

High temperatures in the living room during the summer was especially problematic for passive houses PH1, PH2 and PH4 as these rooms presented temperatures over 26°C for 99%, 22% and 57% of the time respectively.

Aiming to identify the periods of occupants' exposure to high indoor temperature, figure 5.1 shows the temperature and CO_2 levels during the two weeks of monitoring in the living room of passive houses PH1, PH2 and PH4 while table 5.4 shows the duration of occupants' exposure to temperature over 26°C. Those three passive houses were chosen for further analysis as they presented long periods of time with indoor temperatures above the recommended threshold.

Since humans are a source of CO_2, this gas can also be used when trying to identify indoor occupancy levels. When CO_2 levels were well beyond 400 ppm (which is the range normally found outdoors), the assumption was that the room was occupied.

Such an assumption would only be valid if there was a constant provision of air exchange in the room (e.g. the MVHR was not turned off). This is due to the fact that without constant air exchange, CO_2 levels would have remained higher than 400 ppm for some time after occupants left the room. The qualitative data show that the occupants of all three passive houses never turned off the MVHR system at any time during the monitoring period. However, it is not possible not know whether the MVHR provided adequate air exchange rates to those particular rooms at the time, to enable CO_2 levels to be quickly lowered to levels close to 400 ppm, when the room was unoccupied. Therefore, for the purpose of this analysis, a higher CO_2 level (600 ppm) is used as a proxy for room occupancy. This figure was estimated following an analysis of the CO_2 data obtained in the monitored rooms and the period of time occupants indicated to be in the room[28].

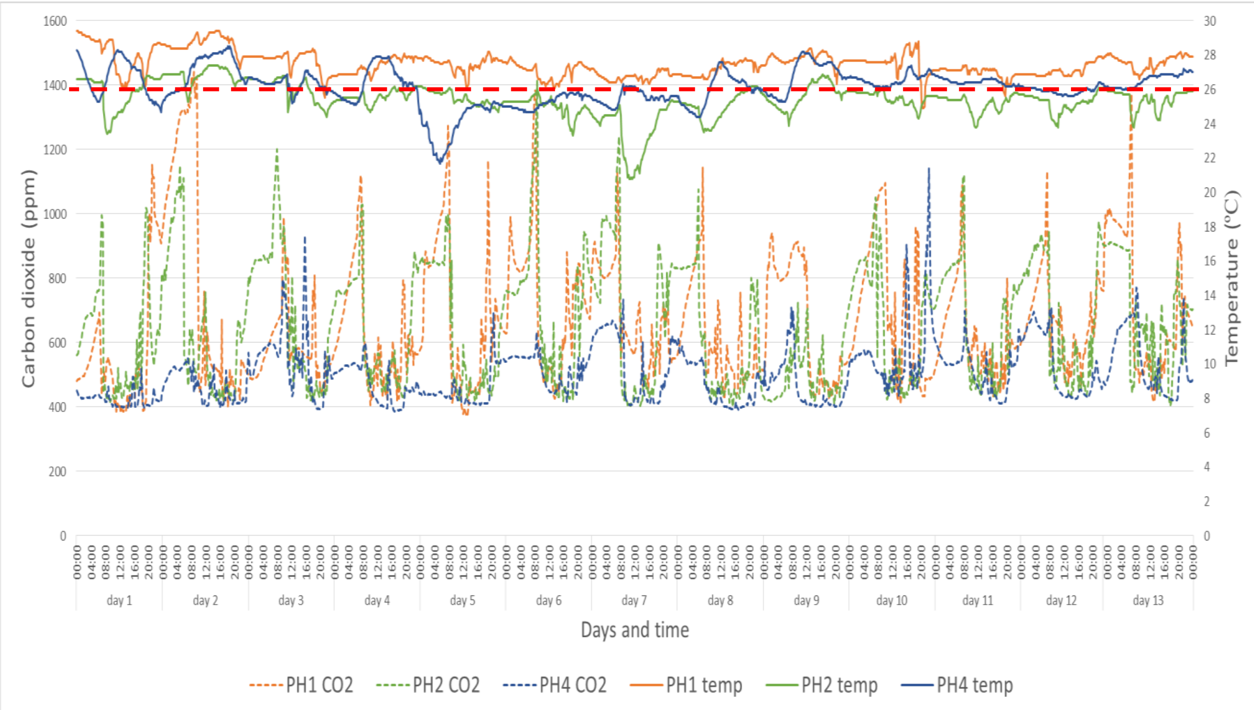


Figure 5.1 Temperature and carbon dioxide in the living room of the passive houses PH1, PH2 and PH4 during the summer season. (The red dashed line represents the maximum recommended temperature threshold)

[28] Refer to Appendix 13 for the sensitivity analysis of carbon dioxide levels.

Monitoring days	Total time of exposure (hours)			Longest time span of exposure (hours)		
	PH1	PH2	PH4	PH1	PH2	PH4
Day 1	6.25	11.25	0.00	2.00	6.50	0.00
Day 2	10.75	11.25	0.00	14.25 (between day 1 and day 2)	7.75 (between day 1 and day 2)	0.00
Day 3	6.00	11.25	3.50	5.25	14.25 (between day 2 and day 3)	2.00
Day 4	10.00	2.00	0.00	7.75	0.00	0.00
Day 5	14.00	2.25	0.00	8.00	3.75 (between day 4 and day 5)	0.00
Day 6	16.50	0.25	0.00	13 (between day 5 and day 6)	0.25	0.00
Day 7	14.00	0.00	0.50	13.25 (between day 6 and day 7)	0.00	0.50
Day 8	9.50	2.50	0.00	7.00	2.50	0.00
Day 9	11.75	0.50	1.50	11.75	0.50	1.50
Day 10	14.75	1.00	3.75	10.75	1.00	2.50
Day 11	9.75	0.00	2.00	7.50	0.00	1.00
Day 12	16.75	1.25	5.00	8.25	1.25	4.25
Day 13	13.50	0.00	5.75	13 (between day 12 and day 13)	0.00	3.00
Total hours of exposure (hours)	153.50	43.50	22.00			
Total percentage of exposure	50%	14%	7%			

Table 5.4 Duration of occupants' exposure to temperatures over 26°C in the living room of passive houses PH1, PH2 and PH4 during the summer season

Data from occupants' interviews show that the living room was used intermittently by different family members during the day and early night, between the hours of 7:00 am and 21:00/22:00 pm. The data from figure 5.1 also suggest that the living room was occupied for many hours during the day time but also during the night on some occasions (e.g. during the night between day 1 and day 2 as CO_2 levels peaked beyond 2000 ppm in living room of PH1 and beyond 1000 ppm in the living room of PH2).

Regarding the living room of passive house PH1, which had temperatures over 26°C for 99% of the time, the data from figure 5.1 suggest that that room was occupied for several hours almost every day. Data from table 5.4 show that occupants were exposed to high temperatures in the living room for a total of 153.5 hours (which represents 50% of the total time), with exposure time span varying from 2 to 14.75 hours.

Although the living room of passive house PH4 had high temperatures for shorter periods of time during the two weeks of monitoring (57%), the data from figure 5.1 also suggest that living room occupants were exposed to temperatures over 26ºC for several hours per day, on some days. Data from table 5.4 shows that during day 3, 10 and 11, occupants were exposed for several hours to high temperature, with the longest time span reaching 9.75 hours of exposure (day 3). The total time of exposure to high temperatures over the 13 days of monitoring was 71.25 hours, which represent 22% of the time.

The data from figure 5.1 and table 5.4 also show that occupants of passive house PH2 were exposed to high temperatures in the living room during the summer, however, for a shorter period (18% of the time) when compared with the other two passive houses considered. Nevertheless, occupancy when the indoor temperatures were over the maximum recommended threshold was identified most days, with the longest time span varying from 0.25 to 14.5 hours of exposure (table 5.4).

The data analysis on occupants' exposure suggest that indeed, occupants of passive houses PH1, PH2, and to a lesser extent, passive house PH4, were exposed to high temperatures (over 26ºC) for several hours in the living room, during the summer season.

Since there is no information from the literature review regarding the level of exposure to high indoor temperature which leads to ill health, it is not possible to make strong connections between occupants' exposure and health effects. However, it is possible to make reasonable estimates of the potential health risk for passive house occupants. For example, in the living room of passive house PH1, occupants were exposed to high temperatures for several hours, almost every day, during the two weeks of summer monitoring. It is reasonable to suggest that those occupants were at a high risk of worsening respiratory conditions (a health effect associated with temperatures over 26°C) since they were exposed to high temperatures for long periods of time, on a daily basis.

On the other hand, low indoor temperatures (under 18°C) were observed for very short periods of time in passive house dwellings. The longest period of low temperatures recorded in the monitored rooms was 9% of the time, observed during the winter, in the bedroom of passive house PH3. Therefore, low indoor temperatures were not considered a significant hazard for passive house occupants.

When comparing passive houses and control houses in terms of possible health risks associated to exposure to temperatures outside the recommended threshold (18°C - 26°C), the research findings suggest that passive houses are potentially healthier when considering exposure to low temperatures (under 18°C) but potentially unhealthier when considering exposure to high temperatures (above 26°C).

This is because low indoor temperatures were observed more often and for longer periods of time in control houses (e.g. 75%, 30% and 29% of the time during the winter in the living room of control houses CH1, CH2 and CH3). In contrast, the control houses had, generally, high indoor temperature less often and for shorter periods of time in both monitored rooms (between 2% and 13% of the time in most cases), when compared with the passive houses.

5.3.2. Relative humidity (RH)

Table 5.5 shows a summary of the occasions when RH levels found in the monitored bedroom and in the living room of passive houses and control houses were outside the recommended thresholds (between 40% and 60%).

Indoor parameter		3 bed houses				4 bed houses			
		Bedroom		Living room		Bedroom		Living room	
		Passive Houses	Control Houses	Passive Houses	Control Houses	Passive Houses	Control Houses	Passive Houses	Control Houses
RH (above 60%)	Winter	PH1 0.5% PH2 0%	CH3 0% CH4 46%	PH1 - PH2 0%	CH3 0% CH4 2%	PH3 0% PH4 1% PH5 0%	CH1 0.5% CH2 0%	PH3 0% PH4 0% PH5 0%	CH1 0% CH2 5%
	Spring	PH1 0% PH2 0%	CH3 0% CH4 20%	PH1 0% PH2 0%	CH3 0% CH4 1%	PH3 0% PH4 0% PH5 0%	CH1 3% CH2 0%	PH3 - PH4 0% PH5 0%	CH1 0% CH2 3%
	Summer	PH1 0.3% PH2 0%	CH3 5% CH4 18%	PH1 0% PH2 1%	CH3 0.1% CH4 11%	PH3 20% PH4 - PH5 23%	CH1 10% CH2 0%	PH3 14% PH4 0.1% PH5 15%	CH1 17% CH2 56%
RH (below 40%)	Winter	PH1 1% PH2 4%	CH3 55% CH4 0.5%	PH1 - PH2 0.2%	CH3 77% CH4 0%	PH3 86% PH4 31% PH5 63%	CH1 2% CH2 70%	PH3 88% PH4 58% PH5 86%	CH1 63% CH2 3%
	Spring	PH1 16% PH2 1%	CH3 33% CH4 8%	PH1 3% PH2 30%	CH3 50% CH4 0.2%	PH3 62% PH4 84% PH5 98%	CH1 2% CH2 50%	PH3 - PH4 66% PH5 98%	CH1 28% CH2 7%
	Summer	PH1 30% PH2 24%	CH3 2% CH4 9%	PH1 18% PH2 19%	CH3 2% CH4 5%	PH3 22% PH4 - PH5 16%	CH1 3% CH2 6%	PH3 22% PH4 21% PH5 18%	CH1 2% CH2 6%

Table 5.5 Proportion of time that the monitored indoor RH levels were outside the recommended threshold which minimises known adverse health effects

High RH (over 60%) were either observed in the monitored rooms of passive houses for short periods of time in most cases (e.g. between 0.5% and 14% of the time) or not observed at all. The longest periods of high RH found in passive houses, were observed during the summer, in the monitored bedroom of the 4 bed passive houses PH3 and PH5, for 20% and 23% of the time respectively.

When analysing low RH (below 40%), the data show that this was particularly problematic in passive houses and especially in the 4 bed passive houses during the winter and spring seasons. For instance, during the winter the monitored bedroom of the 4 bed passive houses PH3, PH4 and PH5 had low RH for 86%, 31% and 63% of the time respectively. During the same period, the 3 bed passive houses PH1 and PH2 had low RH for 1% and 4% of the time respectively.

Low RH was also observed in the living room of the 4 bed passive houses for a long period of time, during the winter and spring seasons. Table 5.5 shows that the living room of the 4 bed passive houses PH3, PH4 and PH5 had low RH for 88%, 58% and 86% of the time respectively during the winter season.

Aiming to identify the periods in which occupants might have been exposed to low RH in the monitored bedroom and in the living of the 4 bed passive houses, the two subsequent figures (5.2 and 5.3) show the RH and CO_2 levels observed in the monitored bedroom and in the living room, respectively, of passive houses PH3, PH4 and PH5 during the winter season. These three houses were chosen for further analysis as they presented long periods of time with RH levels under the recommended threshold. Additionally, the two subsequent tables (5.6 and 5.7) show the duration of occupants' exposure to RH levels below 40% in the monitored bedroom and in the living room, respectively, of the passive houses PH3, PH4 and PH5.

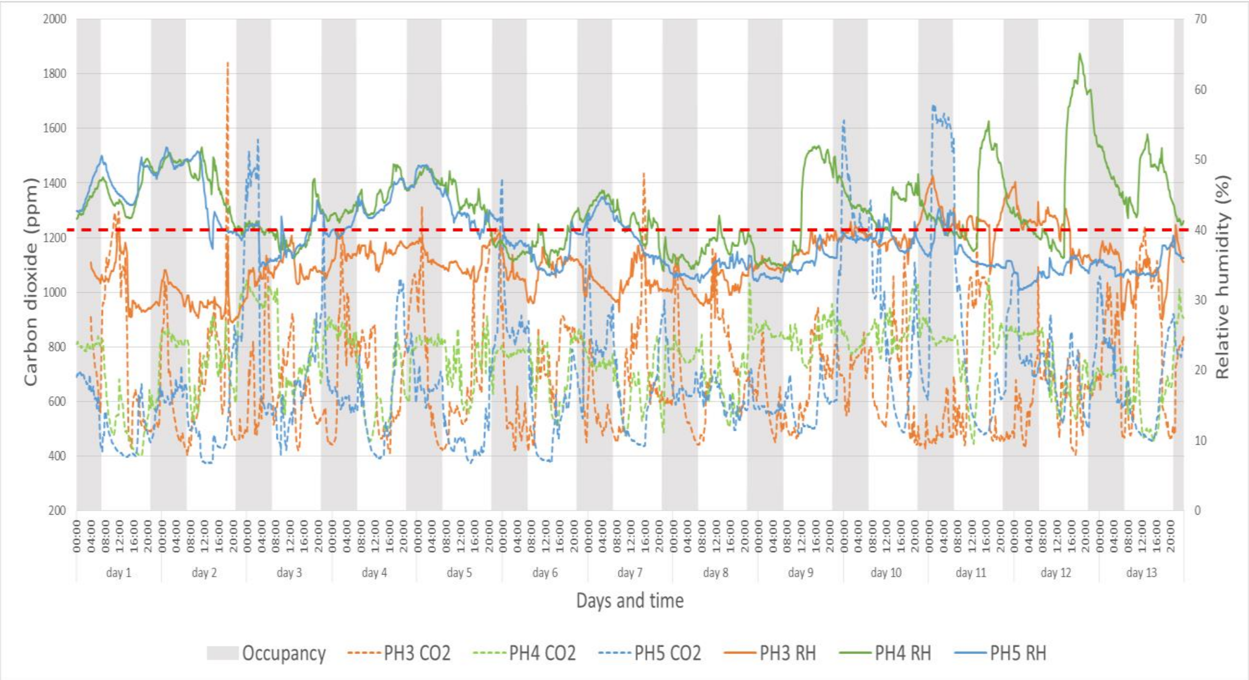


Figure 5.2 Relative humidity and carbon dioxide in the monitored bedroom of the passive houses PH3, PH4 and PH5 during the winter season. The red dashed line represents the minimum recommended RH threshold. The grey columns represent the typical period of bedroom occupancy - from 21:00 to 07:00

Monitoring days	Total time of exposure (hours)			Longest time span of exposure (hours)		
	PH3	PH4	PH5	PH3	PH4	PH5
Day 1	12.00	0.00	0.00	4.75	0.00	0.00
Day 2	11.00	1.25	4.50	6.50	1.00	3.00
Day 3	12.25	12.00	7.00	4.75	7.00	2.00
Day 4	15.75	0.00	2.00	11.00	0.00	1.25
Day 5	13.25	3.25	0.00	8 (between day 4 and day 5)	3.25	0.00
Day 6	13.75	14.25	11.50	11 (between day 5 and day 6)	10.00	8.00
Day 7	14.00	3.25	6.50	7.25	1.00	6.50
Day 8	16.75	19.50	14.75	9.50	15.25 (between day 7 and day 8)	7.50
Day 9	13.50	12.25	7.75	6.75 (between day 9 and day 10)	16.5 (between day 8 and day 9)	2.50
Day 10	11.25	1.25	16.75	5.50	0.50	9.75
Day 11	0.00	6.25	12.25	0.00	5.00	4.75
Day 12	5.00	6.75	19.50	1.00	3.00	17.75 (between day 12 and day 13)
Day 13	17.00	0.00	13.50	10.5 (between day 12 and day 13)	0.00	7.00
Total hours of exposure (hours)	155.5	80	116			
Total percentage of exposure	50%	26%	37%			

Table 5.6 Duration of occupants' exposure to RH levels under 40% in the monitored bedroom of passive houses PH3, PH4 and PH5 during the winter season

Figure 5.2 shows the period of occupancy in the monitored bedroom of passive houses PH3, PH4 and PH5 (from 21:00 to 07:00) as indicated by the householders during the interviews. The monitoring data combined with the interview data suggest that occupants sleeping in the monitored bedroom of passive houses PH3 (two adults) were exposed to low RH for the entire duration of occupancy, on most nights. In addition, these data also suggest that occupants sleeping in the monitored bedroom of passive house PH4 and PH5 (two adults) were exposed to low RH, however, to a lesser extent (e.g. during the indicated occupancy hours on some nights).

As previously explained, the CO_2 data shown on figure 5.2 are also helpful when used as a proxy for room occupancy since humans are the dominant source of CO_2. When analysing the carbon dioxide data shown on figure 5.2 in relation to room occupancy, it is suggested that the bedroom was occupied, on some occasions, beyond the hours between 21:00 and 07:00. The data show that CO_2 levels in the monitored bedroom of all three passive houses were over 600 ppm during the night and also during some parts of the day, on some occasions.

Aiming to identify the duration of occupants' exposure to low RH in the monitored bedroom, table 5.6 shows the total time of exposure as well as the longest time span of exposure for each monitoring day. These data confirm that during the winter season, bedroom occupants in passive house PH3 were exposed to low RH for several hours a day. In addition, table 5.6 also shows that during bedroom occupancy, RH levels were kept low for several uninterrupted hours (e.g. longest time span of exposure varying between 4.75 and 11 hours between day 1 and day 4).

Although the bedroom occupants of passive house PH4 and PH5 were less exposed to low RH levels, they were still exposed to several hours of low RH on some days (e.g. days 6, 8, 9 and 10 for PH4 and days 3, 5, 6 and 8 for PH5). The total exposure to low RH in the monitoring bedroom, during the two weeks of monitoring was considered substantial for all three passive houses: 50%, 26% and 37% for PH3, PH4 and PH5 respectively.

Regarding exposure to low RH in the living room of passive houses PH3, PH4 and PH5, the data from figure 5.3 suggest that occupants of all three passive houses were exposed for several hours to RH levels under 40%. This part of the analysis was performed by comparing RH levels under 40% with periods of time when CO_2 levels were over 600ppm. Unlike the qualitative data obtained from bedroom occupancy (where occupants indicated the time period they were in the bedroom), passive house occupants indicated to use the living room intermittently with no specific occupancy time period. Therefore, figure 5.3 does not provide complementary data regarding a period of occupancy.

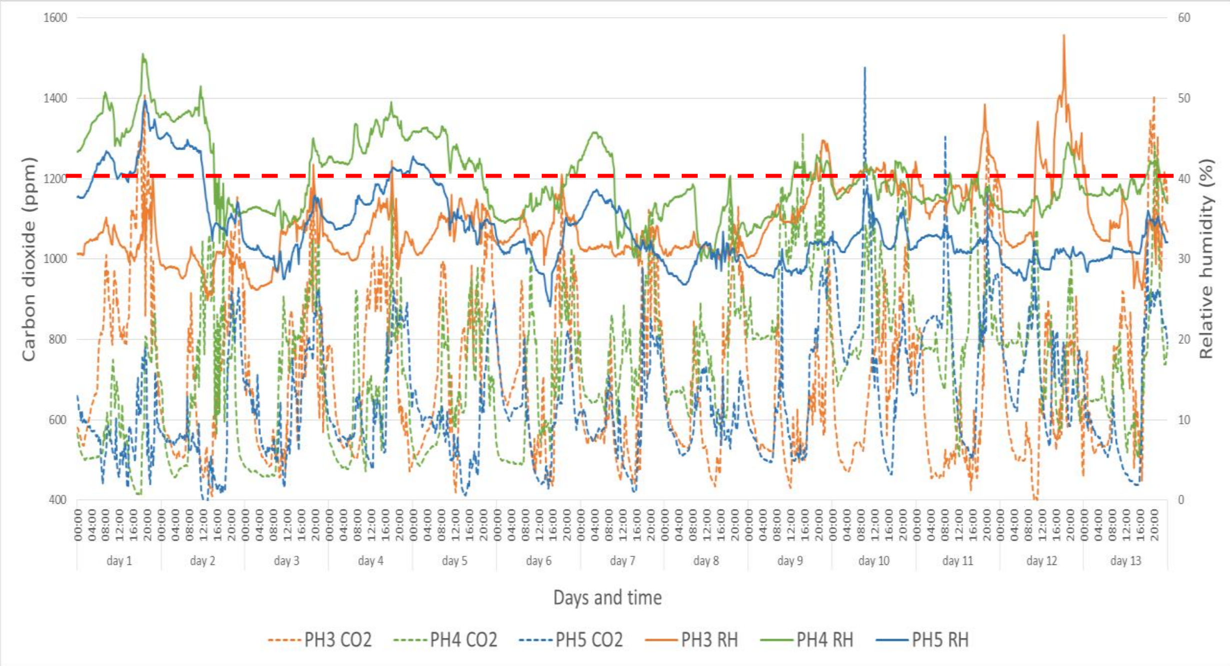


Figure 5.3 Relative humidity and carbon dioxide in the living room of the passive houses PH3, PH4 and PH5 during the winter season. The red dashed line represents the minimum recommended RH threshold

Regarding the duration of occupants' exposure to low RH levels in the living room, the data from table 5.7 show that the total exposure during the two weeks of monitoring during the winter season was very similar among the three passive houses. Occupants in the living room of passive houses PH1, PH2 and PH3 were exposed to low RH levels for around 46% to 47% of the time (which corresponds to a total of 146 to 148 hours of exposure).

All three passive houses showed several hours of occupants' exposure to low RH levels in the living room during the day and during the night on some occasions. The longest time span of exposure to low RH ranges from 0.5 hours (PH5 on day 2) to 20.75 hours (PH5 between day 9 and day 10). Nevertheless, the data suggest that in the living room of all three passive houses, occupants were exposed to low RH intermittently for several hours on many day. In addition, since higher CO_2 levels (over 600ppm) were observed for a long time span between day and night (e.g. from 17:00 to 09:15 between day 5 and day 6 in PH3), it is possible that occupants (or guests) were also sleeping in the living room on some nights. This would suggest that there was occupancy in the living room for several uninterrupted hours on a few nights.

Monitoring days	Total time of exposure (hours)			Longest time span of exposure (hours)		
	PH3	PH4	PH5	PH3	PH4	PH5
Day 1	20.25	0.00	1.50	18.00	0.00	1.00
Day 2	11.75	5.25	5.00	2.75	3.25	0.50
Day 3	13.75	9.00	14.25	11.25 (between day 2 and day 3)	9.00	9.00
Day 4	14.00	0.00	4.50	8.75	0.00	2.00
Day 5	16.25	3.50	6.25	5.00	3.50	1.50
Day 6	17.00	8.25	14.75	20 (between day 5 and day 6)	4.50	8.25 (between day 5 and day 6)
Day 7	9.75	14.00	10.50	1.00	1.50	2.25
Day 8	12.25	22.00	11.50	8.5 (between day 7 and day 8)	28 (between day 7 and day 8)	7.5 (between day 7 and day 8)
Day 9	5.50	14.00	10.50	8.75 (between day 8 and day 9)	17.5 (between day 8 and day 9)	3.50
Day 10	6.50	15.75	20.00	4.75	7.75	20.75 (between day 9 and day 10)
Day 11	3.50	21.25	19.00	1.75	11.75 (between day 10 and day 11)	18.5 (between day 10 and day 11)
Day 12	3.25	17.75	21.75	2.25	22.75 (between day 11 and day 12)	19.5 (between day 11 and day 12)
Day 13	14.50	15.25	9.00	7.00	12.5 (between day 12 and day 13)	7.50
Total hours of exposure (hours)	148	146	148			
Total percentage of exposure	47%	46%	47%			

Table 5.7 Duration of occupants' exposure to RH levels under 40% in the living room of passive houses PH3, PH4 and PH5 during the winter season

Regarding health risks, there is no information from the literature review to inform the level of exposure to low RH levels which leads to those health effects. Therefore, it is not possible to make strong statements between occupants' exposure to low RH levels and health effects. However, similarly to the previous section, it is possible to make reasonable estimates regarding the potential health risk for passive house occupants. In both rooms, living room and the monitored bedroom, occupants of the 4 bed passive houses were exposed daily to low RH levels (under 40%) for several hours, during the two weeks of the winter monitoring period. It is reasonable to suggest that occupants in the 4 bed passive house were at a high risk of dryness of the nasal mucous membrane, eyes and skin (health effects associated with RH under 40%) since they were exposed daily to low RH for long periods of time.

Regarding high RH (over 60%), data from table 5.3 shows that overall all five passive houses had short periods of time when RH levels were over the recommended maximum (between 0.3% and 20% during the summer season).

When comparing passive houses and control houses in terms of possible health effects associated to exposure to RH levels outside the recommended threshold (40% to 60%), the research findings suggest that passive houses are potentially healthier when considering exposure to high RH levels (over 60%) but potentially unhealthier when considering exposure to low RH levels (under 40%).

This suggestion is based on research data which shows that when comparing to passive houses, the control houses had high RH levels for longer periods of time (e.g. 46% and 56% of the time in the bedroom and living room of control houses CH4 and CH2 respectively). In contrast, the control houses had generally low RH levels for shorter periods of time when compared with the passive houses.

5.3.3. Carbon dioxide (CO_2)

Table 5.8 shows a summary of the occasions when CO_2 levels found in the monitored bedroom and in the living room of passive houses and control houses were over the maximum recommended threshold (800 ppm).

Indoor parameter		3 bed houses				4 bed houses			
		Bedroom		**Living room**		**Bedroom**		**Living room**	
		Passive Houses	**Control Houses**	**Passive Houses**	**Control Houses**	**Passive Houses**	**Control Houses**	**Passive Houses**	**Control Houses**
CO_2 (above 800 ppm)	**Winter**	PH1 75% PH2 83%	CH3 8% CH4 89%	PH1 - PH2 94%	CH3 4% CH4 76%	PH3 27% PH4 41% PH5 22%	CH1 78% CH2 92%	PH3 30% PH4 35% PH5 18%	CH1 39% CH2 46%
	Spring	PH1 81% PH2 68%	CH3 0.2% CH4 62%	PH1 86% PH2 83%	CH3 0.5% CH4 57%	PH3 29% PH4 46% PH5 14%	CH1 80% CH2 72%	PH3 - PH4 16% PH5 4%	CH1 43% CH2 55%
	Summer	PH1 36% PH2 15%	CH3 0% CH4 44%	PH1 26% PH2 27%	CH3 0.1% CH4 10%	PH3 0.5% PH4 - PH5 2%	CH1 23% CH2 26%	PH3 0% PH4 1% PH5 0%	CH1 12% CH2 2%

Table 5.8 Proportion of time that the monitored CO_2 levels were outside the recommended threshold which minimises known adverse health effects

All passive houses and control houses presented CO_2 levels over the recommended maximum threshold (800 ppm), at some point during the monitoring period. Nevertheless, the two groups of passive houses presented different trends regarding CO_2 levels in the monitored rooms. The 3 bed passive houses presented high CO_2 levels, for considerably longer periods of time, in both monitored bedroom and living room than was observed in the monitored rooms of the 4 bed passive houses. For instance, during the winter, the monitored bedroom of the 3 bed passive houses PH1 and PH2 had high CO_2 levels for 75% and 83% of the time respectively, whilst the monitored bedroom of the 4 bed passive houses PH3, PH4 and PH5 had high CO_2 levels for 27%, 41% and 21% of the time respectively, during the same period. A similar trend was observed during the spring and summer seasons in the monitored bedroom and living room. However, the winter and spring seasons were considered more problematic as high CO_2 levels were observed for longer periods of time when compared with CO_2 levels observed during the summer.

Aiming to investigate possible occupants' exposure to high CO_2 levels, figure 5.4 shows the CO_2 data obtained during the spring in the monitored bedroom of the five passive houses. The red dashed line represents the maximum recommended CO_2 threshold (800 ppm) while the grey columns represent the period of bedroom occupancy, from 21:00 to 07:00 (as indicated by occupants). Spring CO_2 data in the monitored bedroom were selected for this analysis as they provided a complete data set from all five passive houses.

Figure 5.4 shows that in all five passive houses, occupants sleeping in the bedroom (2 adults) were exposed to high CO_2 levels (over 800 ppm) at some point. However, this was especially problematic for the 3 bed passive houses PH1, PH2 and to a lesser extent, to the 4 bed passive house PH4. Bedroom occupants in passive house PH1 and PH2 were exposed daily to high CO_2 levels during the night for the entire occupancy period. CO_2 levels peaked beyond 2000 ppm and 1600 ppm in the bedroom of PH1 and PH2 respectively, most nights during the indicated occupancy period. As observed on figure 5.4, occupants sleeping in the monitored bedroom of passive houses PH1 and PH2 were uninterruptedly exposed to several hours of high CO_2 levels, well beyond the recommended maximum threshold (800 ppm).

Although lower CO_2 levels were observed in the monitored bedroom of passive house PH4, the data show that occupants were also exposed to CO_2 levels above the recommended maximum threshold for several hours, on most nights.

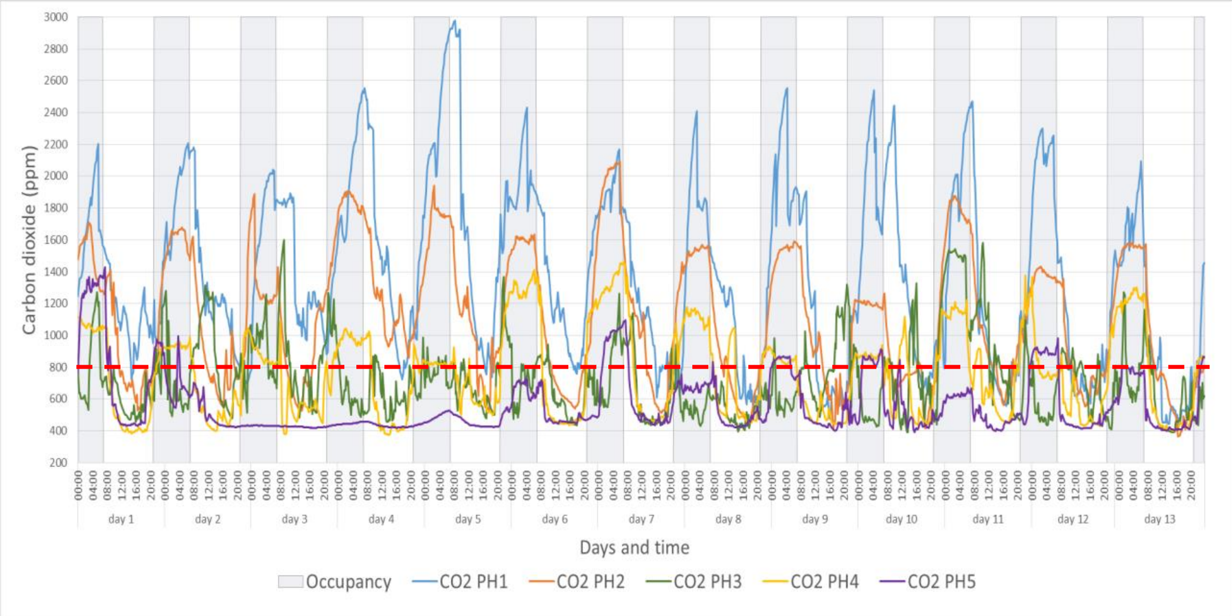


Figure 5.4 Carbon dioxide in the monitored bedroom of the passive houses during the spring season. The red dashed line represents the maximum recommended CO_2 threshold. The grey columns represent the typical period of bedroom occupancy as indicated by the occupants – from 21:00 to 07:00

The high CO_2 levels in the bedroom of passive house PH1, PH2 (and to a lesser extent PH4) during the spring season indicate that those monitored bedrooms were not provided with sufficient ventilation since the indoor generated CO_2 was unable to be purged through ventilation at an acceptable rate (25 m^3/h in PH1 and PH2 and 23 m^3/h in PH4 as designed following the Passivhaus standards).

In relation to health risks, there is no information from the literature review regarding the level of exposure to high CO_2 which leads to adverse health effects, it is not possible to make strong associations between occupants' exposure and health effects. Nevertheless, it is reasonable to suggest that the occupants sleeping in the monitored bedroom of passive houses PH1, PH2 and PH4 (two adults) were at a high risk of eye irritation and upper tract respiratory symptoms (health effects associated with CO_2 levels over 800 ppm) since they were exposed to high CO_2 levels for several hours during the night on a daily basis, during the two weeks of monitoring during the spring season.

When comparing passive houses with the corresponding group of control houses (table 5.8), it was observed that generally, the 4 bed control houses had high CO_2 levels for longer periods when compared with the 4 bed passive houses.

When comparing the 3 bed passive houses with the corresponding 3 bed control houses, different trends were observed. High CO_2 levels were generally observed for longer periods in the 3 bed passive houses when compared with the control house CH3, and generally for shorter periods of time when compared with the control house CH4.

When comparing passive houses and control houses in terms of possible health risks associated to exposure to CO_2 levels over the recommended maximum (800 ppm), the research findings suggest that passive houses can be either healthier or unhealthier than conventional houses.

The research findings showed that 3 bed passive houses (PH1 and PH2) seemed to have much longer periods with high CO_2 levels when compared with the other control houses (with the exception of control house CH4). On the other hand the 4 bed passive houses (PH3, PH4 and PH5) showed the opposite trend.

Drawing from the finding from Chapter 4, it is possible that lower ventilation rates were provided in the 3 bed passive houses, potentially caused by a shortcoming with the MVHR system. Therefore, the ability of the MVHR in continually providing adequate ventilation rates appears to be an influential factor in determining whether these houses are healthy or unhealthy in terms of CO_2 levels.

5.3.4. VOCs

Although some passive houses (e.g. PH1 and PH2) presented concentrations of alpha-pinene and limonene much higher than others (PH3, PH4 and PH5), the concentrations of alpha-pinene and limonene observed in the monitored bedroom of all passive houses and all control houses were well under the recommended maximum levels of exposure. Table 5.9 shows that the mean concentration range found in both passive houses and control houses for alpha-pinene (10.26 to 81.54 μgm^{-3}) and limonene (8.96 to 78.44 μgm^{-3}) are much lower than the recommended maximum levels found within the literature (4,500 and 9,000 μgm^{-3} respectively for 24 hours exposure).

This suggests that passive houses and control houses bedroom occupants were not at risk of the known adverse health effects caused by exposure of high indoor concentration of alpha-pinene and limonene (e.g. sensory irritation).

On the other hand, the mean concentrations of naphthalene were very similar between passive houses and corresponding control houses (ranging from 12.61 to 15.61 μgm^{-3}). Passive houses and control houses showed a mean concentration over the recommended annual average concentration threshold of 10 μgm^{-3}.

Regarding decane concentrations, the 3 bed passive house PH1 was the only house to present it as one of the top ten most abundant VOCs found in the monitored bedroom. The literature review has indicated that decane concentrations as low as 7.3 μgm^{-3} are associated with adverse health outcomes (irritation of the mucous membrane of the eyes). The decane concentration found in the monitored bedroom of passive house PH1 (mean concentration of 22.67 μgm^{-3}) was three times over 7.3 μgm^{-3}.

VOCs (μgm^{-3})	PH1	PH2	PH3	PH4	PH5	CH1	C02	CH3	CH4	Recommended maximum levels (μgm^{-3})
Alpha-pinene	81.54	44.70	13.86	14.46	14.70	-	14.69	-	10.26	(acute 30 min exposure) 45,000 (24h exposure) 4,500
Limonene	51.46	30.87	14.80	19.69	-	78.44	24.81	8.96	78.60	(acute 30 min exposure) 4,500 (24h exposure) 9,000
Decane	22.67	-	-	-	-	-	-	-	-	7.3*
Naphthalene	-	15.61	14.48	-	15.74	-	15.44	12.62	13.61	(annual average concentration) 10

*Table 5.9 Volatile organic compounds found indoor in the monitored bedroom of passive houses and in control houses versus recommended maximum VOC levels to minimise known adverse health effects. (*concentration associated with adverse health effects)*

Regarding exposure to these two VOC species (naphthalene and decane), qualitative and quantitative data have shown that passive house occupants (two adults) were spending several hours during the night and some hours during the day in the monitored bedroom, during the two weeks of monitoring.

Regarding health risks associated with the level of exposure, the literature review provided evidence to support that long-term exposure to naphthalene at > 10 μgm^{-3} was associated to adverse health effects (e.g. chronic inflammation in the nasal olfactory epithelium). The literature also provided some evidence showing that 6 hours exposure to decane at ≥7.3 μgm^{-3} was associated with irritation of the mucous membrane of the eyes.

Nevertheless, it is important to point out that the naphthalene maximum concentration recommendation of 10 μgm^{-3} is based on an annual average concentration, whereas the naphthalene concentrations observed in the monitored bedrooms were based on a two weeks average (mean) concentration. Therefore this comparison can only provide an indication in relation to the possible adverse health risks in the monitored bedrooms of the studied passive houses and control houses.

In terms of the health of occupants, the data analysis suggest that occupants of passive houses PH2, PH3 and PH5 as well as control houses CH2, CH3 and CH4 were exposed to similar concentrations of naphthalene over the maximum recommended threshold. Therefore, occupants in the monitored bedroom of those dwellings were at risk of the health effects associated with average concentrations over 10 μgm^{-3} (e.g. chronic inflammation in the nasal olfactory epithelium).

Regarding the health risks associate with the decane found in passive house PH1, the data analysis suggests that the occupants in the monitored bedroom were also at risk of adverse health effects (e.g. eye irritation and dry eyes). This is due to them being exposed to a mean concentration of decane which is three times over the concentration associated with adverse health effects.

5.4. Conclusion

The aim of the chapter was to analyse whether passive houses provide their occupants a healthy indoor environment. This was attempted through a review of the epidemiological, toxicological and other health related literature to reveal safe threshold levels of the indoor parameters monitored (temperature, RH, CO_2 and VOCs), together with the analysis of the monitored data and occupants exposure to levels outside the recommended threshold. Additionally, it was also attempted to find out how the health status of the indoor environment of passive houses compare with the results from conventional houses.

Based on application of the analytical framework in the previous chapter, the variables which were considered explanatory of the differences in IC and IAQ, are connected to possible health risks identified in passive houses.

Following the data findings from the previous chapter, the indoor climate and indoor air quality parameters from five passive houses and four control houses were analysed and compared with the findings from the epidemiological, toxicological and other health related published research. Using the data and findings extracted from the literature review, a 'recommended threshold to minimise adverse health effects' was adopted for each of the indoor parameters monitored in the studied houses. As indicated in the literature review, an indoor parameter could be considered as a health hazard when outside the recommended threshold. Additionally, a health hazard could be considered a health risk when there is exposure.

From the epidemiological and toxicological literature review, nine health hazards were identified in passive houses: indoor temperature under 18^{o}C, indoor temperature over 26^{o}C, RH under 40%, RH over 60%, CO_2 over 800 ppm, limonene over 4,500 μgm^{-3}, alpha-pinene over 4,000 μgm^{-3}, naphthalene over 10 μgm^{-3} and decane in a concentration equal or over 7.3 μgm^{-3}. Where the literature review failed to identify comprehensive studies linking exposure to particular VOC species to possible health effects, these were excluded. The excluded VOC species are undecane, 1.4 dichlorobenzene, 3-carene, tetradecane, pentadecane, heptadecane, tetracosane, docosane and acetic acid.

Using these identified hazards and the recommended threshold for each of the indoor parameters together with the analysis of occupants' exposure to levels outside the recommended threshold, the following findings were obtained:

First, temperatures over the recommended maximum (26^{o}C) was a problem during the summer and a potential health risk for three out of five passive houses. Passive houses PH1, PH2 and PH4 had much longer periods of time with high indoor temperatures, especially in the living room, when compared with the corresponding control houses. Other studies have also reported that indoor summer overheating was a problem in some passive house standard dwellings (e.g. Brunsgaard et al., 2012; Foster et al., 2016; McLeod et al., 2013). As explained by Mlakar & Strancar (2011) higher indoor temperatures can occur more easily in passive houses if they are experiencing hot summers and especially if they were not provided with some solar shading on elevations which are more prone to heat gains (e.g. South through to West). In the case of the studied passive houses, none of the houses were provided with external shading (e.g. structural overhang, brise soleil) on any façade.

Regarding adverse health effects, further analysis on occupants' exposure and potential health risks has shown that occupants in those three passive houses were exposed to temperatures over 26^{o}C for several hours, on a daily basis. Information obtained from the literature together with reasonable estimates made by the researcher have suggested that passive houses occupants were at a risk of worsening respiratory conditions (a health effect associated with indoor temperatures over 26^{o}C).

Through application of the analytical framework in Chapter 4, the possible source of the problem was identified as a combination of internal heat gains from room occupancy, occupants' ventilation practices (as windows were opened for longer during the day in the summer resulting in additional heat gains from the sun) and the lack of sun shade (internal and external) on the building façades.

On the other hand, low indoor temperatures (under 18^{o}C) were generally observed for significantly longer periods of time in control houses when compared with passive houses. The longest period of low indoor temperature observed in passive houses was 9%.

When comparing passive houses and control houses in terms of possible health risks associated with exposure to temperatures outside the recommended threshold (18°C to 26°C), the research findings suggest that passive houses are potentially healthier when considering exposure to low temperatures (under 18°C) but potentially unhealthier when considering exposure to high temperatures (above 26°C).

Second, regarding RH levels outside the recommended threshold (40% to 60%), the findings show that low RH (below 40%) were particularly problematic and potentially unhealthy in passive houses and specifically in the 4 bed passive houses during the winter and spring seasons. This is because during those two seasons, the 4 bed passive houses presented low RH levels for long periods of time (ranging from 31% to 88%) in the monitored bedroom and living room.

Further analysis on occupants' exposure and potential health risks in the monitored bedroom of the 4 bed passive house has shown that occupants (two adults) were exposed to low RH levels for several hours during the night on some nights in two passive houses (PH4 and PH5) and for several hours every night in passive house PH3 during the winter. The analysis on living room occupancy has suggested that occupants in the 4 bed passive houses were also exposed to low RH levels for several hours on some days, albeit intermittently.

Information from the literature review together with estimates made by the researcher suggested that the 4 bed passive house occupants were at risk of dryness of the nasal mucous membrane, eyes and skin (health effects associated with exposure to RH levels under 40%).

The analysis carried out in Chapter 4 using the analytical framework suggested that occupants' ventilation practices offer a strong explanation for the low RH levels observed in two of those three passive houses. As occupants in passive houses PH3 and PH5 opened the window on a daily basis and for the whole night during the winter, warmer indoor air was replaced by colder and drier air, resulting in low RH levels. Nevertheless, the analysis failed to identify why passive house PH4 also had low RH levels since the occupants indicated that they rarely opened the windows during the winter.

Regarding high RH levels (over 60%), passive houses had overall shorter periods of time with high RH when compared with the control houses. High RH was observed mostly during the summer season between 0.3% and 20% of the time.

When comparing passive houses and control houses in terms of passible health effects associated to exposure to RH levels outside the recommended threshold (40% to 60%), the research findings suggest that passive houses are potentially healthier when considering exposure to high RH levels (60%) but potentially unhealthier when considering exposure to low RH levels (40%).

Third, in relation to CO_2 levels over the recommended maximum (800 ppm), all passive houses and control houses presented high CO_2 levels at some point. However, high CO_2 was considered especially problematic in three out of five passive houses during the winter and spring seasons as they had CO_2 over the recommended threshold for long periods of time. These include the 3 bed passive houses PH1 and PH2 and to a lesser extent, the 4 bed passive house PH4.

Further analysis on occupants' exposure and potential health risks in the monitored bedroom of the three passive houses with high CO_2 levels showed that occupants sleeping in the bedroom (2 adults) of all three passive houses were uninterruptedly exposed to several hours of CO_2 levels beyond 800 ppm on most nights during the spring. Particular concern was demonstrated in relation to CO_2 levels observed in the monitored bedroom of the 3 bed passive houses as those were peaking beyond 1600 ppm for several hours during the night.

Information found in the literature together with estimates made by the researcher have suggested that occupants of those three passive houses were at risk of eye irritation and upper tract respiratory symptoms (health effects associated with CO_2 levels over 800 ppm).

The analysis carried out in Chapter 4 using the analytical framework suggested that those passive houses were not provided with sufficient ventilation as the indoor generated CO_2 was unable to be purged through ventilation. Since the occupants in those three passive houses followed the users' manual recommendation (to not keep the window open during cold months) it was suggested that the MVHR was not providing the ventilation rates as designed, especially in the 3 bed passive houses, where CO_2 concentrations were very high.

When comparing passive houses and control houses in terms of possible health risks associated with exposure to high CO_2, the findings suggested that passive houses can potentially be heathier or unhealthier than control houses, depending on the ability of the MVHR in continuously proving adequate ventilation rates.

Fourth, regarding the VOC species and their concentrations found in the studied houses, the research findings show that the concentration of naphthalene found in three out of five passive houses was around 50% over the recommended threshold whilst the concentration of decane found in one passive house was three times the concentration associated with adverse health effects (dry eyes). All the other VOC species found in passive houses were either at much lower concentrations than those associated with ill health or no information regarding safe health thresholds were found in the literature.

Further analysis using data from the literature have suggested that occupants sleeping in the monitored bedroom in three passive houses (PH2, PH3 and PH5) were at risk of chronic inflammation in the nasal olfactory epithelium (a health effect associated with naphthalene concentrations over 10 μgm^{-3}) while occupants sleeping in passive house PH1 were at risk of eye irritation and dry eyes (health effects associated with decane concentrations at $\geq 7.3\ \mu gm^{-3}$).

When analysing possible causes for the high concentration of those two VOC species, the findings from application of the analytical framework suggested that the choice of cleaning and personal hygiene products as well as the frequency with which they were used were the potential source of naphthalene observed in three passive houses and three control houses. On the other hand, smoking practices performed in the monitored bedroom of passive house PH1 were considered a strong explanatory variable for the high concentration of decane found there.

When comparing passive houses and control houses in terms of possible health effects associated with exposure to VOCs, the research findings suggest that there was very little difference between passive houses and control houses. However, the most prominent difference (the unhealthy decane concentration found in one passive house only and not found in any control house) was probably caused by occupants smoking in the bedroom and not a result of house characteristics.

Based on the evidence suggesting that occupants’ practices strongly contribute to their indoor environment quality, which in turn affect the health of occupants, further questions arise. If occupants’ practices contribute to the quality of their indoor environment, in what specific ways does that happen? Additionally, how might occupants’ practices contribute to the seasonal variations found in the quality of the indoor environment? Finally, how might occupants’ everyday practices contribute to differences in the indoor climate and indoor air quality in identical passive houses?

Therefore, the next research chapter attempts to answer these questions based on the findings obtained in this part of the study.

5.5. Strengths, limitations and recommendations

This study has for the first time, as far as the researcher knows, thoroughly investigated the indoor environment of passive houses, analysing it together with evidence from health related published studies, aiming to establish whether passive houses provide a healthy environment to their occupants.

Nevertheless, the findings revealed here were constrained by the lack of sufficient epidemiological, toxicological and other health related published studies which provided information on the possible health effects (as well as safe threshold) of the indoor climate and indoor air quality levels observed in the passive houses. For instance only a few studies which provided recommendations for minimum threshold for indoor heat were identified within the literature. Additionally, although 13 VOC species were identified in the passive houses and control houses, the literature review search identified relevant health related studies for only four of those. Furthermore, due to time, financial and other constraints, only the 10 most abundant VOCs were monitored and analysed. Although they provided some important insights regarding the indoor environment of passive houses and the health of their occupants, they may not have provided the full picture as many other VOCs (in less abundant concentrations) may have been found if more than 10 were targeted.

Based on these, it is recommended that further work is needed to monitor and analyse a more comprehensive list of VOCs in passive houses, trying to link these with existing information on possible adverse health effects and safe threshold levels.

Chapter 6 – Indoor environment quality in passive house rooms: understanding the possible influences of occupants' practices

6.1. Introduction

The findings from the previous two chapters have shown that there are differences between the indoor environments of passive houses and that these differences may affect the health of occupants in different ways. The findings from Chapter 4 have shown that even identical passive houses (with the same solar orientation, layout and building volume) may present differences in their indoor climate and indoor air quality. Furthermore, findings from others studies (e.g. Gill et al., 2010; Maier et al., 2009; Steemers & Yun, 2009) have suggested that although different building characteristics may contribute to differences in the indoor environment in dwellings, different occupants' everyday practices also play a central part.

The everyday practices of occupants of residential buildings have been extensively examined within the domestic energy consumption literature (e.g. Hargreaves et al., 2013; Guerra-Santin & Itard, 2010; Owens & Driffill, 2008). Many of these studies have established the need to understand occupants' everyday practices as they greatly contribute to different levels of energy demand. For instance, research shows that there is a significant variation in energy consumption (two or threefold) among dwellings with similar or even identical characteristics (e.g. layout, building volume, number of occupants) (e.g. Fabi et al., 2012; Gill et al., 2010; Palmborg, 1986; Tweed et al., 2013). Many of these studies have established that the significant energy consumption variations observed between similar dwellings were due to differences in occupants' practices.

Nevertheless, although there is extensive research exploring occupants' practices and the effect they have on energy consumption in dwellings, little research has explored how occupants' practices might affect the quality of their indoor environment from a health perspective. This topic has been considered very important, especially in relation to passive houses and other energy-efficient houses, since the quality of their indoor environment and its possible health effects have been the cause of great concern (Bone et al., 2010).

The research findings from Chapter 4 have shown that the indoor environment of passive houses varied in three different scenarios. First, IC and IAQ varied in different rooms in the same passive house. Second, IC and IAQ in the same room varied following seasonal changes. Third, IC and IAQ varied between the same room (e.g. main bedroom) in identical passive houses.

Therefore, this chapter aims to provide some more detailed understanding of how passive house occupants (and their everyday practices) have contributed towards the differences observed between passive houses. In attempting to understand these differences, social practice theory is used as the theoretical approach for the analysis of the social context of the indoor environment of passive houses.

The chapter begins by explaining social practice theory in the context of the indoor environment of passive houses and their occupants. It follows by discussing everyday practices and their possible contribution to the indoor climate and indoor air quality in passive houses.

This is presented by using a three part narrative. First, the social context of each passive house, and the practices performed in each of the three monitored rooms (bedroom, living room and kitchen) is examined. Additionally, how these practices might have changed following seasonal variations, will also be analysed. Second, discussions on how everyday practices might have contributed to the main findings revealed in Chapters 4 and 5, are also presented. Some explanatory variables identified in Chapter 4, which are specific to occupants' practices (e.g. ventilating, tobacco smoking, cooking using electrical appliances) are included in the discussions, aiming to providing more detailed explanations of how practices contributed to the indoor environment quality in passive houses.

Third, the four elements which guide the performance of practices are discussed, aiming to understand how these have influenced everyday practices, and therefore how they also may have contributed to the indoor climate and indoor air quality in identical passive houses.

6.2. Theoretical context

Social practice refers to a theoretical approach where practices become the focus of the analysis rather than the individual. Therefore, rather than focusing on individuals' attitudes, behaviours and choices, social practice theory re-directs the focus on the "collective structures of practices and on what guides the practices people perform in their everyday lives" (Gram-Hanssen, 2013, p.94).

Social practice theory has been widely used as an analytical lens for energy consumption studies in domestic settings (e.g. Foulds et al., 2013; Gram-Hanssen, 2012; Gram-Hanssen, 2010; Gram-Hanssen, 2008). Social practice theory has been particularly important in producing new insights into routinised everyday activities and the consequences for the indoor environment (Chappells & Shove 2005). For this reason, this theoretical approach was considered useful and reliable when analysing how occupants' mundane or inconspicuous habits may influence the indoor climate and indoor air quality in passive houses.

Another important characteristic within social practice theory is that it recognises the influence of some elements on the performance of practices. On this matter, Reckwitz (2002, p.249) noted the importance of interconnected elements influencing the performance of practices:

> “a practice is a routinised type of behaviour which consists of several elements, interconnected to one other: forms of bodily activities, forms of mental activities, ‘things’ and their use, a background knowledge in the form of understanding, know-how, states of emotions and motivational knowledge. A practice – a way of cooking, of consuming, of working, of investigating, of taking care of oneself or of others, etc. – forms so to speak a ‘block’ whose existence necessarily depends on the existence and specific interconnectedness of these elements, and which cannot be reduced to any one of these single elements”.

Although there is no complete agreement among theorists on the naming of these elements, for the purpose of the thesis, the researcher has loosely adopted the approach described by Gram-Hanssen (2009; 2010; 2011)[29]. Therefore, based on Gram-Hanssen’s conceptualisation of practice elements, the four elements of practices used in this part of the analysis include: technologies and artefacts; institutionalised knowledge; embodied habits; and meanings and engagements. These four elements are considered important since they guide the performance of practices which contribute to the indoor climate and indoor air quality in passive houses.

Since a practice theory approach is used as the analytical lens for the understanding of practices related to the indoor environment of passive houses, it is necessary to identify which practices are relevant to this study. Thus, the focus here is not centred on the analysis of all routinised practices performed by passive houses occupants. Instead, it is centred on occupants’ everyday practices which may have contributed directly or indirectly to the indoor climate and indoor quality of passive houses. These practices are the focus of the study as they can offer useful insights into the differences in indoor climate and indoor air quality observed in passive house rooms.

It is not controversial to say that the quality of the indoor environment of passive houses relies on these two elements: the adequate exchange of indoor and outdoor air, so indoor pollutants can be removed or diluted; and the type of indoor activities performed by occupants. Occupants’ indoor activities are also important because they may contribute to a better or worse indoor air quality (e.g. constantly smoking in the house may contribute to higher levels of VOCs), and they also may alter the indoor climate (e.g. frequently using electric house appliances or other source of indoor heating may contribute to raising the indoor temperature).

Therefore, this study focuses on three types of occupants’ practices. First, practices which may directly result in indoor/outdoor air exchange (e.g. ventilation and airing practices). Second, practices which may indirectly result in indoor/outdoor air exchange (e.g. smoking indoors and consequently

[29] For the rationale for the adoption of the social practice theory elements described by Gram-Hanssen (2010a, 2010b, 2011), please refer to the Methodology chapter.

opening the window while this practice is performed). Third, practices which may alter the indoor climate and/or indoor air quality (e.g. smoking indoors, heating the house, cooking/washing/ironing or using other electrical appliances).

6.3. The indoor environment of passive houses and the everyday practices of occupants

6.3.1. Five families and their everyday practices in three different rooms: Understanding practices in the main bedroom, living room and kitchen

Passive houses PH1 and PH2 are identical 3 bed, two storey houses, comprising of kitchen, living room and a toilet on the ground floor and three bedrooms and a bathroom on the first floor. The ground floor living room leads to a garden area at the back of the dwelling.

Passive houses PH3, PH4 and PH5 are identical 4 bed, three storey houses. They comprise of kitchen, dining room and a toilet on the ground floor; a bedroom, living room and a bathroom on the first floor; and further three bedrooms and a shower room on the second floor. The ground floor dining room leads to a garden area at the back of the dwelling.

The following sub-sections provide a narrative of the families living in the passive houses and the everyday practices they performed in each of the monitored rooms (bedroom, living room and kitchen) which may have contributed directly or indirectly to the quality of their indoor environment. The narrative also describes how these everyday practices changed, on some occasions, following seasonal variations.

a) PH1: Wants to feel safe in the house and has a fixed routine

Anna and Daniel are a couple in their early thirties. He has a full time skilled job, working away from home during week days and she is a stay at home mum. They have two primary school aged children living with them. The family normally host guests, who are usually the children's friends who stay overnight on Fridays after school.

The main bedroom is not only the place where the couple sleeps but also a place for Daniel to relax and to watch TV after arriving home from work. This room is also used by Anna for watching TV in the evenings, before she goes to bed. Smoking practices also take place in the bedroom in the evening, when Anna and Daniel usually have two or three cigarettes each by the bedroom window.

During the winter season, Anna and Daniel kept their bedroom windows closed all day and night, only briefly opening them in the evening when Anna and Daniel were smoking by it. However, during the spring and summer seasons, windows were open more frequently, as this activity was not only the result of smoking practices taking place in the bedroom, but also the result of airing and cooling practices during warmer seasons. As Anna explains “today I will leave them open all day, smoking or not smoking, but then other than that [warm day in spring season] it is just when we smoke” (PH1). Anna clarifies that she opens the windows to let the air in as she enjoys the breeze coming through the windows on a hot day. However, during any season, the bedroom windows are fully closed in the evening, just before Anna goes to sleep. Anna explains that she always closes all the windows in the house before she goes to sleep for security reasons. She reiterates that she wants to provide a secure environment for their family. For Anna, keeping the windows closed is also a long lived practice which she carried with her when she moved to her new passive house – “I am scared of burglars and stuff… because I’ve always lived in a ground floor flat, so I have always closed them and around this way there is a lot of burglaries going on” (PH1).

In this household, the living room is mainly used for watching TV in the evening, or it is used by the children for playing or occasionally for doing homework when they are not at school. The children‘s school friends also sleep in the living room when they stay with the family. During the day, Anna uses the living room occasionally, but only for short periods of time (about 10 min) for relaxing between housework activities.

During the winter season, the living room window and external door were kept closed at all times, day and night. The only exception was Christmas day, when the couple hosted a meal for a few friends and family, and fully opened the window and external door and kept them open. “It was like an oven in here, it was hot, yes I had to just cool it down a little bit” (PH1) – clarifies Anna. According to the couple, when they host meals and have friends around they normally open the window and external door in the living room as well as the kitchen window as “it gets too hot in the house” (PH1).

However, keeping the windows or/and external doors open during colder months was not something advised on the passive house users’ manual. On the contrary, that was considered unnecessary and something to be avoided since internal heat would be lost through outdoor/indoor air exchange.

During the spring and summer seasons, ventilation and cooling practices were intensified in the living room. The household activity diary shows that during the spring and especially during the summer season, the living room window was kept open multiple times during the day, for a few hours at a time. Again, the occupants explained that they wanted to cool down the house and “let some air in” (PH1) by opening the windows.

The kitchen in the PH1 household is used for many different practices. Anna prepares the family meals there, which include cooked breakfast at around 7 am and hot dinner after the kids get back from school, at around 5 pm. All meals are eaten at the kitchen table. This room is also a place where one of the children always does their homework and a place where Anna irons the family's clothes, nearly every day. The kitchen also has dishwasher and washing machine appliances, where dishes and clothing washing practices also take place on a daily basis (sometimes twice a day).

Anna refers to this room as "the place to come" as she spends most of her daytime there. "I don't know, most of the time I find myself sitting here, I don't know why, it's easiest" (PH1). During the day Anna also chooses this room as a convenient place to smoke a cigarette, as she can open the window and observe the outside. Putting the kettle on and making a hot drink a few times a day is also part of Anna's routine in the kitchen.

During the winter season, the kitchen window was kept closed at all times with only two exceptions. During the day, every time Anna and Daniel smoked a cigarette and when Anna cooked a meal.

Regarding cigarette smoking practices in the kitchen, these were performed by Anna a few times during the day and by Daniel a few times during the week in the evening and during the daytime on weekends. Cigarette smoking practices also resulted in activities which provided additional air exchange in the kitchen as both Anna and Daniel briefly opened the kitchen window every time they smoked there. Cigarette smoking also took place in the garden during the spring and summer seasons.

Cooking practices in the PH1 household were performed every day, with the exception of Friday night, when the family have a takeaway meal. Cooking involves the use of the top hob, the grill and the oven as well as the use of the high level cooker hood extractor. Anna explains that she always opens the kitchen window wide when she cooks as "it is usually really hot in here [kitchen]" (PH1).

During the spring and summer seasons, ventilation and cooling practices were performed more frequently in the kitchen. The kitchen window was left open for longer periods of time to either provide some "fresh air" or to "cool the room down".

Regarding heating practices, Anna explained that during the winter the family felt that the indoor temperature was adequate for most of the time, and therefore they only turned the heating on (gas radiators throughout the house) on five occasions to heat up the house. Nevertheless, interview data also reveals that during the winter season the radiators were turned on not only for occasional heating practices but also for recurring clothing drying practices, which took place twice a day (in the morning and in the evening) for about one hour each time. As Anna explains "if I want to dry washing, sometimes I put it on [radiators] just to dry, because Daniel's big work jumpers and things like that. Now [spring season] I can put it outside, but in the bathroom in the winter, it wasn't drying as quick" (PH1).

b) PH2: Likes fresh air and has an ad hoc routine

Barbara and Carl are a couple in their early thirties. Barbara works part time, away from home but she does not have fixed working days or fixed working hours. Carl is a stay at home dad, spending most of his day time in the house. They have two children: a pre-school and a primary school aged child who live with them and a step-daughter who visits the family every other weekend. Apart from the step-daughter, the family usually does not have guests around the house. The family follows an ad hoc type of routine as Barbara's working days and hours greatly vary. As explained by Barbara, "there is no typical week in this house".

The main bedroom is the room where Barbara and Carl sleep. Carl sometimes uses this room for playing 'Xbox' games. Other practices, such as relaxing and watching TV usually do not take place in the bedroom. Although, they might do on some occasions. The bedroom was also used as a place for drying the family's clothing during the spring and summer periods. However, this occurred infrequently as others locations were also used during those periods (e.g. downstairs toilet, garden).

During the winter season, ventilation practices were infrequent in the bedroom. The couple kept the window closed during the night for most of the time. Barbara complained that they have a problem with insects coming into the bedroom at night time if they left the windows open. Barbara also kept the bedroom window closed as much as possible during the night, as she tried to reduce the noise coming from the nearby train railway line. Barbara explains "it is hard because you want the window open, but you can't really at night time with this noise" (PH2). Thus, in order to maintain a pleasant and comfortable bedroom environment during the night, Barbara and Carl opted to keep the bedroom window closed during the night, even though they felt the room was too hot and opening the window for some cooling was needed.

During the day time however, the bedroom window was opened as and when needed, as ventilating and cooling practices were performed "when it felt like it" (PH2). Barbara explains "I don't think of even opening [the window]. I don't think of anything, if that makes sense? I would just walk over to the window and if I am standing there it might get opened" (PH2). Nevertheless, Barbara admitted that during the day (winter season) the main bedroom window was not opened very often "mainly because we are down here, we are not upstairs so just don't need to open them up there" (PH2).

Nevertheless, during the spring and summer seasons, ventilation and cooling practices were performed more regularly, when compared with the winter period. During the spring and summer seasons, interview and diary data show that the bedroom window was kept open almost all the time, and all the time respectively. Especially during the summer, Barbara explains that “if we are in, they [windows] will be open” (PH2).

The family felt that during the summer season, they had to choose between ventilating the house and not being bitten by “gnats” coming through the window. When questioned about the insects in the bedroom coming through into the room, Barbara explained: “we did have the same issue with gnats [during the summer season], but we will all just rather suffer the gnat bites than suffocate” (PH2).

From Barbara’s point of view, the living room is the most used room in the house. Different practices are performed in the living room between the hours of 6 am and 10 pm. For instance, Carl uses the living room for most of the time, for relaxing and watching TV. When the children are back from school, they alternate between playing in their bedrooms and staying in the living room watching TV or playing. The children also have most of their dinners in the living room. Barbara and Carl watch TV in the living room in the evening until they go to bed.

Barbara and Carl explained that even during the winter season, the living room felt hot from time to time. Thus, they opened the window occasionally to cool the room down. Yet, during the winter, the living room door leading to the garden, was rarely opened for ventilation or cooling, being kept closed for most of the time. Barbara explained that that’s what they do when they are caring and looking after their younger daughter, as the couple did not want their daughter going to the garden unsupervised. Thus, caring for their children was also a practice which influenced the way the couple ventilated their house during the winter season.

Nevertheless, during the spring and summer seasons, ventilation, cooling and child caring practices in the living room were performed somewhat differently when compared with the winter season. Ventilation and cooling practices became more frequent, with the living room window being opened “occasionally” (PH2) or “just if it feels warm” (PH2) and the living room door being kept open “if it is nice out there” (PH2). Child caring practices in the living room during the spring and summer season also resulted in keeping the external door open to give their daughter free access to the garden. The couple explained that “if Brenda is in and out, I usually leave it [external living room door] open” (PH2).

In the PH2 household, the kitchen is used to prepare meals and for cooking but there is no set time for these. Meals might be prepared at any time during the day. Evening meals might be prepared at any time between 4 pm and 9 pm. For cooking, Carl normally uses the top hob, grill or oven, and sometimes the microwave oven. The high level cooker hood extractor was rarely used as part of the family cooking practices. Sitting down at the kitchen table and having a meal mostly occurs during the weekends. Meals were however, not usually eaten in the kitchen during the week.

The kitchen has a washing machine located under the worktop and the couple utilises this appliance to perform clothing washing practices (three or four times a week). However, clothing drying practices were not performed exclusively in the kitchen but in different places in the house, at different times. Nevertheless, during the winter, the family clothes were mainly left to dry either in the kitchen or in the garden. On the other hand, during the spring and summer seasons clothes were left to dry either in the main bedroom, ground floor toilet or in the garden.

Data from the household activity diary shows that the kitchen window was opened every time cooking practices took place. However, interview data also reveals that opening the kitchen window was not only the result of cooking practices but also an activity considered necessary to cool down the kitchen. Barbara refers to the kitchen as a “very hot place” (PH2), regardless of the season. Thus, cooling the kitchen involved opening the kitchen window “for most of the day” (PH2) during all three monitored seasons.

In the PH2 household, heating practices were very infrequent during all three seasons, including the winter season. Barbara recalled only turning the radiators on “once or twice” (PH2) during the winter season and only for a short period of time.

c) PH3: Constantly opens the windows to air the house

Claire and Simon are a couple in their early and mid-thirties. Simon is unemployed and Claire is a stay at home mum. The couple has four children living with them - two primary school and two secondary school aged children. Claire also has an older son who visits the family once a month for the weekend. Apart from Claire’s son, the family has no other visitors staying overnight. However, every now and again the family has children’s school friends coming over after school, for a play. The couple explains that their routine involves staying indoors for most of the time as they are new to the area and don’t have many local friends to go out with.

In this household, the main bedroom is the room where Claire and Simon sleep. The couple spend their night time in this room. Claire explained that sometimes she goes to her bedroom from 7 pm and stays there until 7 am. However, the couple prefers to spend most of their day time either in the kitchen, dining room or living room. In terms of ventilation and airing practices in the bedroom, Claire admitted how airing practices are important to her and that she has to open the windows every day for ten minutes to air the house, even during colder seasons. “I just need to get some air into the house … I don't know, I've been brought up doing that. My mum used to do it, so I've been brought up with doing it as well" (PH3).

During the winter season, in addition to opening the bedroom window for ten minutes every day during the daytime, Claire and Simon also felt the need to air the bedroom during the night by keeping their bedroom window opened all night while they slept. For Claire, airing and ventilating the bedroom during the night was not something she thought about but something she did on a regular basis, as part of her routine. These were the words used by Claire to explain the need to air her bedroom during the night - "I love my windows open in my bedroom … I hate sleeping with the windows closed" (PH3).

During the spring and summer seasons, airing and ventilation practices were still important for the couple. However during these two seasons, opening the bedroom window during the daytime for some air, was an activity that lasted for more than ten minutes. For instance, during the summer season, airing practices were intensified, as Claire kept the bedroom window open all day and night.

In this household, the living room is the room where Simon and the children spend most of their day time. Simon uses the living room for watching TV during the day and during the early evening whilst the children use the room for watching TV and playing, outside school hours. On weekends this room is used by all the family members for watching TV.

Airing and ventilation practices in the living room were very similar to those performed in the bedroom. During the winter, the living room window was opened for ten minutes during the day, "just to get some air in" (PH3), and opened all night "on the lock" (PH3). Claire explains that for security reasons and to ensure her family was safe at night, she kept the living room window and other ground floor windows open to the safety lock (open to approximate 5cm). Night time airing and ventilation practices in the living room, during the spring and summer seasons, followed the trend found during the winter season. However, similarly to what was shown in the bedroom, airing and ventilation practices in the living room were intensified, as living room windows were left open throughout the day and night.

Like in the other households, the kitchen in PH3 passive house is used for the performance of daily cooking and clothing washing practices. In addition, the kitchen is also used for the performance of additional practices such as tobacco smoking and frequent tea/coffee making. Claire uses the kitchen daily for food preparation and cooking as she makes breakfast for the children before they go to school (at around 8am), cooks lunch for the couple (at around mid-day) and cooks dinner for her family in the evenings. When performing these cooking practices at mid-day and evenings, Claire mostly uses the grill, the oven and the high level cooker hood extractor appliance. The family rarely have their meals in the kitchen as they prefer to eat all meals at the table in the dining room.

Although airing and ventilation practices in the main bedroom and living room follow similar trends, this was not the case in the kitchen. Opening the window was an activity that took place multiple times in the kitchen as a result of the performance of specific practices. For instance, Claire explained that every time she cooked, she had to open the kitchen window for the entire duration of the cooking activity. Again, she clarified that is not something she thinks about, but it was just something she does. Similarly, window opening activities were triggered by cigarette smoking practices in this household. During the winter season, cigarette smoking was performed regularly in the kitchen by Claire and Simon, who had a cigarette every hour (from 8 am to 9 pm) by the kitchen window. The kitchen window was kept open for the entire duration of this practice and closed back again straight after the couple had finished smoking.

During the other two seasons (spring and especially during the summer season) smoking practices changed slightly. Although the frequency of cigarette smoking during the spring and summer seasons follow the trend observed during the winter season (hourly, from 8 am to 9 pm), the location where this practice was performed varied. During the spring and summer seasons, the location for the couple's smoking practices alternated between the kitchen (by the window), by the front door and by the back door. In all these three locations, the window or door were open for the entire duration of the activity.

Kettle boiling as a result of tea/coffee making practices was another activity which occurred very regularly in the kitchen. The household activity diary shows that the kettle was used hourly, from 7am to 10pm, every day during the monitoring period. The frequency of this activity was very similar during the three different seasons.

Additionally, since the washing machine was placed under the kitchen worktop, this room was also used for laundry practices (performed twice a day). However, clothes were not left to dry in the kitchen. Instead, they were kept to dry in the downstairs toilet during the winter and in the garden during the spring and summer seasons.

In the PH3 household, heating practices were also performed regularly during the winter. Claire explained that the radiators were turned on daily, for about one hour "just to warm it up and then we turn it off" (PH3). However, turning the radiators on as a result of heating practices became something much less frequent during the spring and summer periods.

d) PH4: Understands the passive house concept and knows how it works

Denise and Matt are a couple in their early thirties. Denise is a stay at home mum and Matt works full time, in a skilled job, staying away from home four nights a week. The couple has three children –

two pre-school aged children and one primary school aged child. The family also has guests staying with them regularly. This includes Denise's father who stays with them overnight occasionally as well as a couple of international students who stay with the family for a few weeks every now and again.

The main bedroom is mainly used by Denise and her youngest child for sleeping during the night. Matt also uses the room for three nights a weeks when he is not away for work. Denise's main bedroom routine includes going to the room with her youngest child at around 7.30 pm and settling him to asleep. Sometimes, Denise uses the main bedroom for watching TV (from 8 or 9 pm).

Interview and diary data indicate that during the winter season, ventilation, airing or cooling practices were rare in the bedroom and as a consequence, the bedroom window was kept closed for most of the time, during day and night. Apart from the background ventilation provided by the MVHR system, Denise did not feel the need to ventilate, air or cool down the house. However, this changed during the spring and summer seasons, when Denise used the words "sticky, hot" (PH4) to describe how it felt living in the house. During those two seasons, ventilation and cooling practices became very frequent in the bedroom. Denise aired the bedroom daily by opening the bedroom window, "to the latch" (PH4) (or approximate 5cm) throughout the day and night time. Sleeping with the window open all night was something that Denise did during both spring and summer season, to cool down the bedroom. As Denise explained, "I can't sleep if I haven't got the window open because it is too warm" (PH4).

Denise seemed to better understand the indoor environment of the passive house when compared to the other four families. The interview and diary data also show data during the spring and summer seasons, all the first and second floor windows were kept open all day whilst all the ground floor windows were kept closed. When asked why she was opening only the windows on the first and second floor during the spring and summer seasons, Denise explained "the heat rises, doesn't it? The top floor was the hottest … the middle floor was still very hot … I would say the bottom floor was probably the most comfortable" (PH4).

Ventilation and cooling practices in the PH4 household was not only performed by means of window opening. Denise also explained that she occasionally boosts the MVHR ventilation:

> *"I done it [boosted the ventilation on MVHR system] a couple of times last week, because it got really warm in here. I will turn it on before I go to bed. It does like a 15 minutes boost and then it goes back to normal. Sometimes I put it on just before I go to bed just to cool the bedroom down a little bit" (PH4, spring interview).*

In Denise's opinion, the living room is the room mostly used in the house. It is used daily by the two pre-school aged children (from 8 am to early evening) and used by Denise in the evening (until 10 pm). The whole family mostly uses the living room for watching TV during the day and evening.

Similarly to the main bedroom, ventilation and airing practices were rarely performed in the living room during the winter season. Interview and diary data show that during that period the living room window was never opened. Nevertheless, ventilation and cooling practices became more frequent during the spring and summer seasons. In addition to opening the living room window all day, Denise would occasionally boost the MVHR ventilation in the evenings, hoping to ventilate and cool down the room.

The kitchen in the PH4 household is used daily for preparing meals and cooking and for clothing washing. Denise uses the kitchen to prepare breakfast before taking her child to school (8 am) and to cook dinner in the evening (from 4.30 to 5.30 pm). Hob, oven, cooker hood extractor and microwave oven are the main appliances used for the performance of cooking practices. Meals, however, are not eaten in the kitchen. Eating takes place at the table, in the ground floor dining room. Clothing washing and drying practices are also performed in the kitchen, on a daily basis, using washing machine and tumble dryer appliances. Furthermore, tea making practices are also regularly performed (around four times a day) in the kitchen, using a kettle appliance.

Although, during the winter ventilation and airing practices were rarely performed in the kitchen, cooling practices were seen as occasionally necessary when particular cooking practices took place. For instance, Denise explained that she would open the kitchen window only if she was cooking a roast dinner for a couple of hours "as it gets really warm" (PH4). Other than these sporadic occasions, Denise and other family member did not feel the need to ventilate or cool down the room. During the spring and summer seasons, ventilation and cooling practices in the kitchen did not change much when compared with the winter period.

Furthermore, heating practices were performed during the winter season only, usually on the first and second floor (where the living room and main bedroom are respectively located) by turning the radiators on in the morning for about 20 minutes. Denise felt that heating the two upper floors for 20 minutes in the morning would help to warm up the part of the house where the family spent most of their day.

e) PH5: Opens windows for cooling practices

Emma and James are a couple in their mid-thirties. Emma works during school hours for three days a week, away from home in a skilled job. James is self-employed, working full time, away from home, also in a skilled job. The couple has three children - two primary school aged and one secondary school aged, who live with them. Because of work, lifestyle and other commitments, Emma explains that during the week days, there is rarely anyone in the house during school hours. Weekends however, appear to be more spontaneous for the family. They might go out or stay indoors, depending on the weather. The family also enjoys hosting guests, normally having friends around during the day every now and again.

The main bedroom is the room where the couple sleeps and it is used only during the evenings. Apart from sleeping, the couple also watches TV in the main bedroom, for about 30 minutes before they go to sleep.

Although only spending the night time in the bedroom, ventilation practices performed by Emma, ensured that the bedroom had a constant flow of outdoor air. During the winter, the bedroom window was kept open, on the lock (approximate 5 cm), all day and night. Opening the windows all day and night was not only the result of ventilation practices performed by the couple but also an activity trigged by cooling practices, seen as necessary to cool down the room.

The living room is described by Emma as “the family room” (PH5) as householders use this room on a daily basis. However, the family mainly uses the living room for watching TV, which usually takes place before school hours (from 6 to 8 am) and after school hours (4.30 to 10 pm). Other practices (e.g. eating, doing homework, playing) are normally performed in the dining room.

Interview data suggest that although during the winter season, the living room was considered “the family room” as householders spent much of their time in there, their routines changed during the spring and summer seasons. During these two warmer periods, family members started to spend less time in the first floor living room and more time in the ground floor dining room, since the latter gave the family direct access to the outdoor garden. Therefore, living room practices (e.g. watching TV) became less frequent during the spring and summer seasons, whilst dining room and garden practices (e.g. relaxing, having a barbeque, playing with the children) were intensified during these two seasons.

During all three seasons, ventilation and airing practices were performed regularly in the living room, by opening the window “just to circulate the air” (PH5). The couple did not feel that the MVHR system, on its own, was providing sufficient air in the room, therefore opening the window was seen as necessary. “It doesn’t do anything though [MVHR system]. If you are sat here with the windows closed you start to get stuffy” (PH5).

Although ventilation and airing practices were very frequent during all three monitored seasons, interview and diary data suggest that during spring and summer these practices became more intense as the living room window was kept open all day and night whereas during the winter season, the window was open only when family members were using the room.

In the PH5 household, the kitchen is mainly used to prepare meals (breakfast) before the children go to school (8 am) and to cook the family dinners (5 pm). Cooking practices are performed most nights using the hob, oven, microwave and cooker extractor appliances. Tea making also takes place in the kitchen (using kettle appliance) a few times a day. Other practices such as clothing washing and drying also take place in this room, with the use of washing machine and tumble dryer appliances.

During all three monitored seasons, ventilation, airing and cooling practices were not frequently performed in the kitchen. In this room, ventilation and airing practices only took place during specific cooking practices. For instance, Emma explained that during that period, she would open the kitchen window only if she was cooking “something that’s really going to smoke the house out” (PH5) or something “smelly” (PH5), otherwise, the kitchen window was kept closed.

Keeping the kitchen window closed for most of the time, during the winter, spring and summer seasons was something Emma did to ensure a safe environment for her family. “I rarely open the kitchen window, very rarely. I am just scared of forgetting they are open and then people will get into the house” (PH5).

Although the kitchen window was rarely opened during all three monitored seasons, which limited the indoor/external air exchange, interview data also show that was not the case elsewhere on the ground floor. While the family often used the ground floor dining room for eating meals, hosting guests, relaxing, doing homework and playing, the external door was left fully open. This was something that happened during the spring and summer season, but not as often during the winter period. Emma explained “the door has been pretty much open the whole time the weather is nice and we are in” (PH5).

Regarding heating practices, these changed throughout the three monitored seasons, being more frequent during the winter, less frequent during the spring and non-existent during the summer. For instance, the couple kept the radiators constantly on throughout the house during the winter, whilst the ground floor rooms were heated (kitchen, dining room and toilet), during the spring only. Additionally, radiators were kept off, throughout the house during the summer season.

6.3.2. Indoor air climate and indoor air quality in passive houses: Understanding differences in the indoor environment using social practice theory

The findings from Chapter 4 have shown that differences do exist in the indoor environment of passive houses. Evidence was presented suggesting three main points. First, it was suggested that there are differences in the indoor climate and indoor air quality of different rooms in the same passive house (bedroom, living room and kitchen). Second, it was shown that the indoor climate and indoor quality in passive house rooms, in the same house, varied following seasonal changes. Third, it was shown that even identical houses (identical layout, building volume and solar orientation) provided a different indoor climate and indoor air quality.

The five narratives presented in this chapter also show that many differences exist between the everyday practices of the families living in the passive houses. They also show how these five families used different rooms to perform various different practices. Although there were some similarities in the practices performed in the three monitored rooms (e.g. the bedroom was mostly used for sleeping, the living room was often used for watching TV, and the kitchen was mostly used for cooking), these practices were not performed in exactly the same way and at the same point in time by all five families. For instance, whilst the kitchen was considered “the place to come” for the passive house PH1 householder, as this room was used regularly and where practices were performed following a more strict routine, the family in the identical passive house PH2 used the kitchen more sporadically.

Importantly, while performing these various practices, the five families interacted with ventilation controls and others appliances, in different ways. For example, window opening in the kitchen was solely the result of very specific cooking practices in passive house PH5, whilst in the identical passive house PH3, the kitchen window was opened multiple times during the day when any cooking and smoking practices were performed. House appliances were not only used more often by some families than others (e.g. kettle appliance for tea/coffee making) but, in some cases, they were also used for different practices altogether. For instance, during the winter season, PH1 family used the radiators daily for drying clothes, while other passive house families used them for heating the house.

The five narratives also show that practices were not static throughout different seasons, but in many cases they were modified during the course of the year. In some instances practices were intensified (e.g. ventilation and airing practices became more frequent during the spring and summer seasons), diminished (e.g. heating practices became less frequent or non-existent during the summer), or altered (e.g. occupants who only smoked in the kitchen during the winter started to smoke in both kitchen and garden during the spring and summer). All these differences have contributed to the differences in the indoor climate and indoor air quality found between the five passive houses.

For instance, the kitchen had overall higher temperatures when compared with the other monitored rooms. The analysis undertaken in Chapter 4 suggested that the higher temperatures found in many passive house kitchens, when compared with bedroom and living room, can be attributed to the everyday practices performed by house occupants, and in particular practices which involve the use of electrical appliances. This is due to the fact that electrical appliances convert electrical energy into heat energy, which in turn contributes to rising indoor temperatures (Parsons, 2001).

Cooking and food preparation practices were performed daily (from one to three times a day) using electrical appliances (hob, grill, cooker, cooker extractor, and sometimes microwave oven). Laundry washed using an electrical washing machine appliance, was also performed by all five householders, on a daily basis by some (e.g. PH1) and three times a week by others (e.g. PH2). Tea/coffee making practices, using kettle appliance was performed many times a day by some householders (PH1 and PH3) and occasionally by others (PH2, PH4 and PH5).

Indeed, passive heat gains from house appliances and occupants' activities are a central part of the passive house concept (International Passive House Association, 2010). Nevertheless, the data show that summer temperatures in passive house kitchens were well beyond 26^oC. Figure 4.3 in Chapter 4 shows summer temperatures peaking beyond 30^oC in the kitchens of passive houses PH1, PH2 and PH4. It is important to reiterate that none of the studied passive house rooms had any sort of solar shading (externally or internally). Although the users' manual advised occupants to draw the curtains during the day during hot seasons, none of the passive house occupants indicated they had done so. Therefore, it is suggested that the lack of shading on the kitchen windows (which were south and west facing) also contributed to the very high temperatures observed there during the summer.

Additionally, practices such as cooking, tea/coffee making, dish washing and clothes washing, which were exclusively performed in the kitchen, do contribute to releasing water vapour into the air (TenWolde & Pilon, 2008), consequently increasing relative humidity levels. All these four practices were performed in all passive house kitchens, multiple times a day in some cases. Furthermore, other householders have indicated that they performed additional practices which may have contributed to increase in RH in the kitchen. For instance, the PH1 family also ironed clothes daily in the kitchen, using an iron with a steam function (which produces water vapour). This practice is interesting since the PH1 kitchen seemed to have the highest levels of RH, during winter and spring seasons when compared with the other houses. This strongly suggested that ironing clothes in the kitchen of passive house PH1 contributed to the higher RH observed there.

Data findings also revealed that, in most cases, the monitored bedrooms and living rooms presented different levels of CO_2. Generally, significantly higher CO_2 levels were found in the bedroom during the winter and spring seasons, whilst lower CO_2 levels were found in the living room during the summer season (figures 4.20, 4.21 and 4.22 in Chapter 4). Since CO_2 is often considered to be a surrogate for the rate of ventilation per occupant (Seppänen, 1999), this indicates that a room showing higher CO_2 levels had less frequent indoor to outdoor air exchange when compared with a room with lower CO_2 levels (the passive house rooms had similar occupancy levels). Analysis in Chapter 4 has suggested that occupancy levels are a strong explanatory variable for the CO_2 variations between the monitored bedroom and the living room, which indicates that family members were using the living room more often during the summer than during the spring and winter seasons.

Findings from Chapter 4 also show that the quality of the indoor environment of passive houses varied according to different seasons, as the indoor climate and indoor air quality in each of the three monitored rooms changed during the course of the year. Temperature, RH and CO_2 levels were very different during the three monitoring seasons, with the summer period showing the highest levels of temperature and RH and the lowest levels of CO_2.

Although the high indoor temperatures and RH levels observed during the summer can be explained by the rise in external ambient temperatures (Nguyen et al., 2014) and the consequent increase in solar gain through the building fabric and especially through glazed areas (Ralegaonkar & Gupta, 2010), it is not unreasonable to expect that some occupants' practices, which were intensified during the summer, have also somewhat contributed towards those higher levels observed. For instance, the more frequent window and external door opening during daytime, as a result of ventilation, airing and cooling practices, also have contributed to the higher indoor temperature observed during the summer. This is due to the fact that during hot summer months, daytime external temperatures can often exceed indoor temperatures resulting in additional heating gains in passive houses when window and external door opening is performed more frequently (Mlakar & Strancar, 2011).

Although it may seem counter-intuitive, the idea that window opening during the summer have contributed to the increase in indoor temperature, is not a new concept and has been acknowledged elsewhere (Blondeau et al., 1997). For instance, Mlakar & Strancar (2011) have demonstrated that during summer months, opening passive house windows during the daytime resulted in a rise of indoor temperature. Accordingly, the authors have suggested that during summer months, window opening as a means of ventilating and cooling down the building, should be done at night as outdoor temperatures were likely to be lower than the indoor temperatures.

Although the night ventilation strategy was advised on the users' manual as a mean to cool down the passive house dwellings during the summer months, the occupants of David's Court passive houses were not aware of it. When the indoor temperatures started rising and the occupants felt very uncomfortable, they complained to the Housing Association. The advice to open the windows during the night and to draw the curtains during the day was then given to the occupants by the Housing

Association representative. However, most occupants seemed very sceptical and reluctant to follow the advice received.

Regarding the CO_2 levels observed during the three monitoring periods, the data findings revealed that in general, both the monitored bedroom and the living room had the lowest CO_2 levels during the summer season. As previously pointed out, practices which resulted in additional indoor/outdoor air exchange can help in explaining the differences in indoor CO_2 observed during different seasons.

Interview and household activity diary data show that practices that contributed towards additional indoor/outdoor air exchange (e.g. ventilation, airing and cooling) involving window and door opening, were much less frequent during the winter season when compared with the other two periods. During the winter, opening windows only occurred occasionally as a result of cooling practices (PH2, PH4), and briefly as a result of smoking practices in the bedroom (PH1). When ventilation practices were performed more often (PH3, PH5), the window was kept open only by a 5cm gap. During the spring, and especially during the summer season, ventilation and cooling practices were intensified, as passive house occupants opened the windows and external doors more frequently to cool down the house. The increase in the frequency in which windows and external doors were opened and kept open were likely to have increased the outdoor/indoor air exchange during the spring, and especially during the summer season, could have contributed to the lower levels of CO_2 observed in both the monitored bedroom and living room of passive houses.

Finally, findings from Chapter 4 also show that even identical passive houses (with identical layout, building volume and solar orientation) did not present a similar indoor environment. Both groups of identical passive houses PH1/PH2 and PH3/PH4/PH5 presented a dissimilar (statistically significantly different) indoor climate and indoor air quality in most cases.

For instance, passive house PH1 presented much higher CO_2 levels in the monitored bedroom during the winter season, compared with the identical houses PH2, during the same period. Higher concentrations of specific VOC species were also found in passive house PH1. In some cases, the difference was twofold.

The research findings suggest that different practices have contributed to the higher CO_2 levels and higher concentration of VOCs (including decane) observed in the monitored bedroom of passive house PH1, when compared with what was observed in the identical passive house PH2. For instance, higher CO_2 levels and higher VOC concentrations can be explained by lower ventilation levels in the bedroom, as ventilation (indoor/outdoor air exchange) can help to dilute air pollutants (Seppänen & Fisk, 2004) and reduce indoor CO_2 levels (Chatzidiakou et al., 2015). Interview and occupant diary data show that during the winter, ventilations practices were rare in the bedroom of passive house PH1. Nevertheless, the bedroom window was occasionally opened, at evenings and only for brief periods, as a result of smoking practices. On the other hand, ventilation practices were more frequent in the monitored bedroom of passive house PH2, during the same period. Although the family kept the window closed, for most of the time during the evening as they wanted to avoid “gnats” coming through the window, ventilation practices were performed more often during the day, in an ad-hoc fashion, when the family “felt like it” (PH2).

The higher concentration of some VOC species found in the monitored bedroom of passive house PH1 (e.g. alpha-pinene and limonene) can also be associated with cleaning and personal hygiene practices performed by the family. As explained in Chapter 4, alpha-pinene and limonene are naturally occurring terpenes which are usually used in cleaning and household products (Brooks & Davis, 1992; Sarigiannis et al., 2011). Although there is no evidence from this study on the possible practices associated with different levels of alpha-pinene and limonene, it is possible that the family in PH1 passive house used cleaning and personal products containing such VOCs more often, or in higher quantities compared with the family in passive house PH2.

Additionally, since decane, a VOC species which can be released from cigarette smoking, was only found in the monitored bedroom of passive house PH1, it is also likely that the everyday cigarette smoking performed in the monitored bedroom by two of the house occupants in PH1, have contributed to the presence of this compound and its high concentration. The occupants of the other four passive houses claimed that they did not smoke in the bedroom.

Regarding indoor climate differences in identical passive houses, findings from Chapter 4 also show that there was a significant difference in temperature between identical passive houses, especially during the summer season. For instance, the living room of passive house PH4 showed much higher summer temperatures than the living room of identical passive houses PH3 and PH5. This is interesting since Denise, one of the occupants of passive house PH4 seemed to have a better understanding of the indoor environment of passive houses, when compared with the occupants of the other four passive houses. This suggests that a better understanding or knowledge of the indoor environment of passive houses do not automatically warrant the provision of adequate indoor climate levels. How knowledge (or in this case, institutionalised knowledge) shapes the performance of practices and consequently how it has contributed to different levels of indoor climate and indoor air quality in the passive houses will be discussed in more detail in the subsequent section (6.3.3).

Interview and occupant activity diary data show that the summer ventilation and cooling practices in the living room were somewhat different in the PH4 passive house when compared with the other two identical passive houses. In the PH4 passive house, the living room window was left open all day to cool down the room, being closed at night time. On a few occasions at night, Denise (PH4 occupant) also boosted the MVHR ventilation aiming to cool down the house. PH4 was the only passive house in which occupants claimed to have used the MVHR boost function. On the other hand, although occupants of passive house PH3 and PH5 also left the living room window open for most of the day, they also left the living room and other windows open (by a few centimetres) during the night, in order to cool down the house.

The additional night ventilation during the summer season, through the means of opening the windows (by a few centimetres) performed in the living room by occupants of the passive houses PH3 and PH5 has contributed to significantly lower temperatures in the living room of these two passive houses when compared with the living room of passive house PH4. The analysis undertaken in Chapter 4 using the analytical framework supports this claim.

As mentioned earlier, window opening during the night in hot summer days has been considered a useful and necessary strategy to cool down passive house rooms. Conversely, window opening during the day in hot summer days can contribute towards increasing the indoor temperature in passive houses (Mlakar & Strancar, 2011). The research findings suggest that the ventilation and cooling practices performed during the night by occupants of passive houses PH3 and PH5 contributed to the lower living room temperature during the summer season. Although the family in passive house PH4 admitted to using the MVHR ventilation boost on a few occasions during the summer, this does not appear to have made a great impact in lowering the living room temperature when compared with night time cooling by window opening.

6.3.3. Investigating the elements of practice

The five family narratives and the mixed methods analysis presented in the two previous sub-sections provided some valuable insights into how everyday practices have contributed to the different levels of indoor climate and indoor air quality found in the three monitored rooms, in the five studied passive houses. In the following sub-section, each of the four elements holding practices together will be discussed. Since these four elements and their inter-relationships can shape a practice (transform, destroy, create) (Foulds et al., 2013), it was considered very useful to present them in conjunction with the socio-material configurations of each of the passive houses (Gram-Hanssen, 2010a). It was also considered interesting and useful to discuss how each of these elements have shaped the practices they are part of, and in turn, how these may have influenced the findings from the indoor climate and indoor air quality monitoring.

a) Technologies and artefacts

Technologies and artefacts are considered very important elements of the social practices related to indoor climate and indoor air quality in passive houses. Technologies especially, were not only part of the passive house building (e.g. MVHR system, windows, doors, super insulation) but they were also in many passive house rooms (e.g. cooker and washing machine in the kitchen, TV in the living room, TV and Xbox in the bedroom, radiators in all rooms). Nevertheless, technologies were not the only material elements that held indoor climate and indoor air quality related practices together. Some artefacts (e.g. cigarette) were also part of social practices (e.g. smoking) which may have influenced indoor air quality.

The relation between social practices and technologies/artefacts should not be understood as material elements determining social practices (Kirsten Gram-Hanssen, 2010a). Instead, material elements could be seen as a structure which enables and constrains practices and which influence how practices are performed.

Technologies such as windows, external doors and the MVHR system were central elements for the performance of ventilation, cooling and airing practices in passive houses. For all five families, ventilating, airing and cooling the house involved physical interactions with these technologies. Nevertheless, how these families interacted with these specific technologies varied from family to family. For example, during the winter season some families stated that they "always open the windows… just for about ten minutes during the day" (PH3), whilst others (e.g. PH4) did not feel the need to constantly open the windows during the same period. It is interesting to note how ventilation practices influenced the frequency of window opening behaviour, which in turn contributed to differences in the indoor air quality in identical passive houses. Figure 6.1 shows the CO_2 levels in the monitored bedroom of passive houses PH3 and PH4, during the two weeks monitoring period, in the winter. It indicates that CO_2 levels in the bedroom of passive house PH3 decreased to nearly 400 ppm daily, sometimes multiple times a day. This suggests that the more frequent window opening, as a result of ventilation practices performed by the PH3 householder, contributed to having on many occasion CO_2 levels similar to those normally found outdoors (Apte et al., 2000).

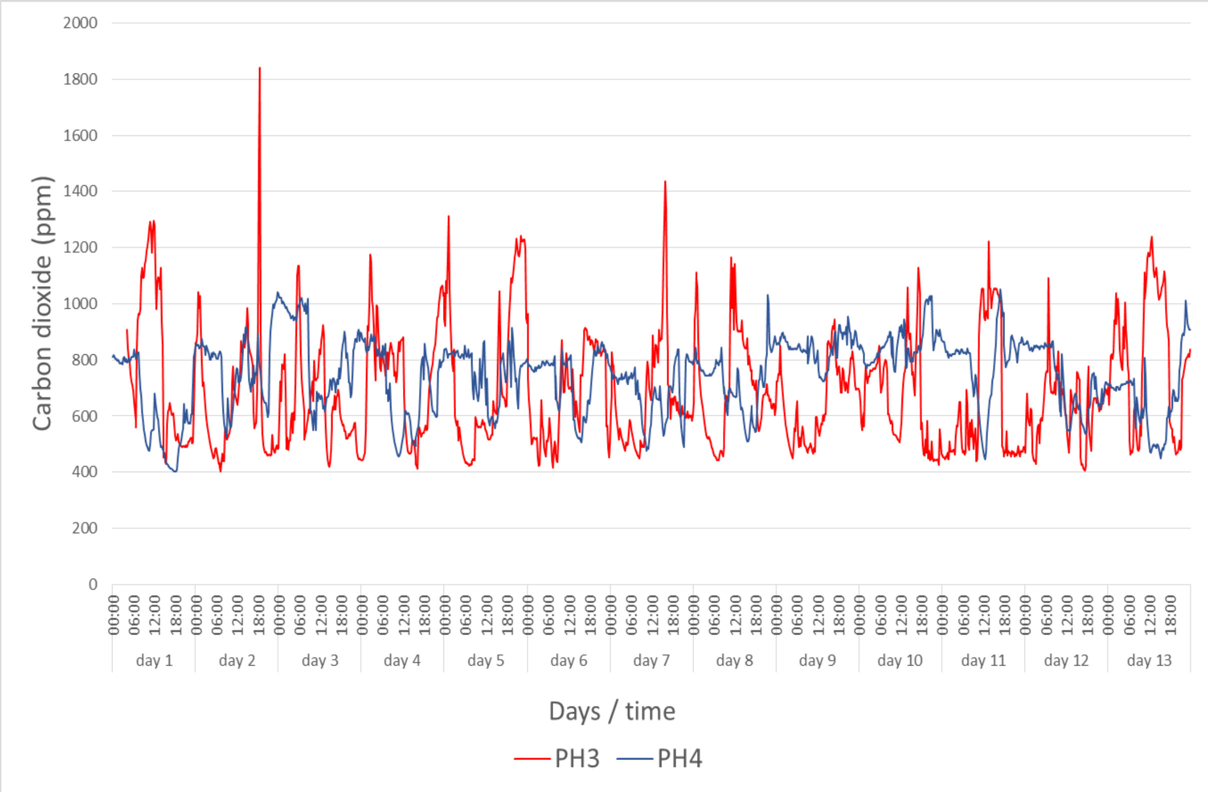


Figure 6.1 Daily CO_2 levels in the bedroom of passive houses PH3 and PH4 during the winter season

Findings from chapter 4 have revealed that in many cases and especially during the summer season, the kitchen in passive houses had the highest temperatures among all three monitored rooms. It is not difficult to understand how practices performed in the kitchen, many of which involved the use of heat generating technology (e.g. electrical appliances), contributed to the higher temperatures observed. In all passive houses, cooking practices involved the use of hob, oven and cooker hood extractor, whilst clothes washing involved the use of washing machine appliance. In addition to those, in some passive houses dish washing was performed with a dishwasher appliance (e.g. PH1) and clothes drying was performed with a tumble dryer appliance (e.g. PH5).

Furthermore, the way in which families performed these practices (e.g. the frequency with which certain practices were performed and the sort of technology used to perform them) are also relevant when considering how they have contributed to differences in the indoor environment of passive houses. For instance, figure 6.2 shows that winter relative humidity (RH) levels were generally higher in PH1 kitchen compared with the kitchen in the identical passive house PH2.

Interview and occupant activity diary data show that although certain practices were performed in both kitchens, the frequency with which they were performed and the technology used to perform them were not quite the same. For instance, in the PH1 kitchen cooking was performed twice a day (breakfast and dinner) and dish washing practices were performed once or twice a day using electrical appliances, hob/cooker/extractor and dishwasher respectively. Furthermore, diary data indicate that during the winter period Anna, in PH1, also ironed clothes in the kitchen on a daily basis, using a steam generating iron appliance. On the other hand, although cooking practices in the PH2 household involved the same appliances (hob/cooker/extractor), they were performed less frequently, only once a day (dinner). Dish washing did not involve an electrical appliance, but other artefacts (e.g. sponge, liquid soap). Furthermore, in PH2 household ironing practices were rarely performed, albeit when they were, it did not take place in the kitchen.

All these three practices (cooking, dish washing and ironing), combined with the technology which enabled their performance, and which can release water vapour in the indoor environment (TenWolde & Pilon, 2008) have contributed to higher RH levels in the kitchen of the PH1 passive house.

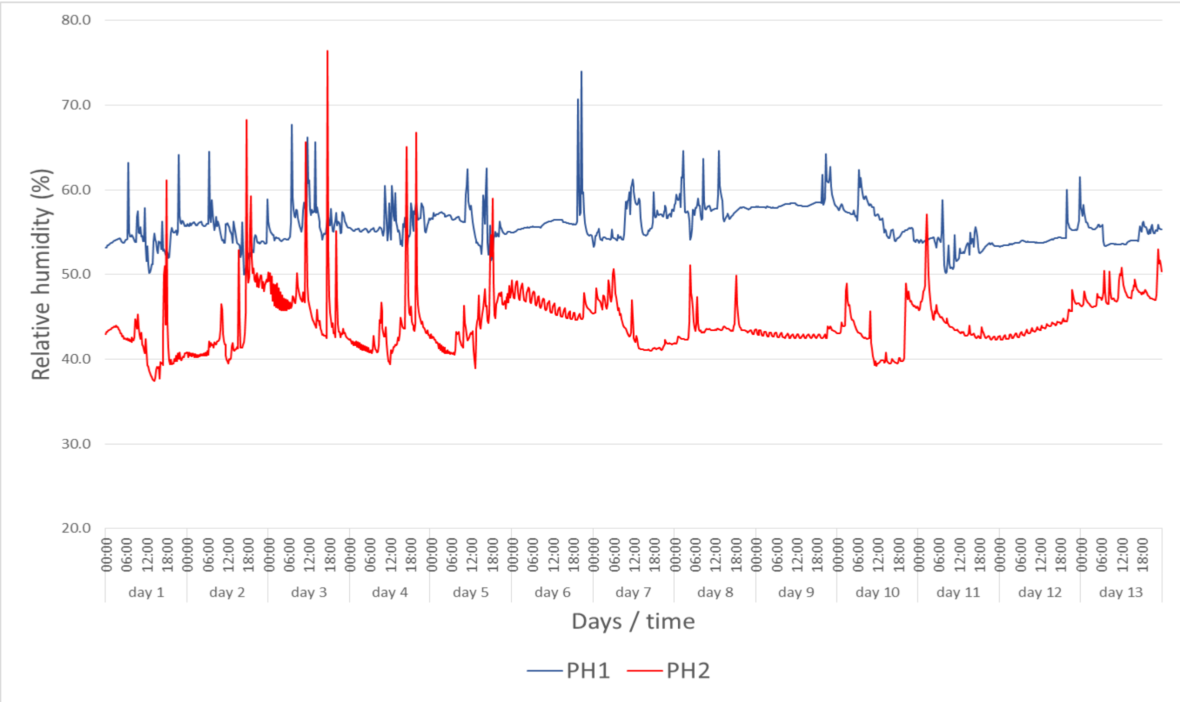


Figure 6.2 Daily relative humidity (RH) levels in the kitchen of passive houses PH1 and PH2 during the winter season

b) Institutionalised knowledge

Institutionalised knowledge regarding the passive house and its indoor climate and indoor air quality were established by and disseminated through a few institutions. The Passivhaus Institute, research organisations, passive house providers (e.g. Housing Association), house designers (e.g. architects, electrical and mechanical engineers) are some of the institutions which defined rules and provided knowledge regarding the passive house and its indoor environment. However, the institutionalised knowledge and rules described here are understood as an element which influenced social practices in different ways and not as a tool for behaviour change based on information provision (Gram-Hanssen, 2013).

The institutionalised knowledge provided to passive house occupants, which mainly originated from the Housing Association provider and house designers (e.g. mechanical engineer) seemed to have had a very small influence on how practices were performed. This might be due to the evidence suggesting that the knowledge provided by these parties lacked effectiveness and impact. In some cases, information given to occupants was not only contradictory but it was also delivered in large volumes, which resulted in occupants becoming disengaged with what was presented to them.

For instance, when the occupants first moved into the passive houses, they were given an induction pack which included the house manual, a large document which explained the passive house and its technologies, together with technical manuals for the heating and MVHR systems. Nonetheless, all passive house occupants admitted they did not read through any of the manuals provided by the Housing Association. The sheer amount of information contained in the manual appeared to be one of the reasons why occupants had somewhat ignored the induction pack.

> *"It is huge [induction pack]. It would probably take me about six months to read it. It is massive" (PH4).*

Nevertheless, smaller doses of information about the passive house, its technologies and indoor environment were also provided via external training sessions (normally held in the local community centre) and home visits (from a Housing Association representative and from the mechanical and heating engineer). However these did not prove to be an effective way of disseminating institutional knowledge about the passive house due to two main reasons. First, the external training sessions only attracted a very small number of participants (e.g. only three passive house residents attended a training session held in the spring 2015 from the 51 passive house dwellings). Second, during the home visits, occupants were given contradicting information by different parties. For instance, during these visits, occupants had very different information on whether and when to open their windows, whether to switch the radiators on and how to set up their heating system.

Because of the discrepancy in information provided by these institutions, passive house occupants seemed to rely more on their previous knowledge and experiences about ventilation, heating and indoor comfort, when performing practices related to the indoor climate and indoor air quality in their houses. Occupants' previous knowledge and experiences, described by the social practice theory as 'embodied habits' (which will be explained in more detail in the next sub-section), seemed to have had a greater influence on how occupants used the passive houses and its technologies than the knowledge provided by institutions.

Nonetheless, one of the passive house occupants, Denise in passive house PH4, also used other institutions as a source of knowledge. Before moving into the new passive house, Denise undertook an internet based research to learn more about the passive house concept. Denise explained that as soon as she was told by the Housing Association that the family was going to move into a passive house, she decided to find out more about the house. Denise indeed seemed to have a better knowledge of the passive house, compared with the other families. This knowledge also appeared to have influenced her ventilation and cooling practices as she was the only householder to use the MVHR boost to cool the house and change the MVHR settings as part of her ventilation practices.

On the other hand, this institutionalised knowledge obtained by Denise, and incorporated into her everyday ventilation and cooling practices did not necessary provide the PH4 household with a cooler indoor environment during the warmer season. As noted on figure 6.3, PH4 living room had higher temperatures during the summer when compared with the other identical passive houses PH3 and PH5. As previously mentioned, the significantly higher temperatures observed in the living room of the passive house PH4, when compared with the living room of the passive houses PH3 and PH5, can be explained by the differences in ventilation and cooling practices performed by the households: PH4 occupants did not open the living room windows to ventilate the room during the night, while occupants in PH3 and PH5 passive houses did.

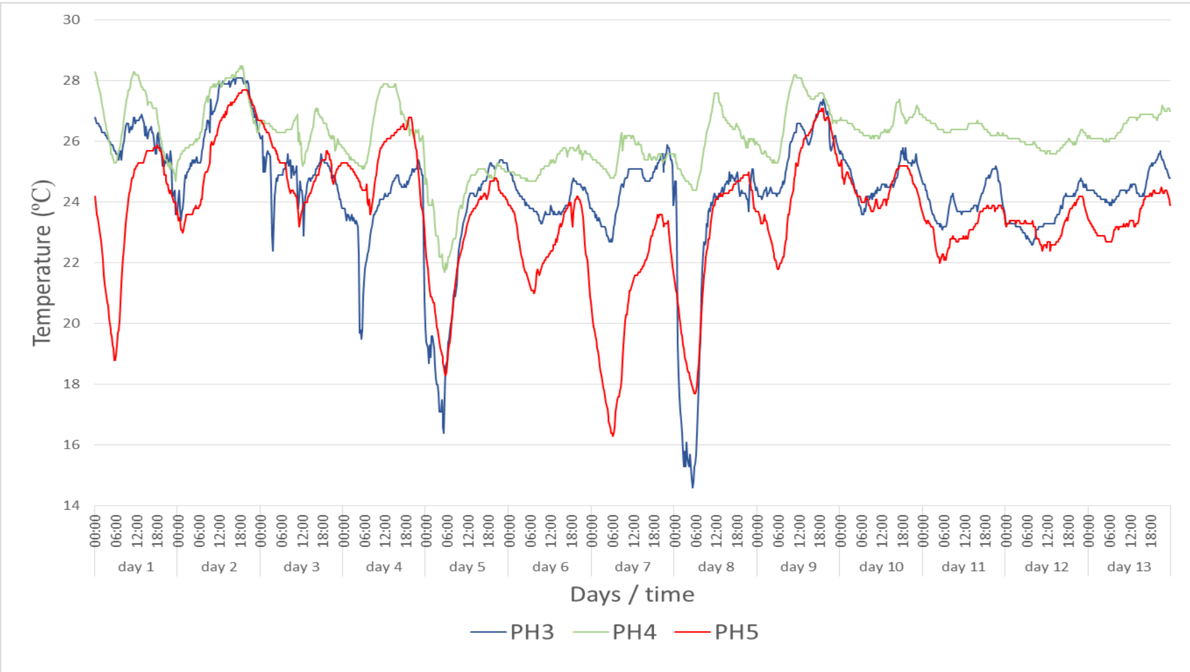


Figure 6.3 Daily temperature levels in the living room of passive houses PH3, PH4 and PH5 during the summer season

c) Embodied habits

Embodied habits are an important element of practices associated with the indoor climate and indoor air quality in passive houses. Different householders have different habits which influence how (e.g. in which ways, how often, where) they interact with technologies and artefacts which influence practices, which in turn may contribute to different levels of the indoor climate and indoor air quality in passive house rooms.

In relation to ventilation and airing practices, such embodied habits were mainly associated with unconscious decisions as well as experiences from previous homes or from childhood. For instance, for Claire in the PH3 passive house, daily window opening throughout the house was not something she thought about but it was a habit which has been part of her life. As Claire explained “I have been brought up to open windows. My mum used to do it, so I have been brought up doing it as well” (PH3). Similarly, Barbara in PH2 passive house explained her window opening habit as an unconscious decision: “I don’t think about opening windows. I don’t think about anything if that makes sense? I would just walk over to the window and if I am standing there it might get opened” (PH2).

Nevertheless, conscious decisions regarding window opening also seemed to have influenced ventilation, airing and cooling practices on some occasions. For instance, although Barbara in passive house PH2, explained that for her window opening was an everyday unconscious habit, she also admitted that during winter evenings she was deliberately leaving the bedroom window closed as much as possible. Such action was considered necessary to stop insects coming in through the bedroom window during the night as well as to reduce the noise generated from a train railway line nearby.

Furthermore, it is interesting to note how other practices, not directly associated with ventilation (e.g. cooking and smoking) were also influenced by embedded habits of window opening. Many passive house families admitted to open the kitchen window every time they cooked. Others acknowledged they opened the bedroom window every time they smoked (PH1). These families post-rationalised these actions as something they just do when performing those practices (cooking, smoking).

d) Meanings and engagements

This element of practice implies that performing a particular practice means something to the people performing it, and that there is a goal or reason guiding the practice (Gram-Hanssen, 2013). However, the same practice can hold different meanings to different people, which may influence the performed practices in different ways.

For some passive house families, ventilating and airing the house meant having fresh air in, or allowing the ingress of fresh air. For instance, to Claire in passive house PH3, who daily ventilated and aired the house during day and night (by opening windows), ventilation meant freshness, or fresh air coming into the house on a daily basis. This feeling of freshness was not only important to Claire during warmer seasons but it was something to be experienced throughout the year.

However, ventilation and airing practices can also hold other meanings or, in some cases, a combination of different meanings, which contributes to the same practice (e.g. ventilation and airing) being performed differently by other passive house families. For example, although Anna in passive house PH1, also related ventilating and airing practices with fresh air, these two practices were very less frequent in this household. In the PH1 passive house, windows were kept closed at night, during all seasons. For Anna, ventilating the house, during the night also meant the provision of an unsafe environment for her family, as she worried that by leaving the windows open during the night might result in burglars entering the house.

Furthermore, meanings related to what certain practices provided for the family also influenced the frequency of homemaking practices (e.g. cooking, dish washing, clothes washing, laundry drying). For example, in the PH1 household, cooking, dishwashing, clothes washing and ironing were practices performed on a daily basis, with some of them being performed twice a day. For Anna, it was important to provide the children with two cooked meals a day (breakfast and dinner). Perhaps this was perceived as a healthy habit. Since two meals were being cooked, it was also considered necessary to wash dishes twice a day to maintain a clean house. In addition, it was also important to Anna to wash clothes twice a day, as she not only wanted to provide the children with clean clothes daily, but she also wanted to ensure that Daniel had clean working overalls every morning. The meaning of good homemaking was part of Anna’s laundry practices.

6.4. Social practices of occupants and the possible outcomes in passive house rooms

The previous sections of this chapter have shown how different social practices were performed by five families and how these practices may have contributed to the quality of the indoor climate and indoor air quality in passive house rooms. In addition, it was also explored how the four interconnected elements, which hold practices together, have shaped social practices, thus contributing to the differences in the indoor climate and indoor air quality observed in similar rooms, in different passive houses.

As revealed by the review of the epidemiological and other health related published literature undertaken in Chapter 5, some adverse health outcomes were associated with certain levels of indoor climate and indoor air quality parameters. The findings from the literature review have provided some evidence suggesting that the indoor environment of buildings, and more specifically, the indoor climate and indoor air quality of buildings can indeed contribute to ill health.

Therefore, since evidence from this thesis chapter has suggested that occupants' practices in passive house rooms have contributed to differences in the indoor climate and indoor air quality (including differences observed between identical passive houses), it is reasonable to suggest that the social practices of passive house occupants have also contributed to different levels of risk of exposure to adverse health outcomes.

For instance, when comparing with the occupants of passive houses PH3 and PH5, occupants of the identical passive house PH4 were at a higher risk of eye irritation and upper tract respiratory symptoms from exposure to high CO_2 levels during the winter. The research findings suggest that the CO_2 levels were higher in passive house PH4 because the occupants opened the windows less often than the occupants in the other two identical passive houses. Nevertheless, the passive house users' manual given to householders stated that opening windows during cold months was unnecessary and not advisable.

The argument brought forward here does not imply that the social practices of passive houses occupants are a determining factor for their health. Instead, it is suggested that the social practices of passive house occupants are a contributing factor to the possible risks of adverse health outcomes that dwelling occupants may be exposed to. The word contributing is used here since other factors have also influenced the indoor climate and indoor air quality of passive houses, consequently also contributing to occupants' risk of exposure to adverse health outcomes. For instance, different choices of furniture, furnishings or cleaning products have contributed to different VOCs species and varying VOCs levels being released indoors (Rothweiler & Schlatter, 1993), as shown in Chapter 4.

Because the social practices of control houses occupants were not investigated as part of this thesis, it was not possible to explore whether the differences observed regarding the quality of the indoor environment between rooms in passive houses and control houses were also attributed to the contribution of occupants' practices in control houses. Consequently, it is not possible to strongly affirm that everyday practices in control houses contributed to the different levels of health risks that occupants were exposed to, when compared with passive houses.

Nevertheless, it is possible to suggest that occupants' practices in passive houses have contributed to some of the differences in the quality of the indoor environment observed between passive houses and the corresponding control houses.

For instance, the living room of the 4 bed passive house PH4 had temperatures over 26°C for longer periods of time when compared with the identical 4 bed passive houses PH3 and PH5. Findings from

Chapter *5* have shown that during the summer, similarly to what was observed in passive houses PH3 and PH5, the living room of the control houses CH1 and CH2 presented temperatures over 26°C for shorter periods of time (less than 25% of the time).

The analysis through social practices lenses has suggested that the night ventilation and cooling performed by passive houses PH3 and PH5 (by keeping the living room window open during the night) contributed to the lower indoor temperatures and lower exposure to increasing respiratory conditions (health effects associated with temperatures over 26°C). On the other hand, occupants of passive house PH4 indicated that they did not open the window during the night in the summer.

Therefore, it is reasonable to suggest that the practices of the occupants of the 4 bed passive house PH4 (e.g. not performing night cooling ventilation) contributed to an unhealthier environment in terms of high indoor temperatures and their associated health effects, when compared with the corresponding 4 bed control houses CH1 and CH2.

Another example of how practices performed by passive house occupants have contributed to an unhealthier environment, when compared with the corresponding control houses, is related to the VOC data obtained in the monitored bedroom. The monitored bedroom of the 3 bed passive house PH1 was the only room (among all the monitored rooms) where decane was found. The mean concentration of decane observed there was three times the decane concentration associated with eye irritation. Interview and diary data have suggested that the daily smoking practices performed by occupants in the monitored bedroom of the passive house PH1, have contributed to the unhealthier environment, in terms of VOC species and concentrations, when compared to the corresponding control houses and other passive houses.

Nevertheless, it could be argued that indoor smoking and the rise in decane and other VOC species associated with smoking is not an exclusive problem of passive houses. Those VOCs can potentially be found in any dwelling where smoking practices are performed indoors. However, because passive house PH1 was the only dwelling where occupants smoked in the bedroom it is not possible to know how smoking practices would have affected the VOC monitoring in the control houses.

6.5. Conclusions

The aim of this chapter is to understand in more detail how occupants' everyday practices have contributed to the differences in the indoor climate and indoor air quality in passive houses, as revealed in the Chapter 4 of the thesis. Qualitative data, obtained from occupant interviews, occupants' activity diaries and field observations were analysed in conjunction with the findings from the indoor climate and indoor air quality monitoring.

Using social practice as the theoretical framework to understand how the social context has contributed to the differences in the indoor climate and indoor air quality in passive houses and drawing on the explanatory variables related to occupants' practices, identified in Chapter 4, this chapter revealed three main findings.

First, regarding the differences in the indoor climate and indoor air quality observed in different rooms, in the same passive house, data findings show that the three monitored rooms (main bedroom, living room and kitchen) were used for the performance of very different practices. Not only were the practices performed in these three rooms dissimilar (e.g. the kitchen was mainly used for cooking/dish washing/clothes washing, the main bedroom was mainly used for sleeping), they were also guided by elements of practice, in different ways, which also contributed to variations in the indoor environment.

For example, for passive house PH1 householders, cooking, doing the laundry and cleaning often meant good homemaking. Those practices being performed a few times a day also intensified the use of technology (electrical appliances). Embodied habits of window opening was also guiding ventilation practices in PH1 passive house: the kitchen window was briefly opened when smoking or cooking practices were taking place.

Second, in relation to differences in indoor climate and indoor air quality observed during different seasons, data findings show that practices were not static through time, but in many cases, they were modified during the course of the year. Some practices were intensified (e.g. ventilation practices during the summer), others diminished (e.g. heating practices became very infrequent during the summer), and some practices were altered (e.g. laundry drying performed indoors in the winter and outdoors in the summer). These changes, in the way practices were performed also have contributed to the seasonal differences in indoor climate and indoor air quality observed in the passive house rooms. The "seasonal adjustment of practices" was something observed in another study exploring residential practices (Hauge, 2013, p.177); Hauge uses this term when describing how some practices performed by householders, changed during different seasons.

Third, when trying to understand how occupants' practices have contributed to the differences in indoor climate and indoor air quality observed in identical passive houses, the findings show that although similarities did exist regarding the performance of practices in a particular rooms in identical passive houses (e.g. the main bedroom was mainly used for sleeping, the living room was mainly used for watching TV), different families did not perform the same practice in exactly the same way, at the same time. Differences were observed in how often practices were performed, how they were performed and when they were performed. Additionally, some practices were only performed in some houses (e.g. cigarette smoking in the bedroom was only performed in passive house PH1).

The findings also indicate how everyday practices were influenced by the four interconnected elements which hold practices together, and thus how these have also contributed to the indoor climate and indoor air quality in passive house rooms.

For instance, how technologies were used and how often they were used when practices were performed, contributed to the differences in the indoor environment. In most passive houses, either meaning & engagements or embedded habits had the stronger influence on how technologies (including window and MVHR) were used. Institutionalised knowledge seemed to have had the least influence on technology use or the performance of practices in general.

Many passive house occupants indicated to open/close the windows or to keep them closed/open as the result of an unconscious decision or the result of a habit that hasn't changed after moving into a passive house. For some occupants, those habits were also linked to meanings which included, for example, a sense of security (by keeping the windows closed) or on the other hand, a sense of fresh air (by keeping the windows open).

Nevertheless, there was an exception where the fourth element of practice, institutionalised knowledge, seemed to have a stronger influence on how practices were performed and how technologies were used. Occupants of passive house PH4 were the only ones who followed some of the instructions given by the passive house institutions. They rarely opened the windows during the colder months. They boosted the MVHR system when they felt too hot. PH4 occupants generally followed the instructions from the users' manual with some exceptions. For example, during the summer months they did not shade the south facing rooms by drawing the curtains as advised by the users' manual. None of the occupants in any of the five passive houses did that.

Initially none of the occupants shaded the rooms during the day because they were unware that closing the curtains could help to cool down the rooms. However, when the outdoor temperatures started increasing and the occupants started to get uncomfortable, the Housing Association representative explained how the house could be cooled down by drawing the curtains during the day and opening the windows during the night.

Although some occupants were already keeping the windows open in some rooms during the night, the new institutionalised knowledge to close the curtains during the day was received with some scepticism by most occupants. The occupants' embodied habit of keeping the curtains open throughout the house during the day intertwined with the meanings of a lighter and brighter house contributed to the initial rejection of the advice received.

Regarding MVHR technology, the research findings also show that the occupants in four out of five passive houses did not have any interaction with the new ventilation system. Although the users' manual instructed occupants to boost the ventilation when necessary, the data show that most of them didn't. The findings suggest that the lack of interaction with the MVHR was also the result of inconsistent information given to occupants by different parties. This made passive house occupants rely on their embodied habits (previous knowledge and experiences) about ventilation, heating and indoor comfort instead of interacting with an unknown new technology.

6.6. Strengths, limitations and recommendations

In attempting to understand how occupants' practices may contribute to the indoor climate and indoor air quality in passive houses, this study has used a mixed methods approach (the use of quantitative and qualitative data) combined with a social practice theory framework. As far as the researcher knows, this has been the first time this methodology has been used when investigating the influence of the social context on the indoor climate and indoor air quality of energy-efficient houses. Furthermore, the use of multiple qualitative datasets (three seasonal rounds of occupants' interviews, three seasonal rounds of occupants' activities diary and field observations) have helped to strengthen the interpretability and validity of the enquiry results (Greene et al., 2008).

Limitations were also encountered in this study. These include for example, some passive house occupants filling in activity diaries with very little information. Nevertheless, because diaries were completed by occupants two weeks before they were interviewed, the researcher had the opportunity to obtain any missing data or clarify ambiguous information given on the diaries, on the day of the occupant's interview.

In additional, although this study attempted to analyse many practices related to, or which contributed to the indoor climate and indoor air in these houses, cleaning and personal hygiene practices were not part of the scope of the study. Although these practices may also contribute to the quality of the indoor air, due to the complexity of the subject (e.g. cleaning and personal hygiene products may release a vast variety of VOCs), these were not included in the study (for further information on the complexity of household consumer products and indoor air quality refer to Trantallidi et al. (2015)).

Therefore, further research is recommended to analyse how these other practices (e.g. cleaning and personal hygiene related practices) may contribute to the quality of the indoor air in energy-efficient houses. However, because of the complexity of the subject, the recommended study may require a different methodological approach, than the one adopted in the thesis.

Chapter 7 – Conclusions

The thesis began by exploring some of the concerns related to the health of occupants of passive houses and other highly energy-efficient dwellings. It showed that although the indoor environment in these dwellings has been well researched from an energy efficiency perspective, there are insufficient studies, especially in the UK, exploring the indoor environment of passive houses and other highly energy-efficient dwellings from a health viewpoint. It also discussed the importance of investigating whether passive houses and other highly energy-efficient dwellings provide their occupants with a healthy indoor environment for three main reasons. First, since passive houses are very well insulated and airtight there have been concerns over the quality of the indoor environment in these dwellings. Second, although passive houses incorporate a MVHR system which aims to provide a constant supply of fresh air, and consequently, adequate dilution of indoor air pollutants, these systems are failing to perform as initially intended (Balvers et al., 2012). Third, since occupants spend most of their time in their residence (Klepeis et al., 2001) and passive house standard buildings are on the rise, the quality of the indoor environment in these airtight dwellings and the possible adverse health outcomes associated with them are important topics to be investigated.

Additionally, through a review of the published literature on domestic energy consumption which highlighted the importance of occupants' practices within the indoor environment, it was also considered vital to understand how occupants' everyday practices may contribute to the quality of the indoor environment in their passive houses and, consequently, how these may affect their health.

From this position, the following research aim and three objectives were adopted in this thesis:

Research Aim:

To investigate the possible health implications of passive houses and to understand how occupants' practices may contribute to the quality of their indoor environment, and their health.

Research Objectives:

1. **To investigate the indoor climate and indoor air quality of passive houses, from a health perspective.**
2. **To analyse whether passive houses provide a healthy environment to their occupants.**
3. **To understand how occupants' everyday practices may contribute to the indoor climate and indoor air quality in their passive houses, and consequently how these may affect their health.**

7.1. Passive houses and potential health risks

Overall, the research findings have contradicted some of the claims made by passive house advocates (e.g. International Passive House Association, 2010) that passive house standard buildings constantly provide for good quality indoor air which improve the living comfort and health of their occupants.

The findings have suggested that passive houses can provide either a potentially healthy or unhealthy indoor environment for their occupants, depending on the health hazard and the explanatory variable being analysed.

An analytical framework was introduced in Chapter 3, aiming to provide explanations for possible differences in indoor climate and indoor air quality as well as explanations for the exposure of possible health hazards in passive houses. Table 7.1 shows a hazards and explanatory variables matrix, which provides a summary of the findings from the three results chapters. It includes the nine health hazards (indoor climate and indoor air quality parameters outside recommended levels) as revealed in Chapter 5. It also shows which of those hazards could represent a health risk for passive house occupants, based on findings from Chapter 6. In addition, table 7.1 elucidates on the causes and contributors for potential health risks in passive houses based on findings from Chapter 4 and 6.

The matrix in table 7.1 also shows a ‘recommendations column’ which explores implications of the research for MVHR manufacturers, passive house designers, buildings codes and Housing Associations and provide recommendations.

Health Hazard	Explanatory variables				Possible Health Outcome	Recommendations
	PH design & construction	Property characteristics	External conditions	Occupants' practices		
Temp over 26°C	Lack of solar shading during the summer on elevations which are prone to heat gains (e.g. South through to the West).	No strong evidence found	Season – High temperature observed during hotter months (e.g. summer)	Practices during the summer which contributed to additional indoor heat gains: Ventilation - opening windows during the day and keeping them closed during the night; Practices which involve the use of electrical appliances (e.g. cooking, washing dishes and clothes, ironing).	Worsening respiratory conditions	**MVHR systems** to provide a night cooling function and boost function triggered by excessive temperature (e.g. over 25°C); **Building codes** to enforce minimum requirements for solar shading strategies to South to West facades in PH standard dwellings. **Passive house designers** to provide internal/external features to minimise heat gains during the summer. E.g. internal layout could be designed to reduce some of the heating gains in the kitchen from occupants' practices (e.g. separate utility area for washing machine, tumble dryer and ironing).
Temp under 18°C	Not considered a health risk in passive houses					
RH over 60%	Not considered a health risk in passive houses					
RH under 40%	No strong evidence found	N/A	Season – Low levels observed during colder months (e.g. winter and spring)	Practices during colder months which contributed to low RH levels: Ventilation – opening windows daily (during the day and night).	Dryness of the nasal mucous membrane, eyes and skin	**Housing Association** to provide consistent recommendations and sound information regarding the benefits of not keeping windows open during cold months (e.g. financial, environmental, health). This information should not be too onerous.
CO_2 over 800 ppm	MVHR performance – poorer ventilation rates than designed	No strong evidence found	Season – High levels observed during colder months (e.g. winter and spring)	No strong evidence found	Eye irritation and upper tract respiratory symptoms	**MVHR systems** to be re-inspected and tested shortly after occupancy (e.g. two weeks) and a few times shortly after (e.g. monthly) to ensure flow rates are kept as designed. Regular maintenance period to be established after that.
Naphthalene Over 10 µgm^{-3}	No strong evidence found	No strong evidence found	No strong evidence found	Occupants' choices of cleaning and personal hygiene products as well as the frequency in which they are used.	Chronic inflammation in the nasal olfactory epithelium	**Housing Association** to provide concise general information to occupants regarding potential health risks associated with indoor VOC concentrations emitted from household products, paints, tobacco smoking, etc.
Decane Equal or over 7.3 µgm^{-3}	No strong evidence found	No strong evidence found	No strong evidence found	Smoking indoors	Dry eyes and irritation of the mucous membrane of the eyes	As above
Alpha- pinene Over 4,000 µgm^{-3}	Not considered a health risk in passive houses					
Limonene Over 4,500 10µgm^{-3}	Not considered a health risk in passive houses					

Table 7.1 Hazards and explanatory variables matrix.

Table 7.1 shows that high temperatures (over 26^{o}C) are a potential health risk in passive houses during the summer. A detailed analysis in Chapters 4 and 6 suggests that high indoor temperatures in passive houses were caused by a combination of two variables: the lack of solar shading on windows (internally and externally) and occupants' practices (opening the windows during the day and keeping them closed during the night).

In relation to solar shading, none of the windows and glazed doors in the studied passive house had external structural overhang, shutters or brise soleil incorporated in the design. Those technologies are however considered important to windows and other glazed areas facing South through to West in order to prevent overheating in dwellings during hot summer months (HPA, 2011). The lack of solar shading is a particular concern in passive house standard buildings since their high level of insulation prevents heat energy from being released through the building fabric (Mlakar & Strancar, 2011). The alternative to external solar shading – internal solar shading – by the means of closing internal blinds or curtains was not a practice performed by any of the passive house occupants during the summer. Although, the passive house users' manual advised occupants to close the blinds or curtains during the day in the summer in order to cool down the house, occupants explained that they were unaware of such a cooling strategy. Even after the Housing Association representative explained to the occupants that they should keep the blinds/curtains closed during the day, occupants were initially reluctant to follow the advice. Closing blinds/curtains during the day was not only contradictory to their everyday habits but it also meant that the house would not be light enough.

Another area of advice contained in the passive house users' manual was about summer cooling. Occupants were advised to keep the windows closed during the day when temperatures were higher and to open them during the night when temperatures were lower. The research findings suggest that the lack of night cooling ventilation in some passive houses contributed to high indoor temperatures. These findings are confirmed by other studies suggesting that indoor overheating can be prevented by the use of solar shading and night ventilation strategies (DCLG, 2012a; Larsen et al., 2012; Mlakar & Strancar, 2011).

Findings from Chapter 6 show that many of the different ventilation practices performed by passive houses occupants were the result of deeply rooted meanings intertwined with unconscious habits which hadn't changed immediately after moving into their passive house. This suggests that some well-established everyday practices could represent a barrier to a healthier indoor environment in passive houses. Although practices are not static and as such they change over time (Southerton et a., 2012), it is important to consider that passive house occupants might not use their dwelling as intended by designers, from the moment they move in. Therefore, it would be helpful to explore possible ways in which MVHR systems could be designed and run as well as to explore ways in which dwelling could be designed in order to ensure a healthy indoor environment, taking into account that well-stablished practices might not change overnight. For example, MVHR systems could be designed with a night cooling and boost function triggered by excessive temperature (e.g. over 25^{o}C). Nevertheless, such strategies would need to be sensitive to the effect of increased MVHR noise in the bedroom.

Another problem identified relating to potentially unhealthy temperatures was the very high temperatures observed in the kitchens during the summer (over 26^{o}C). Although occupants generally spent less time in the kitchen than in other rooms, there were still complaints from occupants about the kitchen being too hot and uncomfortable during the summer. In addition to the lack of solar shading and frequent window opening during the day, heat gains in the kitchen were also attributed to the use of electrical appliances. Temperatures were especially high in passive house kitchens were a combination of electrical appliances were used multiple times a day. A similar issue was reported by Rohdin et al. (2014), where the authors observed that indoor temperature in passive houses was highly affected by internal gains from cooking and other appliances. These results also suggest that there is a need for a re-evaluation of the design of passive house kitchens and their ventilation in order to provide comfortable and healthy temperatures during hot summer months. The design re-evaluation should take into account the possibility of heat gains in the kitchen to be more than expected as the result of frequent practices using multiple electrical appliances. It is suggested that passive houses have a separate area (e.g. utility room, room under the stairs) suitable for the use of washing machine and ironing. This would help to reduce heat gains in the kitchen caused by the use of multiple electric appliances.

In terms of reducing general heat gains in passive houses, building codes could also enforce requirements for solar shading strategies to South and West facades as well as guidance on minimising solar gains through the building fabric during the summer. However, further research would need to be carried out in order to provide further details on specific and sound strategies and guidance for passive house buildings.

Table 7.1 also shows that low RH levels (under 40%) were a potential health risk in passive houses. The research findings from Chapters 4 and 6 suggest that occupants' ventilation practices (opening windows during the day) was the possible cause of the problem. By opening the windows during colder months, warmer indoor air was replaced by cooler and drier outdoor air, resulting in lower RH levels. This ventilation practice explained the low RH levels observed in two out of the three passive houses. Unfortunately the low RH levels observed in passive house PH4 could not be explained by any of the variables considered.

Health risks were a potential problem in passive houses where the advice given on the users' manual was not followed. The passive house users' manual advised occupants not to leave doors and windows open for longer than necessary during the winter. Although this advice was given in order to avoid heating loses through windows and doors, the findings suggest that keeping the windows and doors closed as much as possible during the winter also helped to maintain RH levels between the recommended threshold (40% to 60%) in passive houses. However, as previously explained, ventilations practices were not performed in all passive houses as recommended by the users' manual. Instead of being a conscious decision made after the receipt of some recommendation, ventilation practices were inconspicuous practices rooted in everyday habits and full of meaningful significance which influenced whether occupants were opening window as well as when and for how long windows were kept open.

In addition, the findings from Chapter 6 revealed two other barriers stopping passive house occupants from following the advice from the users' manual. First, because different parties were providing contrasting advice regarding window opening, passive house occupants felt less inclined to follow them. Second, passive house occupants claimed that the users' manual was too onerous and as a consequence, they did not read or refer to it.

As pointed out earlier, some well-established occupants' practices might not change overnight as the result of receipt of information/recommendations. However, it is more unlikely for them to change if the recommendations given to occupants are not consistent or if they are too onerous. Therefore, it would be beneficial if Housing Associations provided less onerous and simpler users' manuals, ensuring that all information/recommendations given to occupants are consistent across the board. This would avoid mistrust between occupants and housing providers regarding the type of recommendation given. It would also potentially provide manuals which occupants would feel more inclined to refer to.

Table 7.1 shows that high CO_2 levels (over 800 ppm) were considered as a potential health risk in passive houses during colder months. Concern was demonstrated over the health of occupants in the 3 bed passive houses PH1 and PH2 since occupants were exposed to several hours of very high CO_2 levels on a daily basis. Further analysis using the analytical framework in Chapter 4 suggested that the 3 bed passive houses were provided with insufficient ventilation rates which were not able to purge CO_2 through outdoor to indoor air exchange at an acceptable flowrate. It was suggested that the MVHR system in operation in the 3 bed passive houses (which was a different model than the one used in the 4 bed passive houses) was not providing the ventilation rates as designed. The findings from the VOC monitoring also support the hypothesis that the 3 bed passive houses had insufficient ventilation rates. The concentrations of many VOC species found in the 3 bed passive houses were significantly higher than those found in the 4 bed passive houses. This also confirms the study findings from Ramalho et al. (2015) who reported a strong association between CO_2 levels and the concentration of certain VOC species (e.g. acetaldehyde, acrolein) and other indoor air pollutants (e.g. $PM_{2.5}$ and PM_{10}).

Other studies have reported that shortcomings with the MVHR system were common in passive houses and other low-energy dwellings (Balvers et al., 2008; Balvers et al., 2012; Dengel, 2013). Most of these studies reported reduction in airflow problems related to dirty filters, blocked ductwork, poor installation and lack of maintenance. Although is not possible to know the exact cause of the possible inefficiency of the MVHR system in the 3 bed passive houses, it would be very beneficial if the system was inspected and tested again shortly after commissioning (e.g. two weeks), and a few times shortly after that (e.g. monthly). Although the suggestion for the frequency of inspection of the MVHR is not evidence based, more frequent inspections would have allowed for the prompt correction of any reduction in flowrates and the identification of any issues arising after commissioning. As pointed out by Bone et al. (2010, p. 5), the "ability of these systems [MVHR] to achieve the recommended ventilation rates post occupancy is rarely measured".

Therefore, it is considered important that Housing Associations or other housing providers/managers ensure that MVHR systems are re-inspected and tested shortly after occupancy (e.g. two weeks) and a few times shortly after (e.g. monthly), until a regular maintenance period is established. This would ensure that they are operating as designed after occupancy and it would also offer an early opportunity for any remediation work to be done if lower flowrates were identified. After ensuring the system was working as designed, an annual maintenance check could be established for checking for blocked filters, replacing damaged parts, checking for controls, calibrating and cleaning dirty heat exchange/outlet/inlet surfaces. Furthermore, after replacing ventilation filters - which manufacturers recommend to be done every six to twelve months, it would be reasonable to test for flow rates in each room. This would identify possible inefficiencies and provide the opportunity for them to be corrected.

Finally, table 7.1 also shows that two VOC species were identified as a potential health risk in passive houses: naphthalene and decane. The findings from Chapter 4 and 6 suggest that the high concentration of naphthalene observed in three passive houses was caused by occupants' choices of cleaning and personal hygiene products as well as the frequency in which they were used. The high concentration of decane observed in one passive house was explained by indoor tobacco smoking practices.

Although potentially unhealthy indoor VOC concentrations are not an exclusive problem in passive houses, it would be helpful if Housing Associations provided general information to occupants about the subject. This information could include potential health risks associated with indoor VOC concentration emitted from household products, paints, furnishings, tobacco smoking etc. This would make occupants aware that their practices and personal choices can also affect whether they will enjoy a healthy indoor environment in their passive houses.

7.2. Comparing the health status of passive houses and conventional houses

When comparing passive houses and conventional houses in terms of indoor environment and possible health effects, the research findings show passive houses are potentially healthier or unhealthier depending on the indoor parameters and associated health hazard being analysed.

In terms of low indoor temperatures, passive houses are potentially healthier than conventional houses. Due to their design characteristics, super insulation and air tightness, passive houses are able to maintain indoor temperatures over 18^{o}C for longer during colder months. In contrast, very low temperatures were observed in the conventional houses for longer periods of time. In the UK, cold homes during the winter season have been identified as a significant problem, which contributes to 30% of the 25,000 excess winter deaths (EWDs) every year (PHE, 2014).

In contrast, during the summer passive houses are potentially unhealthier than conventional houses. The combination of the following factors – exposure to extensive solar radiation, additional internal heat gains and super insulation – contributed to internal temperatures over 26^{o}C for long periods of time in some passive houses. Although, statistics show that in the UK a lower number of deaths (around 2,000) occur per year due to heat compared to the those due to cold (around 25,000) (DCLG, 2012), scientists have predicted that temperatures across Europe will continue to rise over the next decades (WHO et al., 2003).

Therefore, since passive houses and other highly energy-efficient homes are on the rise, it is critical that different strategies are explored in order to prevent high indoor temperatures in passive houses. Further ideas for research on this and other related subjects are provided in section 7.6.

In terms of RH levels, passive houses are potentially healthier than conventional houses when considering high RH but potentially unhealthier when considering low RH levels. Potentially unhealthy low RH levels (under 40%) were observed for longer periods of time in passive houses during the colder seasons as the result of occupants opening the windows more frequently, allowing warm indoor air to be replaced by cooler and dryer outdoor air.

The issue with window opening during the colder months seem to be more problematic in passive houses when compared with conventional houses. Due to their design characteristics -

superinsulation and airtightness – passive houses generally have higher indoor temperatures than conventional houses. Since temperature is inversely related to RH, passive houses also generally have lower RH levels when compared to conventional houses. The frequent window opening in passive houses during colder months represented a potentially unhealthy ventilation practice, since it contributes to the further reduction in RH, to levels below the recommended minimum (40%).

In terms of high CO_2 levels, the research findings suggest that passive houses can be either healthier or unhealthier than conventional houses. When comparing passive houses with conventional houses built after 1995, the findings suggest that passive houses can be healthier than conventional houses as long as that the MVHR system is continuously providing ventilation rates as designed. When comparing passive houses with conventional houses built in or prior to 1995, the findings suggest that passive houses are potentially healthier than conventional houses.

The issue with houses built prior to 1995 relates to the fact that that was the year when the earliest version of UK Building Regulation Approved Document Park F (Ventilation) came into force. This document specifies requirements for the provision of background ventilation in new domestic buildings. Although there are no data available informing the percentage of dwellings in the UK lacking background ventilation, it is possible that the many dwelling built prior to 1995 were not provided with any intentional background ventilation. The research findings suggest that this could be a potential problem since those dwellings might show similarly extremely high CO_2 levels as those observed in the control house CH4.

In terms of VOC species observed in passive houses and conventional houses, the findings suggest that generally, the health status of the indoor environment of these houses is less dependent on their specific design characteristics and more dependent on the following variables: occupants' choices of personal hygiene and cleaning products as well as the frequency in which they are used and indoor smoking practices.

7.3. Key contributions of the thesis

7.3.1. Empirical contributions

By using indoor climate and indoor air quality monitoring data from multiple rooms in five passive houses and four standard control dwellings, during different seasons, the thesis provides evidence which shows that significant differences exist in the indoor environment quality between passive houses (even identical dwellings), among different rooms in the same passive house, and between similar rooms in passive houses and the corresponding control houses.

Although a few studies have explored the indoor environment of passive houses and other highly energy-efficient dwellings, there are insufficient studies exploring more than one location in the same dwelling, and the few studies that do exist fail to provide comparisons on how the results found in these highly energy-efficient homes compare with standard dwellings. Additionally, studies exploring the indoor environment of passive house standard dwellings tend to be focused on either their energy efficiency or occupants' indoor comfort, thus paying less attention to possible health concerns.

Therefore, this thesis has made empirical contributions to the field by exploring in more detail the indoor environment of passive houses from a health perspective, and by comparing these with other less energy-efficient standard dwellings. Through the use of an analytical framework, this thesis has also provided explanations for differences in indoor climate and indoor air quality observed in passive houses. These explanations also provided insights on how different variables contribute (or not) for the potential health risks passive house occupants might be exposed to.

7.3.2. Methodological contributions

One of the main contributions of this thesis relates to the use of a mixed methodology approach which not only made possible the investigation of the indoor climate and indoor air quality in passive houses, but it also provided complementary data which was used to explore the social context around the indoor climate and indoor air quality in passive houses. In other words, qualitative data were used in an attempt to explain the findings generated by the quantitative enquiry.

7.3.3. Theoretical contributions

Social practice theory concepts were applied to this thesis when examining the possible influences of occupants' everyday habits on the quality of the indoor climate and the indoor air in passive houses. Although social practice theory has been used previously when examining the social context within highly-energy efficient homes, this is the first time, as far as the researcher knows, that this theory has been used to gain insights into the social context around the indoor climate and indoor air quality of passive houses, from a health perspective. Furthermore, this has been the first attempt, as believed by the researcher, where a study has tried to understand whether occupants' social practices may influence their risks of exposure to indoor health hazards associated with adverse health effects.

7.4. Methodological reflections

This section of the thesis shows a brief reflection on the methodology used in this research. It starts by considering the challenges faced when undertaking research in dwellings, followed by further consideration of the challenges and opportunities associated with conducting a research study through a 'gatekeeper' that controls some aspects of access. It is followed by a reflection on what went well and what could have been done differently during the research process.

7.4.1. The challenges of conducting research in dwellings

Conducting research in dwellings was not considered by the researcher as an easy and straight forward task. Difficulties were encountered not only during the recruitment phase for households, but also during the subsequent periods, when home visits had to be arranged for both access (for monitoring equipment installation and removal) and for undertaking occupants' interviews.

The difficulties encountered when recruiting households to take part in the research are related to the fact that homes are a private and intimate place, which occupants might associate with the meaning of relaxation, comfort and peace (Saunders, 1989). Recruiting occupants to take part in a longitudinal study, which required the researcher's access to their homes on multiple occasions during the course of a year was problematic since many households viewed this process as too disruptive for their family life or too much nuisance in their private space.

Furthermore, although nine households (including study and control houses) agreed to participate in the research, arranging home visits for both equipment monitoring installation/removal and occupants' interviews was considered a challenge. All households had everyday tasks as well as last minute sporadic commitments at different times. This meant that sometimes it was not possible for the researcher to visit all households on the same day (or even during the same week), resulting in multiple visits taking place on different days (with cost implications for the research budget). Additionally, difficulties were also encountered when households cancelled appointments at the last minute for various reasons (e.g. they had forgotten about the appointment, their child was ill, they had a last minute change of circumstances). These problems not only meant that further funds were needed for travelling to and from the study locations but it also meant that research time was wasted by last minute cancellations and thus, additional time had to be allocated for travelling to and from these dwellings.

7.4.2. The challenges and opportunities of conducting research through a gatekeeper

Amber Housing, the social housing provider, responsible for the construction, delivery and management of the passive house dwellings, acted as the gatekeeper during the research process. As previously mentioned in the Methodology Chapter, Amber Housing would only grant access to the passive house site, if a few conditions were followed by the researcher. These included booking home visits and interviews with the households exclusively through a private research company - Spire Group. This meant that visits had to be coordinated and carried out concurrently with the researcher from Spire Group.

This proved to be challenging, as the researcher had to agree dates which were suitable to herself, the households and the other researcher from Spire Group. Additionally, since there were two sets of research studies being conducted in the passive house dwellings, using sometimes different monitoring equipment and focusing on different questions during the interviews, the researcher was very mindful of interviews and installation/removal of the monitoring equipment taking excessive time or being too onerous, resulting in participants withdrawing from the study.

Another challenge during the research process was to align ethical practices from the two different studies and their research organisations to ensure ethical concerns were fully dealt with. Ethical considerations for this thesis were made according to the University of East Anglia Research Ethics Policy, aligned with some extra considerations from Spire Group ethical procedures. For example, the researcher had to carry photographic identification when visiting the studied homes. Additionally, the researcher had to ensure that when travelling with data (e.g. data stored in a computer or on a USB flash drive), the data had to be encrypted to ensure that third parties would have no access to them, if the computer or the USB flash drive got lost or stolen. These were additional ethical requirements imposed by Spire Group Ethical Policy.

Nevertheless, having a gatekeeper during the research process also offered some opportunities for the study. Since the gatekeeper, Amber Housing, was responsible for the management of the dwellings, it was also very interested in the indoor environment of the passive houses and therefore, very keen on the research and its findings. This interest resulted in Amber Housing offering to pay financial incentives (as explained in the Methodology Chapter) to participants to encourage them to take part in the study. Additionally, Amber Housing also contributed financially towards buying part of the monitoring equipment. This was very important during the research process as many pieces of monitoring equipment were needed and there were insufficient funds from the research grant to buy all of them.

7.4.3. What worked well

Upon reflection on the methodology, there were three aspects of the research design which were considered vital in fulfilling the research objectives, producing further knowledge and providing more detailed insights into the indoor environment of passive houses and their occupants.

First, by using a longitudinal case study the researcher was able to find out that there were seasonal variations in the indoor climate and indoor air quality of passive houses, which in turn represented different levels of exposure to the risks associated with adverse health effects for occupants. Further knowledge such as this, on the indoor climate and indoor air quality of passive houses and the possible consequences to their occupants, would not have been possible without a longitudinal research design.

Second, the researcher adopted an interdisciplinary mixed methods research approach. Although many challenges were faced by the researcher when crossing disciplinary boundaries (e.g. different approaches for data collection and analysis, time pressure, learning how to bring together two disciplines), this design strategy was also considered vital when trying to fulfil the main aim and objectives of the research. Indoor air climate and indoor air quality monitoring were possible through quantitative enquiry (from the environmental sciences) whilst qualitative enquiry (from the social sciences) was used when trying to explain the findings obtained by the first approach. Without mixing these methods and, therefore, crossing disciplinary boundaries, the research main aim and objectives would not have been fulfilled, as the quantitative enquiry would only be able to provide data related to the indoor environment of passive houses, which would not provide further details and explanations of the social context of those data and related findings.

Third, the use of both occupants' interviews and activity diaries provided a rich and detailed account of occupant's everyday practices in each of the three monitored rooms in the studied passive houses. Although the interview with the occupants included a walk-around the house, where a family member provided an account of the family's everyday activities in each room, the use of an activity diary supplied complementary detailed data. For instance, although during the walk-around interview, occupants told the researcher that the kitchen was a place for cooking meals, doing the laundry and smoking, the activity diary detailed how many times during the day these activities took place, as well as what appliances were used when cooking a meal and the at what time these practices were performed. All these additional detailed data were vital when trying to understanding the influences of certain practices on the quality of the indoor environment in passive house dwellings.

7.4.4. What could have been done differently

Reflecting on the research methodology also provided the chance for the researcher to consider aspects of the research design which might have worked better if it was done differently. In the case of this research, there were two aspects of the research design which ought to have been done differently.

First, one of the biggest problems encountered when undertaking this study was related to the monitoring equipment. All the equipment, some mains powered (Wöhler monitoring loggers) and other battery operated (HOBO monitoring loggers), required the researcher to physically access the properties for installation/removal as well as for data download. This process was necessary since these particular types of equipment do not continuously store data for long periods of time (e.g. for months), requiring the data to be downloaded from time to time. Therefore, multiple visits to the studied dwellings were necessary in order to install/remove the equipment as well as to download data during the course of the research. Reflecting on how challenging it was to keep households from withdrawing from the research due to so many visits, perhaps, it would had been less intrusive to use a monitoring equipment, where data are downloaded remotely, thus reducing the number of visits to the studied dwellings. This type of equipment was, however, only available for temperature and relative humidity monitoring and not for CO_2 and VOC monitoring. Additionally, monitoring equipment with remote data downloading function is usually more expensive when compared with the standard data logger equipment.

Second, the researcher monitored the top 10 most abundant VOC species found in the main bedroom. Although the data obtained by this method provided some useful information related to the indoor air quality in the studied dwellings, this was considered insufficient. Due to the limited number of published studies associating concentrations of individual VOC species with adverse health effects, it was not possible to obtain evidence of the possible health effects associated with all the 10 most abundant individual VOC species found in the studied homes. Evidence on the possible health effects associated with individual VOCs were only obtained for 4 VOC species: limonene, alpha-pinene, decane and naphthalene. For that reason, a different VOC monitoring strategy might have worked better when trying to fulfil the objectives of the thesis. An alternative strategy would be to target the monitoring of specific VOC species, for which there is sufficient published evidence associating these with adverse health effects. For example, benzene, formaldehyde, trichloroethylene and tetrachloroethylene could be targeted when monitoring indoor VOC species as there is strong evidence associating these VOCs to adverse health outcomes (WHO, 2000). Nevertheless, this study has provided a baseline for when the epidemiological evidence becomes available.

7.5. Further research

This thesis has provided the researcher with some research ideas for the future. These include research which could strengthen the findings of this thesis as well as research which would further explore some aspects of the indoor environment of passive houses and other dwellings and occupants' everyday practices, which were not investigated here.

Regarding further research which could strengthen the findings obtained from the thesis, the researcher has identified the following opportunities:

1. Continue to monitor the indoor climate and indoor air quality in passive houses and other highly energy-efficient dwellings, from a health viewpoint, focusing on other potential health hazards (e.g. particulate matter (PM), carbon monoxide (CO), nitrogen dioxide (NO_2) and specific VOC species (e.g. formaldehyde, benzene)).

2. Continue to investigate occupants' everyday practices and their possible influences on the quality of the indoor environment of passive houses and other highly energy-efficient dwellings, by focussing on other specific practices associated with indoor environment quality (e.g. cleaning and the use of cleaning products, painting/decorating the house and the use of varnishes, resins and composite wood based products).

Regarding further research which explores aspects of the indoor environment of passive houses and other dwellings, which were not investigated as part of this thesis, the researcher has identified the following opportunities:

1. Explore specific house characteristics (e.g. layout, volume, solar orientation) aiming to find out how these could be adapted in order to maximise the indoor environment quality in passive houses and other highly energy-efficient homes.

2. Explore possible ways in which MVHR systems could be designed and run to ensure a healthy indoor climate and indoor air quality in passive houses and other highly energy-efficient dwellings, taking into account that well-established practices might not change overnight.

3. Explore possible ways in which passive houses and other highly energy-efficient dwellings could be designed to ensure a healthy indoor environment, taking into

account how the performance of practices affects the indoor climate and indoor air quality in different rooms.

4. Investigate the indoor environment quality, from a health perspective, of conventional, less airtight dwellings, where intermittent background ventilation (e.g. fans) and any other background ventilation (e.g. trickle ventilation on windows and doors) were not provided.

5. Investigate occupants' everyday practices in conventional, less airtight dwellings, aiming to find out how practices may influence the quality of the indoor environment in these houses. It would be interesting to know if there are differences between the ways in which practices have influenced the quality of the indoor environment in passive houses and the ways they may influence the quality of the indoor environment in conventional houses.

6. Investigate whether passive house occupants would be more inclined to read the users' manual and follow the advice provided if the manual was more succinct.

7. Explore how changes in ventilation practices could be facilitated in passive houses and other highly energy-efficient dwellings in order for occupants to enjoy a healthy indoor environment.

Appendices

Appendix 1 – Leaflet inviting passive house households to take part in the study

Our responsibilities to you:

We ensure your safety - all our researchers carry photographic identification and have been security checked.

We guard your privacy - your taking part will be treated in accordance with the Data Protection Act. Your contribution will be used for research only and not for any marketing purposes. You will not be named or identified in the research reports. We will not pass on your personal details to anyone else.

We respect your wishes - taking part in the research study is voluntary and you do not have to answer any questions you do not wish to.

We answer your questions - we will be happy to answer any questions you may have about the research study.

What will happen to the information once it is collected?

All the information you provide including your diary entries and what you say in interviews will be completely confidential to the research team. Your name and address will not be used in any of the research findings. [redacted] will know that you have taken part in the study but we will not attribute any of the findings to you personally.

We will record the interviews so that nothing you say is forgotten. The interview recordings stay within the research team and are kept securely so that no-one else can listen to them.

[redacted]

[redacted]

Are you interested in taking part in a small Research Study to help [redacted] build more energy efficient homes?

We are looking for a small number of residents moving into [redacted] new homes who would like to take part in a 12-month research study to help [redacted] understand how efficient these new homes are and what it is like to live in them.

This leaflet explains the research study in more detail.

You will receive **£150** in cash to thank you for taking part.

Front page of leaflet

What is the research study about?

[redacted] has commissioned a small research study to understand how energy efficient are the new homes they are building and to hear first-hand from residents what these new homes are like to live in.

A small number of residents from different sized homes will be invited to take part in a 12-month post-occupancy study. Interested residents will need to have some idea of the cost of their electricity and gas bills in their existing home over the last year, and should be willing to be interviewed 3 times in their first year in their new home.

[redacted]

Who is carrying out the research?

[redacted] has been appointed by [redacted] to carry out this research. [redacted] Innovate will be assisted in this study by a PhD Researcher (Low-Carbon Housing and Health) from the University of East Anglia's School of Environmental Studies.

[redacted] will lead this research study and all contact will be between them and residents, not [redacted].

Why take part?

This is your opportunity to have your say. Your views will be important in helping the design of more energy efficient homes with low utility bills in the future.

£150 (in three £50 instalments) will be paid to the selected residents who participate in the study as a small thank-you for your time.

Can I take part?

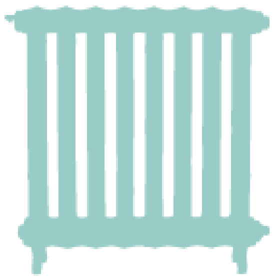
If you would like to take part, please see if you can meet the criteria listed below.

- ☐ **Will you share with us your annual electricity and gas bills, for the last 12 months in your old home, and for the first 12 months in your new home?** You should be able to get this information from your utility suppliers - we can help you to do this.
- ☐ **Will you allow [redacted] and UEA to install some simple environmental monitoring equipment in your home?** This will tell us when your heating is on and the temperature in different rooms.
- ☐ **Will you take part in 3 one-hour interviews in your home with [redacted] and UEA?** The interviews will focus on your experience of living in your new homes at around 6-8 weeks after you move in, after the winter heating season and after the summer cooling season.
- ☐ **Will you complete a simple diary for 1-2 weeks before each of the Interviews** recording how and when you heat and ventilate your home?

What happens next?

If you can tick the 4 criteria boxes, you may be eligible and should contact the Research Team for more details.

Once you have registered your interest with the Research Team, you will then be asked to complete a short questionnaire and maybe telephoned to discuss the research study in more detail. [redacted] will make the final selection of those who will take part in the research study.



Contact the research team

[redacted]

Back page of leaflet

Appendix 2 – Leaflet inviting control house households to take part in the study

PhD Research: indoor air quality in homes

Who I am and what I am doing…

I am a PhD student at the University of East Anglia, researching "Energy-efficient homes and health". I am studying the indoor air quality of the new homes constructed by **(Housing Association name plus development address)**. This new housing development consists of 51 homes, which are very energy-efficient and air-tight. I am also comparing how these new homes compare with traditional homes in terms of indoor air quality.

What I am looking for…

I am looking for a few households in the neighbourhood willing to help me with my research by letting me place three indoor air quality monitors in their homes. This would also be a great opportunity for you to receive some feedback on the indoor air quality in your home.

What does this involve?

I would place two indoor air quality monitors in your home to monitor carbon dioxide, temperature and humidity (one in the living area and another one in the main bedroom). I would also place a small volatile organic compound (VOC) sampler in your bedroom. The equipment would be placed in your home for a period of two weeks, in three different rounds (November/December 2014, April/May 2015 and October 2015). This would equate to a total of six weeks.

<table>
<tr><td>This is what the carbon dioxide monitor looks like:</td><td>This is what the VOC sampler looks like:</td></tr>
<tr><td>


</td><td>

</td></tr>
<tr><td>Monitor dimension: 120mm diameter x 100mm depth</td><td>Tube dimension: 71mm length x 11mm diameter</td></tr>
</table>

If you are interested in the indoor air quality in your home and would like to help me to find out how the indoor air quality of these new energy-efficient homes compare with traditional homes, please be part of this research! Please contact me as soon as possible!

Contact details:

Patricia Kermeci
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Phone: **(number)**

Appendix 3 – Interview topic guide

INTRODUCTION

Introduce interviewers

Introduce the Study

Talk through key points:

1 hour interview

Part of it will be a walk-around

Interview will be like a discussion, but covering specific topics.

No right or wrong answers, their views are important.

We are recording the interview

Confidentiality and anonymity, interview recordings and transcripts will be filed securely. Findings will be anonymised, there will be no explicit reference to name or house number.

START RECORDING

BACKGROUND AND PERSONAL CIRCUMSTANCES

Could you start off by telling me a little about yourself and who you live with?

Household Composition

Name, age

Partner, name, age

Children, name, ages

Languages spoken

Pets

Occupancy Patterns

Main Day-time Activities

Living patterns - typical weekday and weekend

Kind of work / education

Other interest areas / activities

PREVIOUS ACCOMMODATION

Where were you living before you moved into this house / flat?

Understanding previous context

House / flat / hostel

Location

Number of rooms (establish if over-crowded; number of kids sharing etc)

How long were you there? (where did you live before - establish stability)

What were the advantages / disadvantages?

Tell me a little about how the property was heated?

Heating

Heating spaces

Ventilation

Any Energy efficient measures - double glazing, insulation, PVs, MVHR etc

Heating water

Keeping warm with clothes, bedding, hot water bottles etc

How did you pay for your electricity and gas?

Any idea how much - weekly, monthly, yearly?

Do they know how much they paid / and establish if access to bills is acceptable

NEW HOME - FIRST IMPRESSIONS

When did you move in and what were your first impressions of your new home?

Overview

Moving date

Location

Size

Number of rooms (establish who is sharing etc)

Satisfaction with indoor temperature / comfort in new home

Comparison with previous home in terms of comfort

General advantages / disadvantages of new home v old

Establish how they will pay for electricity / gas - bills /pre-pay etc

Were you given any explanation about why this is a Passive House?

Passive House

Difference from a standard house?

Awareness of Energy Efficiency measures?

Usefulness of induction 121 / literature / external session

Are you OK if we have a **walk-around** now? We will continue the discussion (and recording as we go.)

WALK-AROUND

Boiler/ MVHR control / Kitchen

Ask HH to explain how system works

Has HH received guidance about how system works - 121, Handover Pack, external session

Controls - record settings

Is the setting constant / in what circumstances is it changed?

Is there anyone 'responsible' for changing the settings?

Do you ever use the kitchen extractor - how often / what circumstances?

MVHR Cupboard- Living / Dining Room

Ask HH to explain how the home is ventilated: extract fans, full mechanical ventilation; window opening

Ask HH to explain how system works

Has HH received guidance about how system works - 121, Handover Pack, external session

Controls - record settings

Is the setting constant / in what circumstances is it changed?

Is the setting constant / when is the Boost used?

Are you confident in using the system?

Do you think it provides sufficient ventilation

Noisy / quiet?

Extractor Fans - Bathroom

Do you ever use - how often / what circumstances?

Ventilation - All rooms

Do you open windows: which windows/doors opened – when and why?

Which windows/doors kept closed and why?

Do they sleep with windows opened/closed?

Are there smokers in the household? Do they smoke inside? Explore patterns of window/door opening.

Do behaviours change when more people - guests/ family are in the house?

Has anyone complained of feeling: hot / cold / stuffy / humid / smelly / dry / stale air? Explore related patterns of ventilation

And ventilation behaviours related to cooking, bathing or drying clothes

Have you noticed any condensation or mould - where?

WRAP-UP

Aim - to allow further discussion around specific heating and ventilation behaviours.

Appendix 4 – Interview transcript extract

(This extract was taken from a first round of interviews during the interview walk-around)

Interviewer:	“Could you just tell me how and when you use this room?” [kitchen]
Respondent:	“Yes, this is the room I mostly eat in, the cooking, breakfast, things like that, preparing the dinners. [daughter] does all her homework up there; everything seems to happen in the kitchen, really. I don't know why. This is the place to come.”
Interviewer:	“Do you do a lot of cooking?”
Respondent:	“Yes.”
Interviewer:	“So do you cook every night?”
Respondent:	“Yes, apart from Friday; Friday night I don't do any cooking, takeaway night.”
Interviewer:	“So what appliances would you use for cooking? Would you use hob, oven, microwave?”
Respondent:	“Mostly the oven and the top, the hob.”
Interviewer:	“What about the windows in here, do you open much?”
Respondent:	“Only if I have a cigarette.”
Interviewer:	“Do you smoke in here?”
Respondent:	“Yes and I have one in my bedroom at night time.”
Interviewer:	“What about when you cook; do you normally switch that on?” [cooker hood extractor]
Respondent:	“Yes, I put that on every time. Yes, every time.”
Interviewer:	“What about settings on the ventilation system [MVHR]; do you normally change the settings?”
Respondent:	“I just put it on number 2, yes.”
Interviewer:	“So do you know what that is?” [MVHR touch screen on kitchen wall]
Respondent:	“Yes. Well, I know what it is but I should have it on number 2 and - where is it? Number 24, yes; 2 and 24 and that's what I really need. But I know if it gets too hot to turn it up to number 3; he calls it the party mode. If it gets a bit cooler in here and then to put it down to number 1 and that's all I know. But at the moment I've just kept it as the same settings.”
Interviewer:	“Have you changed it at all?”
Respondent:	“No, I don't want to touch it, really.”

Appendix 5 – Blank copy of occupants' activity diary

Household Activity Diary (example)   Date: ______________ ___/___/___

Instructions: Please fill in the blank boxes with the start and the finish time for any activities you did during the day and night. If you did not engage with a particular activity, please leave the box in blank. Also, please provide any details about your activities in the box 'activity details'. Examples are given on the first page of this document. Please note that there are no right or wrong answers. You should fill in the blank boxes according to the activities you and your family engaged in your household. Thank you!

Activities	Living Room	Bedroom 1	Bathroom	Kitchen	Activity detail
Changing the ventilation settings on the ventilation control Activity detail - Why did you change the settings? What setting did you change to?					
Cooking Activity detail - What appliance was used for cooking? E.g. hob, oven, microwave.					
Using the cooker hood extractor Activity detail - Why did you use the cookerhood extractor? What setting did you select?					
Using the kettle					
Drying clothes indoors					
Ironing Activity detail - Did you iron with steam?					
Opening windows Activity detail - Did you open the window for any particular reason?					
Showering/Bathing Activity detail - Did you boost the extractor (and/or) opened the windows when showering/bathing?					
Smoking indoors					
Using cooling fans Activity detail - Why did you use a fan?					
Using humidifiers Activity detail - Why did you use a humidifier?					

How many people were in the home during the day? (Including guests)			
How many people slept in the **main bedroom** during the night?			
During the night the **main bedroom door** was	fully open ☐	partially open ☐	closed ☐

Appendix 6 – Extract of occupants' diary filled in

Household Activity Diary

Date: 11/4/15 ___/___/___

Instructions: Please fill in the blank boxes with the start and the finish time for any activities you did during the day and night. If you did not engage with a particular activity, please leave the box in blank. Also, please provide any details about your activities in the box 'activity details'. Examples are given on the first page of this document. Please note that there are no right or wrong answers. You should fill in the blank boxes according to the activities you and your family engaged in your household. Thank you!

Activities	Living Room	Bedroom 1	Bathroom	Kitchen	Activity detail
Changing the ventilation settings on the ventilation control Activity detail – Why did you change the settings? What setting did you change to?					FAN 2 ALL DAY.
Cooking Activity detail – What appliance was used for cooking? E.g. hob, oven, microwave.					17.30 till 18.30
Using the cooker hood extractor Activity detail – Why did you use the cookerhood extractor? What setting did you select?					Cooker hood 17.30 till 18.30.
Using the kettle				06.45 08.01 12.46	19.53.
Drying clothes indoors					13.00 in Dining Room
Ironing Activity detail – Did you iron with steam?					
Opening windows Activity detail – Did you open the window for any particular reason?					windows open in all bedrooms from 10am till 4pm.
Showering/Bathing Activity detail – Did you boost the extractor (and/or) opened the windows when showering/bathing?					BATH at 14.00 Shower at 19.40
Smoking indoors					

How many people were in the home during the day? (Including guests)	4		
How many people slept in the **main bedroom** during the night?	2		
During the night the **main bedroom** door was	fully open ☐	partially open ☐	closed ☑

HAD STUDENTS.

Appendix 7 – Field diary and analytical thoughts

PH2 Interview 1 on 19/11/2014 at 13.00pm

Passive house, 3 bedrooms mid terraced

PH2 family - 4 members: couple and 2 children

Notes and observations:

1. **Interviewee opened the kitchen window as soon as the interviewer got in the kitchen. She said "too many people… I need to open the windows."**
2. **Interview was carried out in the kitchen, followed by the walk-around.**
3. **Monitoring equipment were installed at around 14.00pm.**
   Recordings: MVHR = number 2 setting
4. **Space heating (radiators) were off. Occupant said that the space heating system is always kept off as they feel that house is too hot.**
5. **Kitchen window was open during the interview and walk-around.**
6. **There were curtains in all windows and during the interview and walk-around, these were open.**
7. **The family members were wearing T-shirt in the house during the interview and walk-around.**
8. **Interviewee complained many times during the interview and walk-around that the house felt too hot and that she was feeling very thermally uncomfortable.**

My thoughts:

1. **During the interview, I too felt that the house was 'warm'.**
2. **It felt cold outside (around 10°C). The radiators were off throughout the house. Why did it feel 'so warm' inside? Any special activities? (e.g. cooking a lot during the day, using the kettle too many times, etc.)**

Appendix 8 – Spreadsheet showing extract of each monitoring day in different rooms

PH1		Spring Season M2											
Bedroom													
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13
No of occupants	2	2	2	2	2	2	2	2	2	2	2	2	2
Room orientation	S	S	S	S	S	S	S	S	S	S	S	S	S
% CO2 over 1000ppm	98	75	100	100	100	100	83	95	100	90	100	98	93
% CO2 over 1500ppm	78	63	85	93	100	100	70	83	70	70	75	58	63
% CO2 over 2000ppm													
CO2 mean	1765	1500	1944	2254	1960	1837	1614	1877	1766	1787	1878	1602	1684
CO2 peak	2209	2043	2555	2957	2429	2168	2410	2554	2541	2468	2299	2094	2636
Mean room temp	25	24	24	24	24	26	24	25	25	25	26	25	26
Mean room RH	45	49	48	47	46	47	46	45	45	42	45	48	44
Door open/closed/partially open?	PO	PO	PO	PO	PO	PO	PO	PO	PO	PO	PO	PO	PO
Smoking	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes

PH1		Spring Season M2											
Kitchen													
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13
No of occupants	3	4	4	0	0	3	1	0	4	0	0	2	1
Room orientation	S	S	S	S	S	S	S	S	S	S	S	S	S
Mean room temp	24	24	25	24	23	23	24	25	25	25	25	25	24
Mean room RH	47	47	49	48	47	46	45	43	46	46	42	44	41
Cooking (How many times)	3	3	2	2	1	2	2	2	3	1	1	1	1
Cooker hood used?	3	1	0	0	0	2	0	2	3	0	0	1	0
Kettle used? (How many times)	4	4	3	2	3	4	4	3	3	3	2	2	2
Ironing with steam	1	1	1	1	1	1	1	1	1	2	0	1	0
Smoking	yes	yes	yes	no	no	no	yes	yes	yes	yes	yes	yes	yes

Appendix 9 – Participant consent form

Research Study: Residents' Consent Form

YOUR OBLIGATIONS

In signing this agreement, you and all other household members agree to take an active part in this Research Study in relation to the two areas below:

1. *Installation of Loggers and Sensors*

   You agree to:

- **allow the researchers to install Loggers and Sensors around your home to record, collect and analyse data relating to electricity usage, radiator temperature and room temperature, humidity, and air quality;**
- **ensure, to the best of your ability, that all members of your household, guests or pets do not tamper (i.e. move or otherwise interfere) with equipment at any point;**
- **contact us at the earliest opportunity if you suspect any of the equipment may have developed a fault, been damaged, or lost; and**
- **notify the research team immediately if you no longer wish to be a part of this study and allow them to collect and remove the equipment;**

2. *Research Interviews*

   You agree to:

- **take part in 3 rounds of interviews**
- **complete an activity diary for 2 weeks around the times of the 3 interviews**
- **help the Research Team to find out the cost of your utility bills over the last 12 months and over the next 12 months of the Study period.**

OUR OBLIGATIONS

- **respond to any non-urgent enquiries from you within five working days and any urgent enquiries within one working day;**
- **ensure that your personal data is protected in accordance with the Data Protection Act;**
- **provide you with an incentive to be paid by cash totalling at least £150 to be paid in instalments to thank you for your participation and on condition that you play an active part in the research study**
- **make good any damage caused by the Research Team or by the equipment, provided that such damage has not been caused through tampering or interference as detailed above in your obligations.**

Please initial box

I confirm that I have read the Information sheet provided to me by the Researcher and understand the purpose of the study.	
I confirm that I understand my obligations as set out in this document and have had the opportunity to ask questions.	
I confirm that I am happy in principle with the installation of the Loggers and Sensors and have had the opportunity to raise any concerns or questions.	
I confirm that I have received a Health and Safety briefing from the installer, concerning the equipment and the risks associated with tampering or physical contact.	
I confirm that I have been informed about the length of the Energy Research Study, and the number of visits and interviews and other feedback activities that will be requested by the research team.	
I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason, but may forfeit some of the later incentive payments if I do so.	
I agree to take part in the above study.	
I confirm that all residents within this household have agreed to take part in this study.	
I understand that my personal data will treated confidentially and will only be used for the purpose of the research activity. I understand that this personal information will not be shared with anyone else except where it is in a completely anonymised form such as the final report or thesis.	
I agree to the use of anonymised data, information and interview quotes in the research publications.	

Property Address:			
Ref:	**Print Name**	**Signature**	**Date**
Resident			
[redacted]			
UEA			

Appendix 10 – Research information sheet

Research Information Sheet

The purpose of this research is to investigate the performance of the mechanical ventilation system in energy-efficient homes and also to find out how residents use their ventilation system and controls. This is an important area to be studied since the UK Government are aiming to construct more energy-efficient homes, which rely on the use of mechanical ventilation systems.

The research is funded by the Engineering and Physical Sciences Research Council (EPSRC) and carried out by myself as a PhD student of the University of East Anglia (UEA). This study is for research purposes only, and not commercial. My contact details are include at the end of this document.

The research will be conducted in collaboration with (**name of Housing Association**). The research will be carried out over a period of 12 months and it includes some indoor air quality monitoring for a period of two weeks in each of three different rounds (around 5 weeks after you moved in the new home, in April/May 2015 and October 2015). In addition, you will also be asked to fill in an activity diary during the two weeks monitoring period (in each of three rounds of air quality monitoring). There will be also three rounds of interviews. The first interview will be conducted a few weeks after you moved in your new house, and the two other interviews, a few weeks after the indoor air quality monitoring period. The first interview will take place when the air quality monitoring equipment is first placed in your home.

Your identity (and the address of the household) will be kept confidential and they will not be identified in any document produced as a result of the research. Transcripts and notes of interviews will not contain the name of the participants. Data from monitoring, activity diaries and interviews will be held securely by the researcher at the University of East Anglia and will only be shared with other researchers or the project funder once it has been completely anonymised.

Participation in this research is voluntary and participants will be asked to give written consent to their participation using the accompanying consent form. Should participants change their mind and wish to withdraw their participation, they can do so by contacting the researcher and indicating their wish to withdraw. Any information you provided will not be used in this study if your withdrawal happens within the first 30 days of the information being collected.

The findings of this study will form part of the researcher's PhD project, being included within her thesis as a case study as well as potential publications, teaching and reports on indoor air quality. If you would like to receive copies of any reports produced or interview transcripts, these can be requested by contacting the researcher involved. However, it is planned that home occupants will receive feedback regarding the findings of this study, after the final monitoring/interview period.

Contact information for the researcher involved in this project:
Name: Patricia Kermeci
Address: School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ.
Email address: p.kermeci@uea.ac.uk, phone: (**number**)

Appendix 11 – Ethical Approval

Patricia Kermeci
School of Environmental Sciences
UEA

Research and Enterprise Services
East Office (Arts Building)

University of East Anglia
Norwich Research Park
Norwich NR4 7TJ
United Kingdom
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7th October 2014

Dear Patricia,

I am writing to you on behalf of Professor Peter Kitson, Chair of the General Research Ethics Committee, in response to your submission of an application for ethical approval for your study 'Low-carbon housing and health'.

Having considered the information that you have provided in your correspondence Professor Kitson has asked me to tell you that your study has been approved on behalf of the Committee.

You should let us know if there are any significant changes to the proposal which raise any further ethical issues.

Yours sincerely

Tasha McGowan
Administrative Assistant
Research and Enterprise Services East Office
University of East Anglia
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Appendix 12 – Conversion Calculations

Decane conversion

10, 35 and 100 µl/l (from µl/l to µg/m^3)

Decane (density) = 0.7263g/ml @ 25^{o}C = 726.3g/l

100µl = 0.1ml

Density g/ml*ml = g

Density 0.73g/ml*0.1ml = 0.073g

0.073g*1000 = 73µg/m^3

0.73g/ml*0.035ml = 0.026g = 26µg/m^3

0703g/ml*0.01 = 0.073g = 7.3µg/m^3

Appendix 13 – Sensitivity Analysis of CO_2 levels

Duration (hours) and percentage of time (%) when temperature was over 26°C in the living room during the summer and CO_2 levels were over 500, 600 and 700 ppm.

	PH1		PH2		PH4	
	Hours	%	Hours	%	Hours	%
CO2>500	244.25	78	55	18	70.25	22
CO2>600	154.75	50	44	14	21.25	7
CO2>700	106.5	34	32.25	10	6.5	2

Duration (hours) and percentage of time (%) when relative humidity levels were under 40% in the monitored bedroom during the winter and when CO_2 levels were over 500, 600 and 700 ppm.

	PH3		PH4		PH5	
	Hours	%	Hours	%	Hours	%
CO2>500	216.25	70	94.25	30	169.25	54
CO2>600	155.5	50	80	26	116	37
CO2>700	111	36	61	20	69	22

Duration (hours) and percentage of time (%) when relative humidity levels under 40% in the living room during the winter and when CO_2 levels were over 500, 600 and 700 ppm.

	PH3		PH4		PH5	
	Hours	%	Hours	%	Hours	%
CO2>500	236	76	163.25	52	233	75
CO2>600	148	47	146	46	148	47
CO2>700	110	35	110	35	89	29

Thesis abbreviations, acronyms and units

ACH	Air changes per hour
Bq/m^3	Becquerels-per-cubic-metre
CEL	Critical exposure limit
CO	Carbon monoxide
CO_2	Carbon dioxide
COPD	Chronic obstructive pulmonary disease
CSH	Code for Sustainable Homes
°C	Degrees Celsius
DECC	Department of Energy and Climate Change
GHG	Greenhouse gas
H_2CO	Formaldehyde
IAQ	Indoor air quality
IEQ	Indoor environmental quality
IC	Indoor climate
kWh	Kilowatt-hour
LOAEL	Lowest observed adverse effect level
m	Metres
m^2	Metres squared
m^3	Metres cubed
mgm^{-3}	Milligram-per-cubic-metre
μgm^{-3}	Microgram-per-cubic-metre
µl/l	Microlitre-per-litre
min	Minutes
MMR	Mixed methods research
MVHR	Mechanical ventilation with heat recovery
MV	Mean vote
NHBC	National House Building Council
NTP	National Toxicological Program
NO_2	Nitrogen dioxide
NOAEL	No observed adverse effect level
Pa	Pascal
PM	Particulate matter
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfaction
ppm	Parts per million
RH	Relative humidity
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compound
VVOC	Very volatile organic compound

WHO	World Health Organization
W/m^2K	Watts-per-metre-squared-Kelvin
ZCH	Zero Carbon Hub

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